Lathe Machining in the Era of Industry 4.0: Remanufactured Lathe with Integrated Measurement System for CNC Generation of the Rolling Surfaces for Railway Wheels

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Abstract. Many projects and researches in the field of remanufacturing of specialized lathes are presented in the specialized literature. In the process of design for remanufacturing, a great number of solutions contain different aspects and data important to consider. The paper presents important stages of theoretical and applied research regarding the modernization of a conventional lathe with two working units by adaptation of four driving chains for CNC advance/ positioning movements and improvements of translation couplings, adaptation of CNC equipment for driving and measuring simultaneous both wheels mounted on axle. The reducing of geometrical errors of the running profile is very important in reshaping the worn wheelsets. The lathe remanufacturing process involves the restoration of functional requirements and measurement of the geometric precision. The CNC capabilities of the remanufactured lathe require a database of parametric representation of profiles and rolling surfaces using CAD techniques according to international standards.

Keywords: Railway wheel profile · CNC lathe remanufacturing · Rolling surface reshaping · Wheelset

1 Introduction

Future industry relies on new design concepts and methods, data acquisition, processing, visualization, automation and manufacturing technologies [1]. Industry 4.0, a term coined by the German Government, is to undertake the challenges in integrating technologies like Cyber-Physical Systems, the Internet of Things, and the Internet of Services to advance improvements in industry as shown in Fig. 1. One of the main identified challenges is lack of adequate skill-sets and human resources to expedite the march towards industrial 4.0.
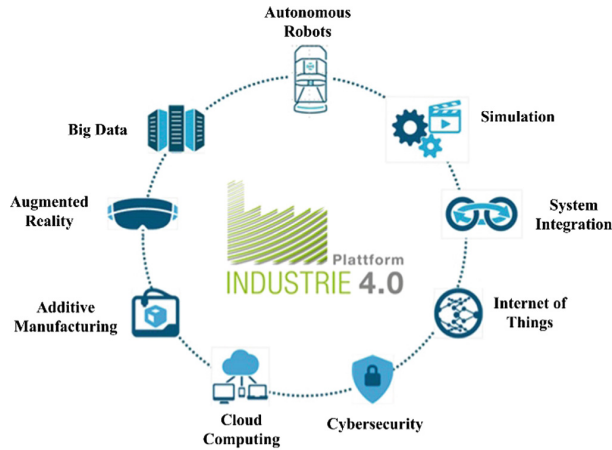
Fig. 1. Primary technologies of the new industrial paradigm – Industry 4.0

The lathes for processing the wheels and wheelsets of the railway vehicles are diversified and modernized in accordance with the requirements of railway transport standards and norms in the field. During the operation of the railway vehicle, the contact surfaces between the wheels and rail become worn [2]. This wear lead to changes in wheel and rail profile, contact surface and, consequently, to instability in the movement of vehicles. Therefore, the maintenance and repair of the rolling stock are important for traffic safety and passenger comfort [3, 4].

The wheelsets are the most loaded components of railway vehicles. They are subject of a continuous process of wearing according to difficult running conditions: non-uniform loads, alteration of rail and wheel profile, temperature variations, curved paths, sudden changes of speed, breakings, etc. In the moment that the wheels reach a critical level of wear, they must be reshaped or replaced, when the material to be removed by cutting exceeds a certain limit. Using wheels with appropriate profile reduce the risk of derailment and minimizes the dynamic interaction between the vehicle and the track, reducing noise, vibration and wear [5]. The researches in the domain of rail transport focus on increasing the reliability of the rolling stock and traffic safety, operating costs reduction, improvements of the manufacturing technologies, control, maintenance management, reduction of noise and wear in operation [6].

