APPLICATIVE CAD/CAM METHODOLOGY FOR PARAMETERIZATION THE ROLLING SURFACE OF RAILWAY WHEELS

Ionuț Gabriel GHIONEA[1], Doina CIOBOATĂ[2], Adrian GHIONEA[3], Saša ĆUKOVIĆ[4]

During the operation of the rolling stock, the contact surfaces of the wheels and rail become worn. The wear can lead to unwanted changes of the wheel and rail profile and, consequently, to changes in the properties of the contact surfaces which can direct to instability in the movement of vehicles. Therefore, the maintenance and repair of the rolling stock are important for traffic safety and passenger comfort.

The paper presents the main types of defects that arise while rolling the wheels of the rail transport vehicles, some types of machine tools and cutting tools and recommended values of shaping or reshaping parameters. It is also presented a methodology of parametric representation of profiles and rolling surfaces using CAD techniques. There are analysed some profiles among those indicated in European norms in the field.

Keywords: railway wheel sets, wheel lathing, railway wheel profile, wheel wear

1. Introduction

The development in the field of the current railway transport focuses on the manufacture and operation of a new generation of vehicles characterized by increasing the reliability of the rolling stock, increasing the cruising speeds and achieving a high level of traffic safety [1], reducing the costs of design and manufacture/remanufacture, operation and maintenance, reducing the time and costs assigned to the repairs [2], compatibility with the rail infrastructure in the European Union countries etc.

The rolling profile of the railway vehicles wheels must fit within the geometrical characteristics governed by internal and international regulations [3],

[1] Eng. Lecturer PhD, Dept. of Machine Manufacturing Technology, University POLITEHNICA of Bucharest, e-mail: ionut76@hotmail.com
[2] Eng., PhD The National Institute of Research and Development in Mechatronics and Measurement Technique, e-mail: cioboatadoina@yahoo.com
[3] Eng. Prof. PhD, Dept. of Machines and Manufacturing Systems, University POLITEHNICA of Bucharest, e-mail: adrianghionea@yahoo.com
[4] Eng., PhD student, Faculty of Mechanical Engineering Kragujevac, University of Kragujevac, Serbia, e-mail: cukovic@kg.ac.rs

[4], being an important factor for the passengers' comfort and decrease of the environmental impact by reducing the noise caused by the wheel – rail contact [5], according to the current standards.

In recent years more and more emphasis is placed on the development of modernized or new advanced equipment, that enables precise machining and accurate measurement of the wheel and rolling tracks profiles both in static and dynamic mode [6].

The surface and profile of the railway vehicles wheels have a complex geometry that must fit within certain sizes governed by national and international regulations [7]. The wheels and the wheel set are the most stressed components of railway vehicles and are subject to a continuous process of wear.

Under difficult conditions of loading, rolling and braking on the wheel surface (fig. 1) they appear cracks, flattening, metal deposits, etc., which negatively influence the performance of the vehicle. It appears, thus, an increased risk of derailment, there is minimized the vehicle-rail dynamic interaction, with an increased noise and vibration, the wears are emphasized, both at the level of the wheel and at the level of the wagon's suspension system [7].

Fig. 1. Defects of the wheels due to excessive wear

When the wheels attain a critical level of non-compliance, they need to be reshaped or even replaced if the machining cutting depth exceeds the limit marked. Reshaping the wheels of the railway vehicles is an important part of the rolling stock maintenance.

This paper proposes an applicative methodology for parametric drawing of the rolling profiles and surfaces using the CATIA v5 program. The parameterized surface can be used in order to achieve digital templates for the lathing process, measurement and analysis of the rail wheel profile.

It is also useful a functional model of a cutting process, measurement and analysis system of the rail wheel profile, on a shaping/reshaping technological system using a specialized, numerically controlled machine tool [8] for wheel sets or wheels in mass production.

