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The Use of the Rapid Prototyping Method for the Manufacture and Examination of Gear Wheels

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1. Introduction

Rapid prototyping systems make it possible to manufacture prototypes of complex shapes, including gear wheels prototypes. RP systems are increasingly employed in gear wheels testing. The use of RP systems is particularly vital to the process of manufacturing gear wheels of non-standard (non-involute) tooth profile. For this kind of gear wheels, it is not possible to use traditional tools for tooth cutting; therefore the prototypes of such gear wheels are made by the RP methods directly on the basis of the 3D-CAD model.

The chapter is composed of four parts. Part 1 provides an analysis of RP methods in terms of application for the manufacture of gear wheels. Part 2 describes the method for preparing geometric data for the RP process. Part 3 discusses the determination of the real geometric accuracy of gear wheels prototypes made by means of selected RP methods. Part 4 shows the possibility of using RP systems for gear wheels testing, including tooth contact analysis (TCA) and fatigue tests of non-involute gear wheels.

2. An analysis of RP methods in terms of application for the manufacture of gear wheels

The subject matter of his chapter centers around RP techniques utilizing processes of shaping the model through the increment of material, consisting in its gradual addition until the moment of obtaining the required shape. The manufacture of the model involves the conversion of the object computer imaging into its physical form, with a minimal manual intervention and in the shortest time possible (fig. 1). The first step in the rapid prototyping process is to define the object as a computer-generated CAD-3D model. The achieved image is then converted into a specific form of data set by means of various formats of data conversion, suitable for RP systems (Budzik, 2009).

Almost all available rapid prototyping methods are based on the same rule of dividing the model into horizontal layers, from which the physical prototype of the object is built in the proper order. In this way, the incremental shaping of objects becomes very effective in the case of piece or small-batch production.

On account of high dynamics of changes in the field of RP systems, the percentage of individual RP methods in the market is also changing rapidly. RP processes can be classified according to a wide range of division criteria, including:

- the kind of input data,
- the physical or chemical principle of operation of the RP method,
- the initial state of the processed materials,
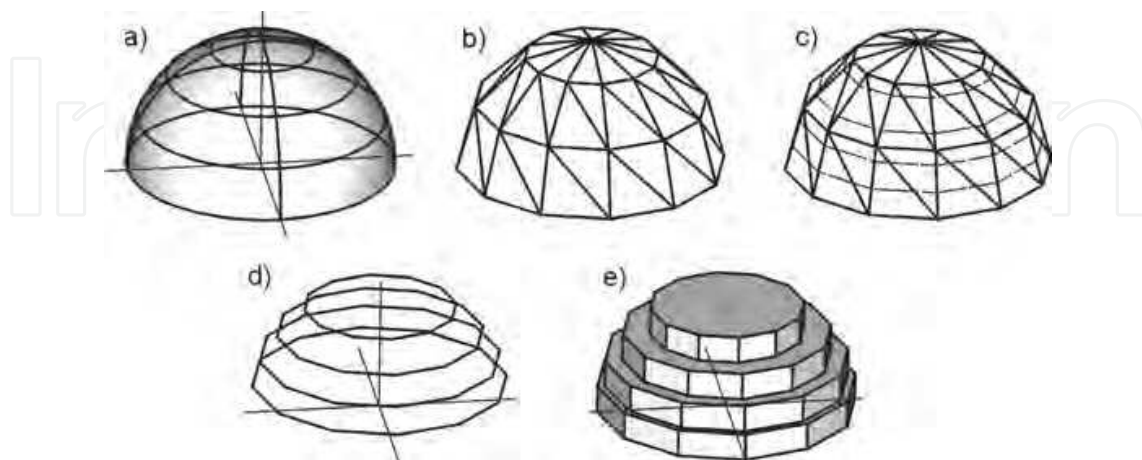- the preferred RP applications.

Fig. 1. RP process: a) 3D-CAD model, b) 3D-STL model, c) STL model divided into layers, d) layer model, e) physical prototype

RP processes and methods are most often classified according to the initial state of the processed materials. There is no classification that would encompass all known RP methods, as the applied techniques and materials used in them are constantly evolving.

Analyzing individual incremental RP technologies, it is possible to define the criteria of method selection, divided as follows:

- the accuracy of the prototype fabrication,
- the prototype material properties,
- the time of the prototype fabrication,
- the cost of the prototype fabrication.