The main requirement of this approach is the profile processing and maintaining the contact surfaces of wheels and rails within geometric and functional parameters. Profiling and re-profiling of wheels are performed by technological processes on specialized lathes. Due to the high cost for acquisition of such a modern new machine tool, the manufacturers often have an option for the remanufacturing [7] of an existing machine tool. Thus, there is a need for development and implementation of an automated equipment for simulation, manufacturing and measuring of wheels running profile, both static and dynamic by adding driving, command and measurement systems. The remanufacturing costs are soon recovered by increasing the productivity and profiling/re-profiling accuracy. Also, the life of the lathe is highly increased.

2   Initial Setup: Structure of the Technological System

The analyzed technological system is composed of: a Polish machine tool UBC 150 RAFAMET lathe [8], modern measurement equipment, certain turning tools [9, 10] for this type of machine tool, CNC equipment, clamping devices, etc. A representation of the remanufactured lathe as it will be in the end of the project is done in Fig. 2 using a scheme of rotational and translational couplings that ensure the generation and auxiliary trajectories. The lathe processes the rolling surfaces of the wheelset in a single clamping, having two working units. Each one of these units has in its structure two radial sledges, a longitudinal sledge and a transversal sledge [11].

The two working units WU1 and WU2 have identical structures and driving systems. Their role, from the point of view of generating the running surfaces of the wheelset (WS), consist of movement B11, B12 and C1 for unit WU1, respectively, B21, B22 and C2 for unit WU2. Involving of wheelset in a cutting movement A (n_c) at both ends of the axle is ensured by two electric motors ME1, respectively ME2. The main spindles MS1 and MS2 using the clamping and fixing devices CD1, respectively
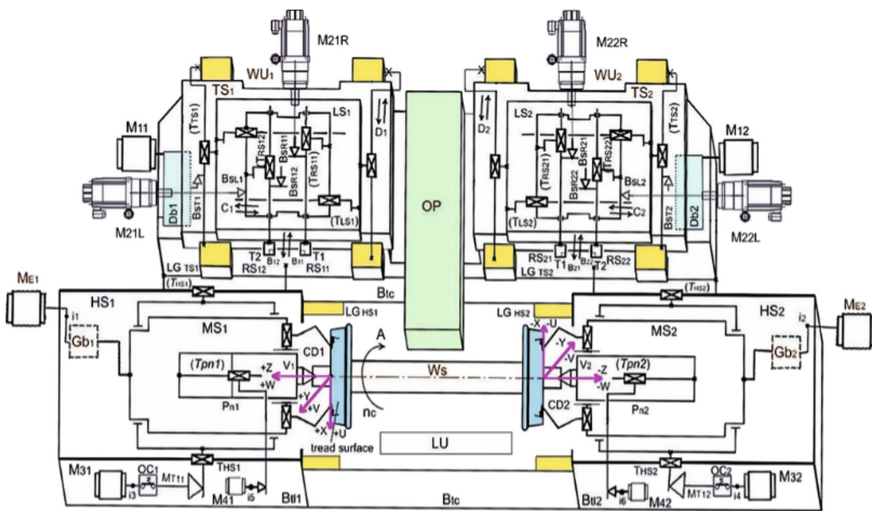
Fig. 2. Structure of the UB 150 RAFAMET lathe: A – main cutting motion, B1, B2 – advance radial motions and positioning, Bg – bearing, Bs – ball screws (L-longitudinal, T-transversal, R-radial), Btc – central bed, Btl – lateral beds, C1, C2 – advance longitudinal motions and positioning, CD – clamping devices, D1, D2 - transversal positioning, Db - distribution box, Gb – gearboxes, HS – headstocks, i - transmission ratios, LG – linear guides, LS1, LS2 – longitudinal sledges, LU - loading and unloading system of the wheelset, M11, M12 – advance and positioning electric drives with continuous adjustment, M21, M22 – synchronous servomotors (longitudinal L and radial R), M31, M32 – headstocks positioning electric drives, M41, M42 – pinolas positioning electric drives, ME11, ME12 – main electric drives, MS - main spindle, MT11, MT21 – nut screw mechanisms, OC – overload coupling, OP – operating platform, Pn – pinolas, RS11, RS12, RS21, RS22 – radial sledges, T1, T2 – tools, (TLS1), (TLS2) – translational couplings, TS1, TS2 – transversal sledges, (T), (R) – motion joints, Ws – wheelset, WU – working units.