2. Machine tools and cutting tools for wheel reshaping

In the Interoperability Technical Specifications relating to the "rolling stock" subsystem, developed according to the Directive 2008/57/CE and its annexes, there are established the parameters of the wheel profiles and it is specified the fact that the compliance assessments must be documented.

Fitting the wheel profile within the geometrical sizes established by regulations represents an important requirement for the railway traffic safety, essential for increasing the operational performance. It is theoretically proven [9] and by numerous experimental researches that the wheel and rail profiles influence the sustainability of the wheel-rail coupling when rolling, but also the passengers safety and their comfort by reducing the noise and vibration level [7].

Currently, several types of specialized machine tools such as horizontal or vertical lathes are used, with one or two main shafts. By applying the technological lathing process, the following types of machining are carried out: reshaping of a single wheel, simultaneous reshaping of both wheels mounted on axle, lathing of the wheel profile dismounted from the vehicle and lathing of the wheel profile without being dismounted from the vehicle.

Depending on the destination, several types of lathes were developed: mounted underground [7], fig. 2,a. or at ground level, placed on foundations. The first are generally used for rail wheel reshaping without dismounting the wheels from the vehicle.

a. Lathe mounted below the ground level

b. Ground-mounted lathe

Fig. 2. Lathes for machining/profiling the rail wheels

Ground-mounted lathes (fig. 2,b.) are used for machining the wheel/axle profiles that are not mounted on the vehicle. These lathes are intended for machining in the repair and maintenance workshops or those that manufacture the wheel set. In recent years it has been observed an increased interest for the automation of wheel reshaping process and measurement systems adapted on machine tools equipped with CNC.

The company RAFAMET [10] from Poland makes surface lathes in the non-automated version with template type port program and electrical copying system with contacts, partially automated, and in the version with 2+2 numerically controlled axis for radial and longitudinal sledges.

In Fig. 3 is presented a partial view of RAFAMET UBC 150 lathe from the equipment of SC Uzina de Vagoane Aiud. The modernization of the lathe, with the purpose to adapt two numerically controlled, translation axis, for each working unit and implement a modern measurement and control system, is a constituent part of a national research project PN-II-PT-PCCA-2013-4-1681, with completion in 2016.

Fig. 3. RAFAMET UBC150 lathe in its current, non-automated version [8]

Recently manufactured lathes, with numerical control are modern machine tools and many repair workshops do not have the necessary funds for such a facility that includes electric motors, command, control and measurement equipments.

There is, however, the possibility of modernizing many of the existing lathes by integrating CNC equipments, related systems and methods of measuring the machined surfaces according to the requirements in the field.

The automation of the lathes and using equipments with advanced measurement systems represents a necessary modernization version of the technological processes that are applied in repair and maintenance workshops of the rolling stock. CNC equipments provide the achievement of several command and control functions of machine tools that involves coordinating the drives, establishing the number of passes, the control and limitation of movements on the controlled axes, the control of the generation movements (main, feeding), optimization of the machining parameters and display of the generated trajectory.

The main advantages of using numerically controlled lathes for reshaping the rail wheels are: it is eliminated the need of using a large number of expensive, rigid, difficult to execute and adjust templates; the numerical programs are flexible, they can be easily modified in order to move from one type of profile to another, the adjustment errors of the operator are eliminated, it is allowed the automation of the entire machining process. The major disadvantage of using this type of equipment is represented by the high costs of implementation, maintenance and repair compared to a common machine tool.

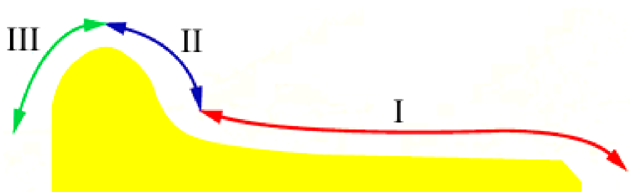
The machining precision of the profile is influenced by the precision of executing, clamping and adjusting the template and of the gauge and especially of the transducer with copying contacts.