The isolation of the individual criteria is a complex task, as for certain methods, individual criteria may be mutually exclusive. Also, within groups of starting materials and the assigned RP methods based on a definite physical or chemical principle, it is possible to specify a variety of rapid prototyping processes (Budzik, 2009).

2.1 The JS method

The method of layer jetting of liquid photopolymer (JS – Jetting Systems) consists in the application of a layer of polymer from the print head and subsequent hardening of the polymer layer by means of UV light emitted by a lamp integrated with the print head. In this system there are two materials applied on the working platform during the construction of the model: the model material and the material supporting the model. Models are built on a working platform moving along the vertical axis (z) of the working space. Polymer layers are applied one by one by the print head on the parallel plane of the working platform (x, y). The Jetting System methods of the ProJet (3D Systems) and PolyJet (OBJET) systems enable the application of resin materials for the manufacture of prototypes of various mechanical properties. Figure 2 presents gear elements produced by ProJet methods (fig. 2a – an adjustable spanner worm gear) and PolyJet methods (fig. 2b – a gear wheel of a cycloidal profile).
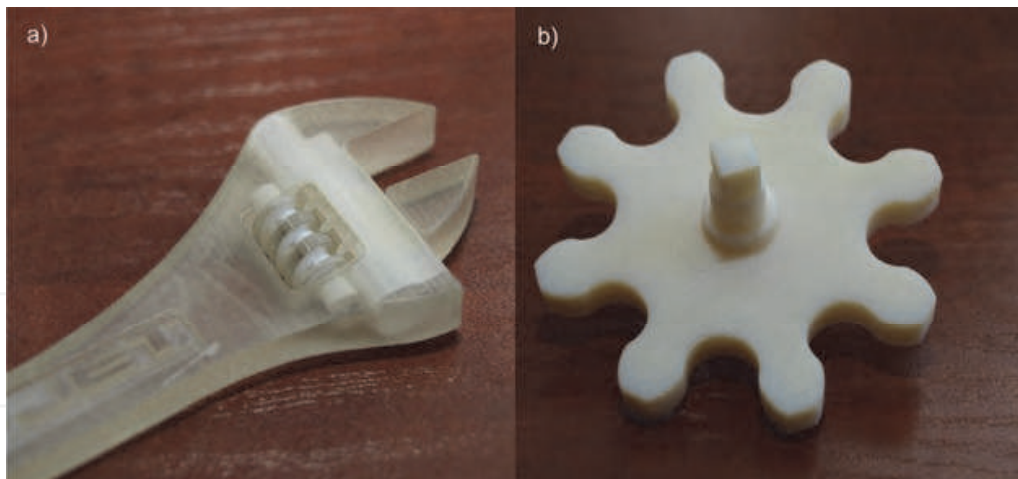
Fig. 2. Gear elements produced by JS method: a) gear manufactured by ProJet technique, b) gear wheel of cycloidal profile manufactured by PolyJet method

2.2 The SLS method

The Selective Laser Sintering (SLS) method consists in hardening the surface of powdered material by means of a laser beam. The physical model is constructed on the basis of 3D-RP geometry saved in e.g. the STL format.

The SLS method involves the use of a powdered material, which is spread in layers by means of a shaft on the working platform. The laser beam causes the sintering of the layer in accordance with the defined boundaries and filling of the solid cross-section. After the hardening, the working element is lowered by the value of the layer thickness and powder is spread again. During the sintering of the next layer, the previous one gets partially melted, thanks to which a uniform model solid is formed. Once the complete model is produced, the powder which has not been sintered is removed.

Being built, the model is supported by the powder, which fills the working space, hence no separate propping structures are necessary. The received model has a porous structure. Depending on the function of the model, it can be impregnated with other materials, which leads to the improvement of its mechanical properties. Figure 3 shows models of gear wheels made by the SLS method: a gear wheel made from polyamide - EOS Formiga P100 device (fig. 3a) and gear wheels made from TiAl6V4 powder - EOSINT device (fig. 3b, c).

2.3 The SLA method

Stereolithography (SLA) is one of the oldest rapid prototyping methods. The commencement of building the model and its mounting on the platform require the construction of supporting structures. The supports can be automatically or manually generated and it is possible to correct their shape. The method necessitates the propping of both the whole first layer of the model, the out-of-plumb elements and the fragments of the model, the building of which starts at a certain height. Once one cross-section has been hardened, the working platform is lowered, together with the manufactured part of the model, which is placed inside a container filled with liquid resin, having the thickness of the layer. Figure 4 shows models of gear wheels made by the SLA method.