CD2, provides driving rotational movement of the axle. The positioning movement is performed and controlled by CNC equipment on +Z and −Z directions, to determine the reference position depending on which they will be performed the movements for simultaneous processing of running profiles.

Figure 3 presents a simplified representation of the radial sledges RS' flow, of the longitudinal sledges LS and of the transversal sledges TS movements. There are indicated the electric motors M11, M21 for working unit WU1 and motors M12, M22 for working unit WU2 (see Fig. 2) [11]. Those movements (B11, B12, and C1) are performed with the feed rate v_{fn} for processing for positioning and with speed v_r for positioning. These movements are received from the motors M21, respectively M22. The D1 movement is achieved by motor M11 at the speed v_r and it is simultaneous with the D2 movement achieved by motor M12.
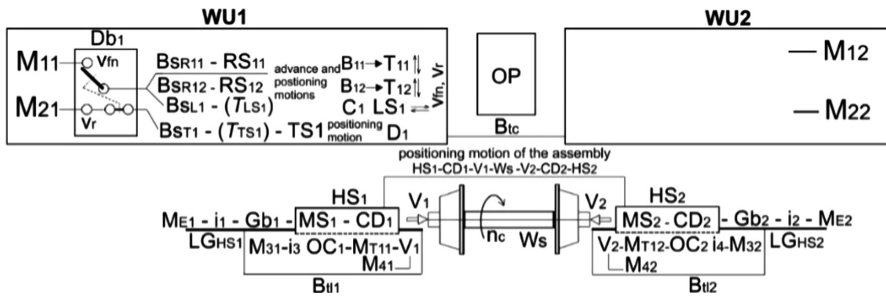

Fig. 3. The flow of the machining and positioning movements.

3 Requirements for Measuring Running Surfaces of the Wheels

In the Interoperability Technical Specifications relating to the "rolling stock" subsystem, developed according to the Directive 2008/57/CE, there are established the parameters of the wheel profiles. Running tread of the railway vehicles wheels is regulated by the normative covered by national and international rules [12]. The currently used profile of train wheels is composed of several spline segments, with fillet regions having well-defined geometry, forming a continuous curve at any point (Fig. 4). Since the form of the rolling profile is conditioned by form and inclination of the rails and because these parameters may vary from one country to another, each National Railway Administration has implemented or adopted a profile that satisfies the specific conditions of operating on its own railway network.

In Romania was created the profile S-78 [13], standardized for passenger and freight wagons fitted with UIC normalized flange.

Whatever form they have, profiles of the train wheels are defined by nine constructive areas. The UIC 510-2 [12] standard presents the main parameters that are defining the wheel profile: flange height, flange thickness, width of rim-tire, diameter of running tread, angle of external surface of flange.
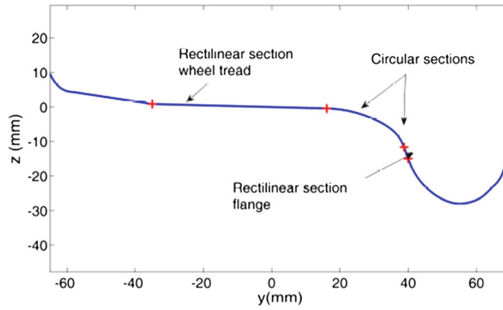
Fig. 4. Usual wheel profile geometry.