The cutting tools (Fig. 4) recommended for reshaping of the wheels for the rail transport vehicles usually have two inserts geometrically defined in the catalog [11], [12] and can machine the entire wheel profile in a single pass.

Fig. 4. Tools and examples of the profile longitudinal machining

According to the active part geometry of the tools, wheels and machining method, the longitudinal lathing is carried out with an insert fixed on the tool holder, having a length of 30 mm and the radius at the tip of the main cutting edge of 4 mm.

This insert can be used for the roughing and semi-finishing machining of the I^{st} and II^{nd} zones (fig. 5). The second tangential insert, with a length of 19 mm and a radius of 4 mm, is positioned perpendicularly to the largest insert and it is used to machine the III^{rd} delimitation zone of the wheel. The cutting depth may range from a_p: 0.3… 2 mm, depending on the condition of the surfaces that form the three zones I, II and III along the wheel width (fig. 5). In the table attached to the figure there are indicated some recommendations for the machining parameters to the lathing of the rolling surface profile.



Zone	Cutting speed, v_c [m/min]	Cutting depth, a_p [mm]
I	30-70	0.3 – 1.8
II	50-100	0.5-2.0
III	50-100	0.5-2.0

Fig. 5. Recommendations for the lathing parameters of the three zones of the wheel profile

For the lathe machining of the wheel profile, RAFAMET manufacturer recommends using inserts of hard material, quality S30 [10]. Establishing the working parameters is done depending on the permissible size of the cutting tool edge wear, but also on the hardness of the surface to be machined. Thus, for wheels on whose surfaces there are hardened zones or non-metallic inclusions/ deposits it is recommended to reduce the cutting speed by modifying the speed level of the main shaft, selecting as appropriate one of the speeds n_c: 9, 11.2, 14, 18, 22.4, 28, 35.5 rev/min, stepped adjustment: electric motor with two speeds and adjusting mechanism by gearbox.

3. Considerations on the profiles and rolling surfaces of the wheels

The classification and indication of the geometric parameter limits for the railway vehicle wheels are indicated by EN 15313 standard [13] and in [3]. All constructive versions of wheel sets [14], [15], [16] on which the wheels cannot turn independently of one another or related to the axle. On the periphery, each wheel is provided with a lip (zones II, III, fig. 5) having a profile and sizes that are designed to provide the vehicle guidance inside the two rails of the railway, with a rolling surface which rolls on the rail (zone I).

The wheel profile is given by its periphery contour in a median plane of the wheel set. This profile is complex, being composed of a multitude of spline curves [3], 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.

Depending on the shape of the rolling surface, there are used tapered profiles and so-called profiles of wear [3]. Originally, the purpose of the tapered profiles was to prevent longitudinal sliding occurring between wheels and rails when driving on curves and to achieve a centering of the axle so that it does not permanently run in contact with the lip. Since there is a wide variety of vehicles with different modes of driving on curves with different radius, avoiding longitudinal sliding is not possible and the centering achieving condition is not fulfilled on tapered profiles.

The European railway authorities have experimented profiles with different tapering of the rolling surface, to find an optimal solution that guarantees both the traffic safety and a good driving quality of the vehicle [17].

The most widespread tapered profile is the normal UIC profile (International Union of Railways), with internationally and internally standardized shape and sizes (STAS 112 / 3-90).

A disadvantage of the tapered rolling surfaces consists in that it typically yields the dual-contact with the rail that is in addition to the contact on the rolling surface it also appears a contact point on the lip. These contact points are vertically and longitudinally shifted between them. The additional sliding, determined by these gaps, yields a pronounced wear during rolling by abrasion with important material dislocations from the flank of the lip guidance zone and the inner flank of the rail, being also amplified by the longitudinal sliding on the rolling surface.