The finishing of the model – the so-called Post Processing – includes the removal of the supports, the washing of the model with the use of acetone or isopropanol (cleaning the

liquid resin remnants off the surface) and additional UV irradiation for the purpose of completing the polymerization in the whole volume of the model.
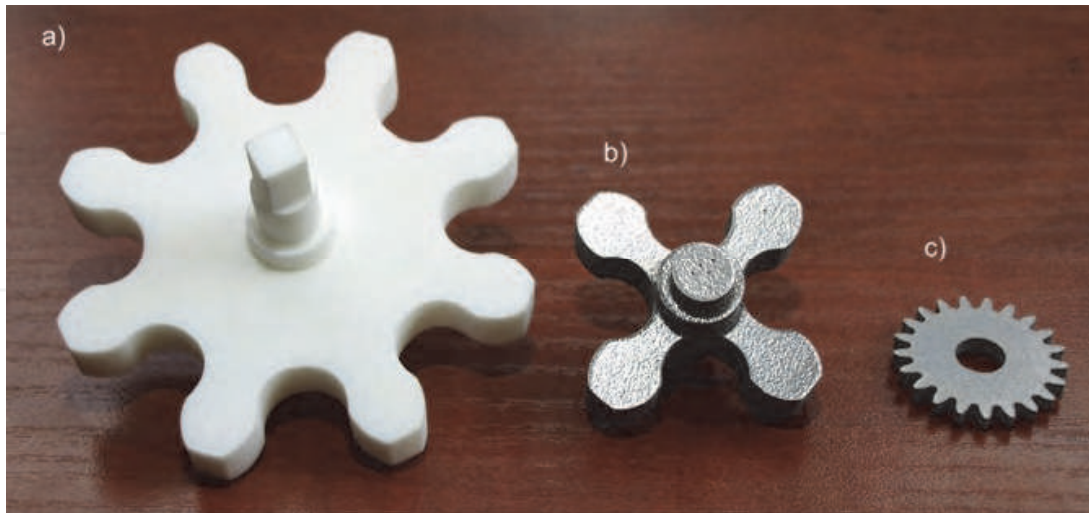

Fig. 3. Gear wheels made by SLS method: a) gear wheel made from PA2200 polyamide, b), c) gear wheels made from TiAl6V4 titanium

Considering the fact that different powders can be utilized in the SLS technique (e.g. powders of plastics and mixtures of metal and ceramic powders), this method is suitable for the manufacture of metal and ceramic tools.

Fig. 4. Gear wheels made by SLA method: a) gear wheel of cycloidal profile, b) bevel gear wheels, c) cylindrical gear wheels

2.4 The FDM method

The FDM method consists in the building of the model in the form of layers with the use of a material heated by the head and fluidized, which is pumped through a nozzle also equipped with a mechanism controlling and cutting off the material supply. The nozzle is mounted in a holder having the possibility of moving horizontally and vertically, which enables the placement of a material layer in the working space in accordance with the defined geometry of the cross-section. The applied layer solidifies as soon as it flows out of the nozzle binding to the layer applied before. During the construction of the model,

another nozzle pumps out a material supporting the proper model. This material also serves the purpose of joining the proper model with the working platform. The supporting structures generated together with the model are removed once the complete object has been built. It is possible to construct supports using a water-soluble material, which makes it easier to remove them.

Several kinds of materials can be applied in the FDM method, such as waxes, alkylbenzenesulfonates and polycarbonates as well as bicompatible materials. Figure 5 presents models of gear wheels produced by the FDM method.

Fig. 5. Gears made by FDM method: a) single-stage gear with wheels of cycloidal profile, b) single-stage gear with wheels of involute profile, c) planetary gear

2.5 The 3DP method

The method of three-dimensional printing (3DP) consists in combining a powdered material in layers by means of a binding agent applied by the print head. The printing process begins with the application of a powder layer from the supplementary container. A measured amount of the powder is dosed by a system moving the piston in the cylinder of the device and then spread (distributed) with the use of the roller on the surface of the working platform. The binding agent is applied onto the prepared powder layer in accordance with the defined cross-section of the solid. The agent binds the powdered material, thus creating a layer of the model, after which the working platform is lowered by the value of the layer thickness (e.g. 0.1 mm) and the cycle is repeated.