The designed shape of a wheel is represented by wheel profile drawing. The requirements to draw the wheel profile are described below and they are based on several parameters *Sd*, *Sh* and *qR* [1], which are represented in Fig. 5, where: *Sd* - flange thickness, *Sh* - flange height, *qR* - flange slope quota, *D* - running tread diameter, *ΔD* - deviation of this diameter, *L1* – top of flange, *L2* – total width of the profile, *L3* – running profile height. Usually, for the railway wheels, the most used values of the parameters are *L1* = 2 mm, *L2* = 70 mm, and *L3* = 10 mm. For tramways or light rail systems, these parameters may have different values.
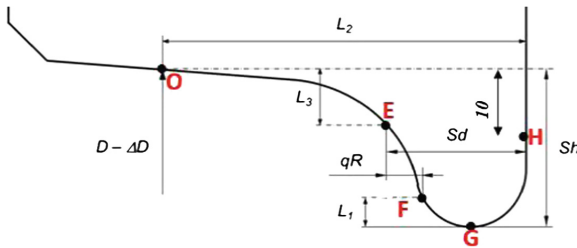
Fig. 5. Wheel profile standard values.

The flange thickness *Sd* is very important as it limits the lateral clearance of wheelset with respect to the track, which influences the vehicle stability and prevents it from derailment. The flange slope quota *qR* is also an important parameter because if it is too small, the wheel flange will be almost vertical, which implies that the transitions and the flange contacts will occur abruptly causing high contact forces that damage both wheel and rail. All these parameters can be measured and controlled using mechanical and optical instruments [14].

Wheel profile measurement must be made before re-profiling, to determine the wear and after processing, to determine the wheel conformity with specifications. Wheel profile measurement before and after re-profiling are still done on a large scale by manual methods. Manual measuring methods are more likely to generate errors and the operator may not be aware of them. The conventional systems are not capable of determining the correct position of a wheel profile to be obtained by re-profiling if the

wheel is too worn, especially along its wheel rim and wheel flange, especially when the worn wheel flange extends almost perpendicularly to the wheel rim.

Based on these criteria adaptation of measurement systems on the CNC lathe [15] has the following advantages:

– Allows measurement of the profiles of both wheels on the axle mounted on the machine tool before and after processing, in the same coordinate system as the turning system;
– Enables processing of measured data (before re-profiling) for choosing the optimal profile for both wheels of one axle to be obtained by removing the minimum quantity of material;
– Allows the measured data to be live recorded in order to create a database for rolling stock traceability and follow up the stocks. These data can be also statistically processed to improve the CNC re-profiling;
– Increases accuracy and measurement speed.

The modern measurement instruments are adapted to be mounted on the lathe with two tools posts integrated with CNC controller, each tool post comprising longitudinal sledge movable in Z-axes direction and radial sledge movable in X-axes direction.

To achieve precision measurements, the machine tool shall have high accuracy tool positioning, drive and control system, least vibration and noise level, because the measurement systems are placed on the same radial sledges as the tools [14]. Probing of the wheel profile is done with two measuring systems (Fig. 6), positioned on the radial sledges numerically controlled of the two working units.