The wear of the wheel-rail coupling surfaces is influenced not only by the sliding, but also by the stresses and irregularities in the contact zone. Subject to the action of the normal forces, due to the wheel and rail material deformation, the contact is made on an elliptically shaped zone, the contact points being the centers of these ellipses [3]. The coefficients of friction and adhesion depend on the sizes and orientation of the ellipse along the rail or crosswise on it. The wears are all the more evident as the ellipse sizes are smaller and the normal force (wheel load), respectively the guidance ones, are higher.

At the beginning, the wear determines the profile change, on the same zone, in a concave shape with different slopes, which then determines a displacement of the contact points on the rail and, therefore, a gradual expansion of the contact point zone on the wheel and rail [14].

After approximately 20,000-30,000 rolling km, the profile reaches a stabilized shape of wear, which does no longer changes over time. At the same time, the dual contact disappears and the lip wear process slows down. This finding suggested the idea of achieving from the beginning a wear profile with a stable shape that functions under single contact conditions on all types of rail used on the network.

On such a profile, as the wear manifests through a translation parallel to the axis of the axle, without the noticeable changing of the lip thickness, the repairs which are carried out during the revision period can be often summed up to correcting the tip portion of the lip, but also to correcting the outer zone of the rolling surface, without interventions on the hardened part on the rolling surface and lip connection.

Since the stable shape of the wheel profile is conditioned by the shape and inclination of the rails and as these parameters vary from one country to another, each railway authority achieved or adopted a wear profile that meets the specific operating conditions on its own railway network.

The need of introducing profiles of wear was imposed as a consequence of the unfavorable effects, with economic and technical implications. The studies conducted by ERRI, UIC (Union Internationale des Chemins de Fer), Technical Committee of CEN European Norm Elaboration, led to the achievement of internationally unified profiles.

4. Wheel profile drawing and obtaining the rolling surface

For the numerically controlled machining of the wheel profiles it is necessary to achieve digital templates with as many versions of wheel profiles of the railway vehicles in traffic. When drawing these profiles will be also taken into account the possibilities that the current machine tool, in non-automated version, has for machining.

Each profile is defined by complex equations which characterize a certain rolling zone, in contact with the rail at some point. The parameterization of the profiles and their drawing using CATIA v5 program leads to an increased flexibility in creating the NC 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 it is facilitated the automated control of the rolling surface.

The old means and methods of measurement and control, the templates for shaping are thus partially or totally replaced, increasing the machining precision and productivity. The digitization of rail wheel profiles also allows choosing the optimal reshaping profile so that by lathing it is removed a minimum material quantity.

For exemplification, it was considered UIC/ERRI profile for wheels with diameters ranging between D = 1000 mm and d = 760 mm and the lip height of 28 mm (Fig. 6). On the profile there are marked the points delimiting its main zones and whose coordinates are essential for the generation of the correct profile [3], [7]. Drawing and checking the profile is done based on the parametric equations set for each zone within A-H range. The coordinates of the limit points and those of the curves' centers that define the profile, denoted $D_M…H_M$ are also presented.

The profile may undergo some changes as a result of the shaping/ reshaping on the lathe, but it must comply with the recommendations of the limit deviations specified in UIC norms and standards [16].