This method makes it possible to print out geometric models (fig. 6a) as well as moulds (fig. 6b) for casting alloys of pouring temperature up to 1100°C (fig. 6c).
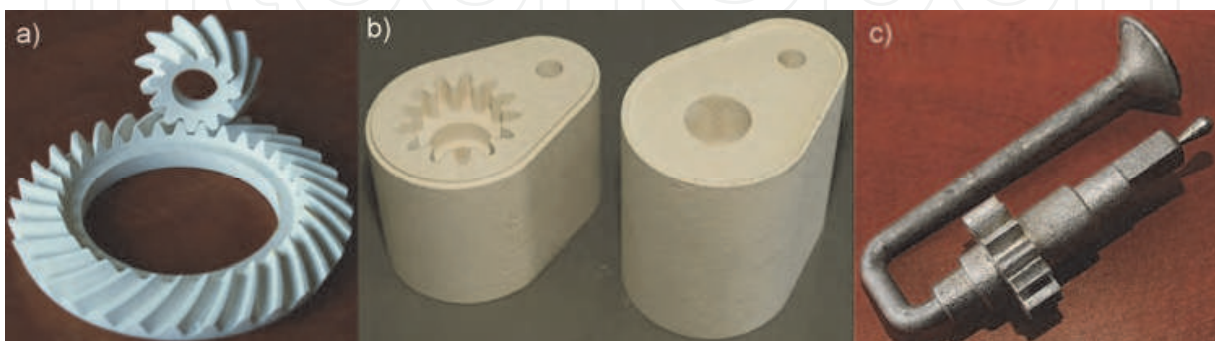

Fig. 6. Models produced by 3DP method: a) gear wheels, b) gear wheel casting mould, c) cast made in the mould from Al alloy

Some devices also enable three-dimensional printing in a 24-bit pallet of colors (e.g. Z 510 made by Z Corporation), which makes it possible to map paint covering or reconstruct the appearance of objects made from several different materials. In the working space of devices designed for the 3DP method, it is possible to produce a few models at the same time or generate a model consisting of a few different-colored elements (Budzik et al. 2010).

3. A description of the method for preparing geometric data for the RP process

Physical prototypes made by incremental or decremental RP techniques are based on the 3D-CAD model. Depending on the RP method, proper computer data processing is required. The generation of the prototype is possible on the basis of a geometric (volumetric) CAD model. Computer processing begins in the CAD environment, from which the model is exported into the proper format of the RP system.

It is also possible to fabricate the prototype on the basis of data directly from the RE process. It should be remembered, however, that data of this type is less accurate than data processed in 3D-CAD programs. Programs dedicated to RP devices verify the correctness of models. Further file processing comes down to defining the right parameters of the device operation (the layer thickness for the incremental systems or the path for the CNC decremental systems). It is the so-called program post-processing, which consists in the preparation of the final data, essential to the construction of the physical model (files in the RP device format).

The process of data preparation has a considerable influence on the accuracy of the model generated in the rapid prototyping process. The parameters of data exported from CAD systems should always be higher than the accuracy of the RP device. Thanks to this, in the process of the model construction, the RP device does not repeat program errors.

The process of data preparation has a significant influence on the accuracy of the model received in the rapid prototyping process. Computer-aided design systems have a certain accuracy of mapping the 3D-CAD model geometry (e.g. the linear accuracy of the model made in the CATIA system is 0.001mm). At the current stage of technological development, this accuracy is higher than the accuracy of mapping the geometry of the prototype produced with the use of rapid prototyping systems. The parameters of geometric data exported from CAD systems should be adjusted to the assumed accuracy of the physical prototype fabrication. In general, the accuracy of the 3D-CAD model should be higher than the accuracy of the mapping of the RP device geometry. Thanks to this, in the process of the physical model construction, the RP device does not repeat program errors (Budzik et al. 2010).

3.1 Data formats for the CAD/RP process

Rapid prototyping systems require that the files of 3D-CAD digital models be saved in the proper formats. The most popular 3D-RP formats include: STL format (Stereolithography Language), SLC format (Sliced Layer Contour), CLI format (Common Layer Interface), HPGL format (Hewlett Packard Graphic Language) and The MGX format– a format of the Magic RP program.