The measuring cycle for determining the dimensional and geometric characteristics of the wheel profile is shown in Fig. 7. The measurement is carried out on radial and axial directions. The measurement results are processed, displayed and transformed in functions by the CNC equipment.
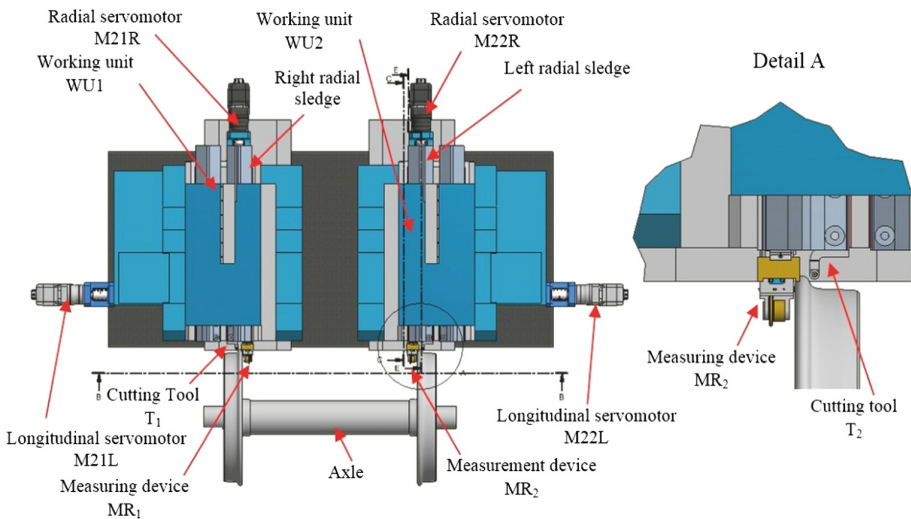
Fig. 6. Measuring system integrated on the same sledges with the tools.
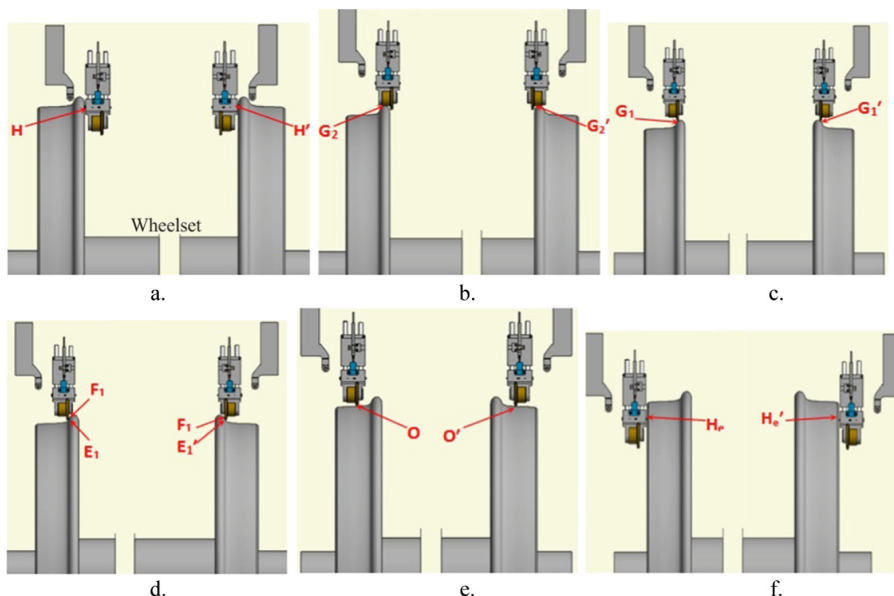
Fig. 7. Wheel profile measurement cycle: a. Internal frontal surface of wheel probing (points H and H′), b. Probing the top of the flange (G_2, G_2'), c. Probing the start point of the fillet of external flange surface (G_1, G_1'), d. Probing points delimiting external surface of the flange (F_1, E_1, F_1', E_1'), e. Probing the running diameter (O, O′), f. Probing the external surface of the rim (H_e, H_e').

The measurement cycle begins with the palpation/probing of a point on the inner front surface of the wheel (H point in Fig. 5) for determining the position of the profile with respect to the coordinate system of the machine tool. Then, the axle is rotated at low speed for determining the runout of the internal surface of the wheel. The measurement is made simultaneously for both wheels on the axle.

Maximum positive deviations determine the starting position of the cutting tools on longitudinal direction for profiles processing (Fig. 7).

For the equipment calibration, there is a method of palpating of one point on each of the wheel rolling surface, on the radial direction (points G2 and G2') and of a point on the internal frontal surface of each wheel (points H and H'). The transducers of the two measuring systems are set to the zero value. The calibration is done using an axle with known dimensions (standard wheelset, not used in traffic).

## 4   Application: Database of Wheels Profiles and Rolling Surfaces

For the CNC programming and machining of the wheels profiles it is necessary to create a digital database of templates with different profiles versions for the majority of the railway vehicles in traffic.

Each profile is defined by a set of complex equations which define a certain rolling zone, in contact with the rail at some point. The parameterization of the profiles [16] in a database is done using CATIA v5 program that leads to an increased flexibility in creating the machining program.