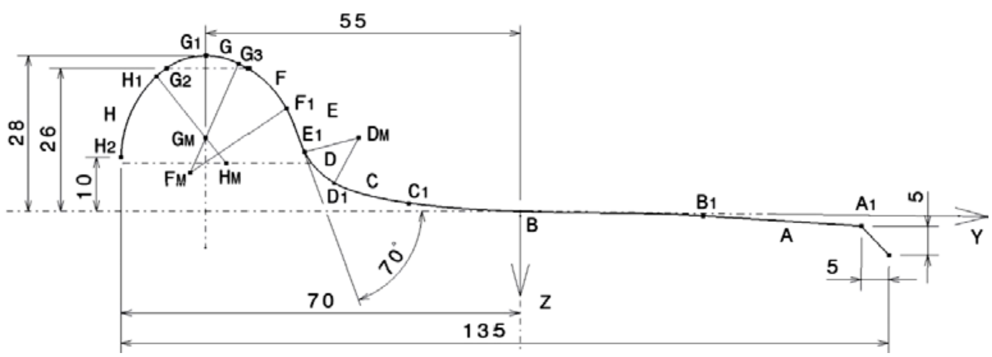


Fig. 6. UIC/ERRI wheel profile with diameters between D = 1000 mm and d = 760 mm

The quotas, in mm, on Z-axis of YOZ coordinate system for each zone, denoted *A, B, ..., H,* are defined by the following equations [3]:

Zone A: $z= 1{,}364323640 – 0{,}066666667\cdot y;$ (1)

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

Zone C: $z= – 4{,}320221063\cdot 10^{+3} - 1{,}038384026\cdot 10^{+3}\cdot y -1{,}065501873\cdot 10^{+2}\cdot y2 -$
$6{,}051367875\cdot 10^{0}\cdot y3 - 2{,}054332446\cdot 10^{-1}\cdot y^4- 4{,}169739389\cdot 10^{-3}\cdot y^5 –$
$4{,}687195829\cdot 10^{-5} y^6 - 2{,}252755540\cdot 10^{-7}\cdot y^7;$ (3)

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

Zone E: $z = +93{,}576667419 - 2{,}747477419\cdot y$; (5)

Zone F: $z = +8{,}834924130 + \sqrt{20^2 - (y + 58{,}558326413)^2}$; (6)

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

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

In order to check the profile, it is established the validity zone through the points A (y = + 60, y = + 32,158), B (y = + 32,15796, y = - 26), C (y = - 26, y = - 35), D (y = - 35, y = - 38,4267), E (y = - 38,4267, y = -39,7645), F (y = - 39,7645, y = - 49,6625), G (y = - 49,66251, y = - 62,7647), H (y = - 62,764705, y = -70).

The limit point coordinates of the profile are also identified. These are mandatory and will be considered in the process of establishing the part program corresponding to the numerically controlled equipment. For the analysed case, these are: A_1 (y= +60, z= -2,636), B_1 (y= +32,158, z =-0,780), C_1 (y= -26, z = +2,741), D_1 (y = - 35, z = +6,867), E_1 (y = - 38,427, z = +12), F_1 (y = - 39,764, z= +15,675), G_1 (y= - 49,553, z= +25,748), H_1 (y= - 62,765, z= +25,149), H_2 (y = - 70, z = +9,519), in mm.

The curves centers coordinates are: D_M (y= -26,211, z= +16,45), F_M (y= - 58,558, z= +8,835), G_M (y= -55, z= +16), H_M (y= -49,5, z= +9,52). Using the equations that determine the profile according to A->H zones, 263 pairs of points were created using Microsoft Excel program. A part of the table, with 30 pairs of coordinates, is shown in fig. 7.

According to the values in the table, the first point of the profile is even A_1 (y= +60, z= -2,636), the other points are positioned on the Y-axis with an increment of 0,5 mm, the coordinate on Z-axis being given by the formula corresponding to A->H zones. Figure 7 also shows a formula as inserted and accepted by Excel.

Of course, the limit points of the profile are found among those calculated, also having a role of verifying the precision of the equation writing.

B4 =1,36432364-0,0666666667*A4

	A	B	C	D	E	F	G	H
1	y	z		y	z		y	z
2	60	-2,63568	12	55	-2,30234	22	50	-1,96901
3	59,5	-2,60234	13	54,5	-2,26901	23	49,5	-1,93568
4	59	-2,56901	14	54	-2,23568	24	49	-1,90234
5	58,5	-2,53568	15	53,5	-2,20234	25	48,5	-1,86901
6	58	-2,50234	16	53	-2,16901	26	48	-1,83568
7	57,5	-2,46901	17	52,5	-2,13568	27	47,5	-1,80234
8	57	-2,43568	18	52	-2,10234	28	47	-1,76901
9	56,5	-2,40234	19	51,5	-2,06901	29	46,5	-1,73568
10	56	-2,36901	20	51	-2,03568	30	46	-1,70234
11	55,5	-2,33568	21	50,5	-2,00234	31	45,5	-1,66901

Fig. 7. Pairs of points belonging to the profile

The pairs of points parametrically determined are inserted into CATIA v5 program. To that purpose, 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 pairs of points are correctly determined and sequenced in the file, as a result of running the Macro in Sketcher module, the 263 points become available, linked by a spline curve [18]. 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 Z and Y numerically controlled axes.

For each axis it is used a kinematic chain composed of electric servo motor, gear reducer, screw-nut precision mechanism and transducer. Such a structure ensures generation movements (feeding), with the v_f speed [mm/min] and auxiliary, approach and fast withdrawal movements.

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 related to the point B in fig. 6.

The profile and surface are continuous and correct represented in fig. 8. There is no need to model the other elements of the wheel, the simulation of the shaping / reshaping machining and the creation of CNC code are possible based on this surface.

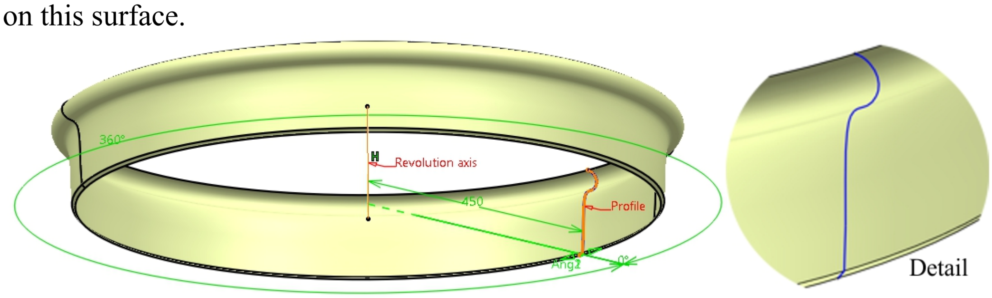


Fig. 8. Wheel surface obtained based on the parametrically drawn profile

On the profile generated, created by points, but also on the rolling surface obtained, may be applied different techniques to verify the precision of the drawing. These 263 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 step between the points on Y-axis, appropriately increasing their number.

The rolling surface thus established turns into solid using Part Design module of CATIA v5 program. 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. Generation of the machining trajectories by CAM simulation

At this stage, the 3D model of the wheel set is inserted in Lathe Machining module. The surface is machined by coordinated movements of the tools, fixed in the radial sledge [8] of each working unit.

By positioning, generating and measuring movements it is achieved the orientation of the tool cutting edge on the two CNC axes of the machine's two working units. It is generated the real profile of the wheel's rolling surface having as benchmarks, points measured by the measurement and control system, but also the parametric equations defining the prescribed profile (fig. 6). For the simulation precision it is necessary that the model thus created is similar to the real wheel surface.

CAM simulation module requires linking the geometric parameters of the profile and tool cutting edge with the technological parameters. For this, there are used tool libraries, optimal trajectories, working parameters etc. [19]. At the configuration stage of the machining parameters are imposed conditions by which these libraries are chosen depending on the machining criteria (roughing/ finishing, number of passes, etc.).

For the smoothing of the machined surface, at a first stage is proposed and defined roughing machining of the profile from two directions with a specialized tool [11], [12]. At the next stages there are elaborated machining strategies from multiple passes. The cutting depth is defined as a parameter that can be calculated and/or modified by the user. Other cutting parameters are introduced based on the standard calculation methodology, also following the recommendations of the tools manufacturing companies.

After the process simulation and the application of various corrections necessary, CATIA v5 program calculates and represents the trajectories to be machined (fig. 9), the estimated working time, potential collisions between the tool and the wheel or between the tool and the clamping-fixing device etc.