It is also possible to introduce certain correction parameters of the profiles that deviate over the allowable limits from the standard shape and facilitate the automated measurement and control of the rolling surface. The digitization of rail wheel profiles also allows to choose the optimal reshaping profile so the machine tool removes a minimum amount of material.

The old, metallic templates are partially or totally replaced by this database with profiles to increase the machining precision and productivity.

The UIC/ERRI profiles (Fig. 8) of the wheels are ruled by SR EN 13715 + A1-2011 [17]. The most used profiles are: the profile UIC/ERRI for wheels with diameter D = 1000 mm and d = 760 mm, having the flange height h = 28 mm, UIC/ERRI D = 760 mm, d = 630 mm, h = 30 mm and UIC/ERRI D = 630 mm, d = 330 mm, h = 32 mm. These profiles have many points in common in certain zones, being drawn by the same equations.
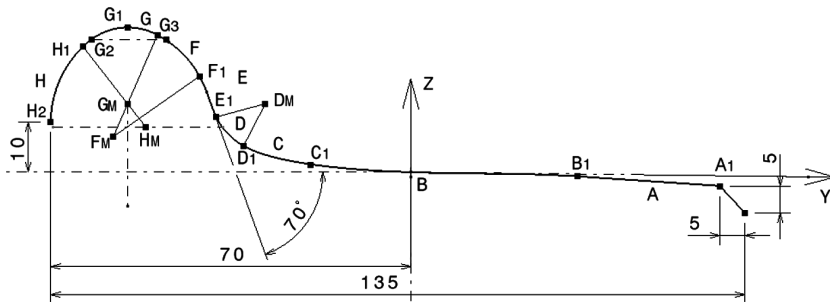
Fig. 8. General UIC/ERRI wheel profile

Following the standard UIC 510-2 [12], for each profile, the database contains a table with 263 pairs of points, having an increment of 0,5 mm on the horizontal Y axis. The respective coordinates on the vertical Z axis are given by the each formula corresponding to A…H zones. In the standard there are some check points on the profile, measured after a reshaping process. The profile may undergo some changes as a result of the shaping/reshaping on the lathe machine tool, but it must comply with the recommendations of the limit deviations specified in UIC norms and standards.

Also, on the profile there are marked the limit points delimiting its main zones and whose coordinates are used in the generation of the correct profile (A1, A2, .. H1, H2). Drawing and checking the profile is done using the parametric Eqs. (1)–(8).

As an example on how the database was created, we present by comparison two UIC/ERRI profiles for wheels with diameters ranging between D = 1000 mm and d = 760 mm and the flange height of 28 mm (first profile) with the UIC/ERRI D = 630 mm, d = 330 mm and h = 32 mm (second profile).

The quotas, in mm, on Z-axis of YOZ coordinate system for each zone, denoted A, B, …, H, are defined by the following equations:

$$Zone\ A:\ z = 1,364323640 - 0,066666667 \cdot y; \tag{1}$$

$$Zone\ B:\ z = 0 - 3,358537058 \cdot 10^{-2} \cdot y + 1,565681624 \cdot 10^{-3} \cdot y^2 - 2,810427944 \cdot$$
$$10^{-5} \cdot y^3 + 5,844240864 \cdot 10^{-8} \cdot y^4 - 1,562379023 \cdot 10^{-8} \cdot y^5 + 5,309217349 \cdot$$
$$10^{-15} \cdot y^6 - 5,957839843 \cdot 10^{-12} \cdot y^7 + 2,646656573 \cdot 10^{-13} \cdot y^8; \tag{2}$$

$$Zone\ C:\ z = -4,320221063 \cdot 10^{+3} - 1,038384026 \cdot 10^{+3} \cdot y - 1,065501873 \cdot 10^{+2} \cdot y^2$$
$$- 6,051367875 \cdot 10^0 \cdot y^3 - 2,054332446 \cdot 10^{-1} \cdot y^4 - 4,169739389 \cdot 10^{-3} \cdot y^5$$
$$- 4,687195829 \cdot 10^{-5} y^6 - 2,252755540 \cdot 10^{-7} \cdot y^7; \tag{3}$$