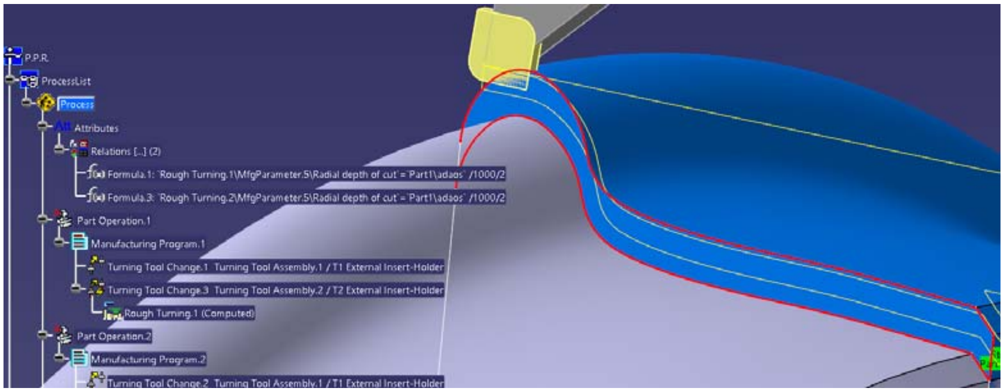


Fig. 9. CAM Simulation for the generation of the machining trajectories

By editing the working parameters chosen or indicated by the program, the technologist has the possibility of choosing the optimal variants of trajectories, the shape of the tool's cutting edge and the working parameters based on criteria imposed by the specific conditions in which the axle is located.

The numerical code obtained by simulation (fig. 10) is easily adaptable to a large range of lathes and CNC equipments having different post-processors [20]. It is advisable to check the code using specialized programs.

```
%1000
N1 G54 G64 G40 G90 G17 G94 G49 G80
N2 G53
N3 T1 M6
N4 G0 X456.364 S70 M4
N5 Z3.657
N6 G1 G95 Z1.657 F.3
N7 X461.253 Z-3.232 F.4
N8 X461.465 Z-3.02 F.8
N9 G0 Z6.
N10 X451.364
N11 G1 Z4. F.3
N12 Z1.657 F.4
N13 X456.253 Z-3.232
N14 X456.355 Z-4.728
N15 X458.377 Z-35.283
N16 X458.379 Z-35.331
N17 G3 G18 X458.674 Z-44.098 CR=235.912
N18 G1 X458.675 Z-44.128
N19 X458.883 Z-60.681
N20 G2 X459.289 Z-71.317 CR=294.753
N21 X459.944 Z-79.566 CR=177.842
N22 G1 Z-79.568
N23 G2 X460.77 Z-85.785 CR=103.986
N24 X461.702 Z-90.359 CR=59.373
N25 G1 X461.705 Z-90.372
N26 G2 X462.646 Z-93.538 CR=31.986
N27 X463.471 Z-95.401 CR=13.696
N28 X464.392 Z-96.8 CR=9.701
N29 X468.124 Z-99.575 CR=8.999
N30 G1 X472.402 Z-101.139
N31 X473.888 Z-101.762
N32 X475.362 Z-102.505
N33 X476.779 Z-103.348
N34 X476.84 Z-103.387
N35 G3 X484.844 Z-111.955 CR=23.999
N36 X486.112 Z-114.743 CR=17.251
N37 G1 X486.117 Z-114.759
N38 G3 X487. Z-120. CR=16.
N39 G1 Z-131.
N40 X487.212 Z-130.788 F.8
N41 G0 Z6.
N42 X446.364
N43 G1 Z4. F.3
N44 Z1.657 F.4
N45 X451.253 Z-3.232
N46 X451.355 Z-4.728
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Fig. 10. CNC code sequence obtained by simulation

6. 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 regulations in the field. 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 behaviour 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.

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