$$Zone\ D:\ z = +16,446 - \sqrt{13^2 - (y + 26,210665)^2}; \tag{4}$$

$$Zone\ E:\ z = +93,576\,667\,419 - 2,747477419 \cdot y; \tag{5}$$

$$Zone\ F:\ z = +8,834924130 + \sqrt{20^2 - (y + 58,558\,326413)^2};\ \ first\ profile \tag{6}$$

$$z = +12,568005262 + \sqrt{23^2 - (y + 63,109590233)^2};\ \ second\ profile \tag{6'}$$

$$Zone\ G:\ z = +16 + \sqrt{12^2 - (y + 55)^2};\ \ first\ profile \tag{7}$$

$$y = +20 + \sqrt{12^2 - (x + 55)^2};\ \ second\ profile \tag{7'}$$

$$Zone\ H:\ z = +9,519259302 + \sqrt{20,5^2 - (y + 49,5)^2};\ \ first\ profile \tag{8}$$

$$y = +13,519259302 + \sqrt{20,5^2 - (x + 49,5)^2};\ \ second\ profile \tag{8'}$$

As shown in the equations presented above, the A -> E zones are identical. These equations were determined by theoretical and experimental studies.

In order to check the profiles, there are established the validity zones through the points A (from y = +60 to +32,158), B (y = +32,15796 to −26), C (y = −26 to −35), D (y = −35 to −38,4267), E (y = −38,4267 to −39,7645), F (y = −39,7645 to −49,6625), G (y = −49,66251 to −62,7647), H (y = −62,764705 to −70), in mm for the first profile. For the second profile, the coordinates are: A (y = +60 to +32,15796), B (y = +32,15796 to −26), C (y = −26 to −35), D (y = −35 to −38,426669071), E

(y = −38,426669071 to −41,496659950), F (y = −41,496659950 to −46,153174292), G (y = −46,153174292 to −62,764705882), H (y = −62,764705882 to −70), in mm.

The curves centers coordinates are: DM (y = −26,211, z = +16,45), FM (y = −58,558, z = +8,835), GM (y = −55, z = +16), HM (y = −49,5, z = +9,52), in mm for the first profile and DM (y = −26,210665, z = 16,446), FM (y = −63,109590233, z = 12,568005260), GM (y = −55, z = 20), HM (y = −49,5, y = 13,519259302), in mm for the second profile.

It can be observed that many coordinates are identical for the two profiles, leading to an easier CNC programming and a more flexible database [17].

The values that are mapping the profile have a very good accuracy up to nine decimal places, their compliance is important, being determined by satisfying the kinematic and dynamic conditions. All these data are stored in the database to be used in the CNC machining process and in the measurement and control phases.

The coordinates of all points on each profile were created using the Eqs. (1) to (8) in the Microsoft Excel program. A part of the table, with several pairs of coordinates, is shown in Table 1. It can be observed the increment of 0,5 mm on the Y axis and the respective calculated values on the Z axis applying the formula in the $f(x)$ field.

Table 1. Coordinates of points (pairs) defining the profile.

B10   fx   =1,36432364-0,0666666667*A10

A	B	C	D	E	F	G	H	I	J	K	L	M	N
y	z	13	54,5	-2,26901	25	48,5	-1,86901	37	42,5	-1,46901	49	36,5	-1,06901
60	-2,63568	14	54	-2,23568	26	48	-1,83568	38	42	-1,43568	50	36	-1,03568
59,5	-2,60234	15	53,5	-2,20234	27	47,5	-1,80234	39	41,5	-1,40234	51	35,5	-1,00234
59	-2,56901	16	53	-2,16901	28	47	-1,76901	40	41	-1,36901	52	35	-0,96901
58,5	-2,53568	17	52,5	-2,13568	29	46,5	-1,73568	41	40,5	-1,33568	53	34,5	-0,93568
58	-2,50234	18	52	-2,10234	30	46	-1,70234	42	40	-1,30234	54	34	-0,90234
57,5	-2,46901	19	51,5	-2,06901	31	45,5	-1,66901	43	39,5	-1,26901	55	33,5	-0,86901
57	-2,43568	20	51	-2,03568	32	45	-1,63568	44	39	-1,23568	56	33	-0,83568
56,5	-2,40234	21	50,5	-2,00234	33	44,5	-1,60234	45	38,5	-1,20234	57	32,5	-0,80234
56	-2,36901	22	50	-1,96901	34	44	-1,56901	46	38	-1,16901	58	32	-0,76901
55,5	-2,33568	23	49,5	-1,93568	35	43,5	-1,53568	47	37,5	-1,13568	59	31,5	-0,73471
55	-2,30234	24	49	-1,90234	36	43	-1,50234	48	37	-1,10234	60	31	-0,70353

These parametric values, in pairs, are inserted into CATIA v5 program. Due to the complexity and accuracy of the wheel profile and shape, it is used the Generative Shape Design (GSD) module and a file GSD_PointSplineLoftFromExcel.xls. The file also contains a few code lines to run a Macro.

If the coordinate values are correctly determined and sequenced in the Excel file, as a result of running the Macro in the Sketcher module, these points are inserted and connected by a spline curve. This is, in fact, the complex curve that establishes the profile to be followed for machining, as trajectory of the cutting tool edge tip through simultaneous movements on the two numerically controlled axes (see also Fig. 2).

The representation of the rolling surface of the wheel is possible by the profile rotation around the axis of the axle, located at the coordinate z = 450 mm (for the first profile) related to the point B in Fig. 8. This point B is located on the profile in the median plane of the running tread.

Fig. 9. Wheel surface obtained based on the parametrically drawn profile

The profile and surface are continuous and correct represented in Fig. 9. There is no need to model the other elements of the wheel, the simulation of the shaping/reshaping machining and the creation of the CNC code are possible based on this surface.

On the generated profile, created by points, but also on the obtained rolling surface, it is possible to apply different techniques to verify the precision of the drawing. These 263 pair of points are enough for an accurate resolution of the profile and surface. If a better precision is necessary, it can be achieved by decreasing the increment between the points on Y-axis, appropriately increasing their number.

The rolling surface thus established turns into solid using the Part Design module of CATIA v5 program. With this parametric surface (for each profile in the database) it is possible to perform the turning process simulation and develop the CNC program [18]. The complete modeling of the wheel and axle is certainly possible and even necessary in order to conduct complementary simulations to determine the mass, center of gravity position for various analyses (forces, stresses, temperature variations etc.) by the Finite Element Method.

5   Conclusions

The paper analyses the importance of the profile shape and the rolling surface quality of the railway vehicle wheels in accordance with the European and Romanian standards.

The parametric drawing methodology of the wheel profile shown in this paper aims to improve the shaping/reshaping by the cutting process of the rail wheels in order to improve the operating behavior of the wheel-rail coupling.

Following the modeling stages of the rolling surface and CAM simulation ones until obtaining CNC code, it is ensured the creation of a database with complex information on the profile shape, recommendations of the working parameters depending on the tools and on the chosen machine tool.

The creation of this database contributes to the modernization of RAFAMET UBC 150 lathe in accordance with the terms of the research contract and represents an important stage which will lead to an increased number of orders received by the

beneficiary partner, but also as a working model for other users with manufacturing activities in the field.

The paper proposes, also, a complex structure of a measuring mechatronic system to be used in the profile evaluation after the processing on the lathe, versus the theoretic drawn profile. Implementing the profile measurement systems on CNC machine tools allows increasing the efficiency, quality, capability and accuracy of wheelsets profiling/re-profiling. Standard routines built into modern CNC controls simplify the integration of measuring cycles into machining operations.

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