In the process of data processing by means of 3D-CAD/3D-RP there are also universal 3D-CAD formats applied, such as STEP, IGES or 3DS. By way of example, ZPrint, a program for operating three-dimensional printers, makes it possible to read in the CAD model with

colored texture saved in the 3DS format. The universal Magisc RP program allows for the reading in of files in most formats applied in CAD systems, depending on the installed translators. However, in practice, the most commonly used formats are STEP and IGES.

Comparing the possible applications of the STEP and IGES formats in the process of 3D-CAD/3D-RP data processing, it should be noted that, whereas in most cases the use of the STEP format enables accurate mapping of the CAD model shape, mapping errors often occur in the IGES format, such as defective or lost surfaces of the model. In the case of gear wheels, such faults may emerge on the surface (fig. 7).
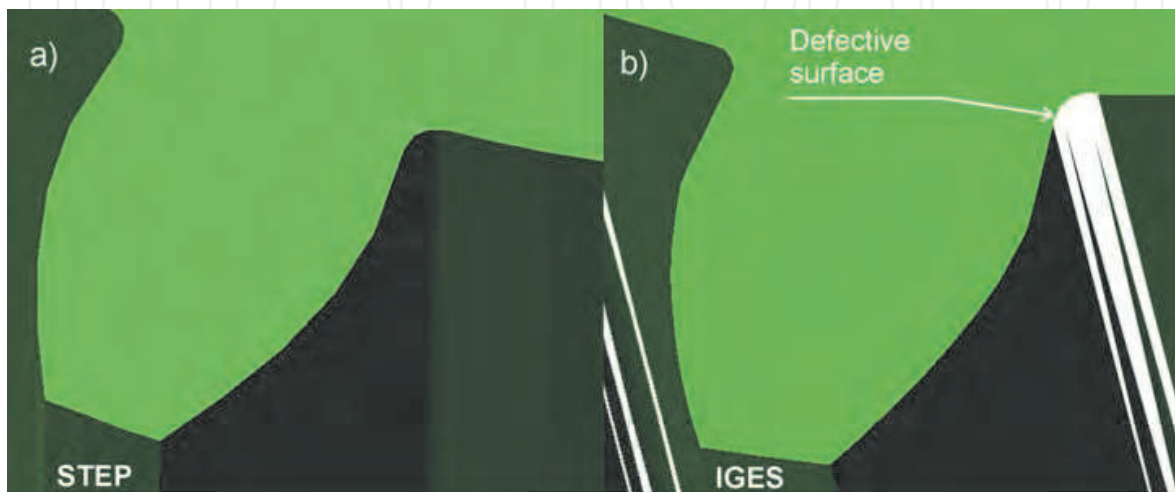
Fig. 7. 3D-CAD gear wheel models saved in: a) STEP format and b) IGES format with visible surface defects

Faults of this kind are most often transferred in further data processing in the RP process, which, for example in the STL model, takes the form of lost surfaces (Budzik et al. 2008).

In such case, it is not possible to build the physical prototype by an incremental method. However, an attempt can be made to correct the STL model by using proper program tools (e.g Magics RP).

Formats for saving files are constantly being developed by manufacturers of rapid prototyping devices. This development requires a cooperation with the producers of CAD software. Because of the application of the STL format, a vast majority of CAD programs have the possibility of exporting data in this format. These programs include: AutoCAD, Alibre, CATIA, I-DEAS, IronCAD, Mechanical Desktop, ProE, Rhino, SolidDesigner, SolidEdge, SolidWorks, Think3, NX and 3D Studio Max.

Data export is usually realized through the "save as *.stl" command, sometimes the command of export to STL. On rare occasions, there is a separate command entered in the program dialog window (e.g. "amstlout" in Mechanical Desktop). Depending on the program, it is possible to determine the accuracy of the model mapping. Some programs allow for a very detailed definition of the parameters of the STL file (e.g. Mechanical Desktop). The STL format is used to describe and approximate the shapes of various surfaces by means of flat triangular surface flakes. Figure 8 shows a single flat triangular unitary surface.

The description of the single surface includes a normal vector (facet normal) and coordinates of three vertexes. In addition, for each surface, the normal vector (facet normal) N is defined, directed outside the approximated solid.
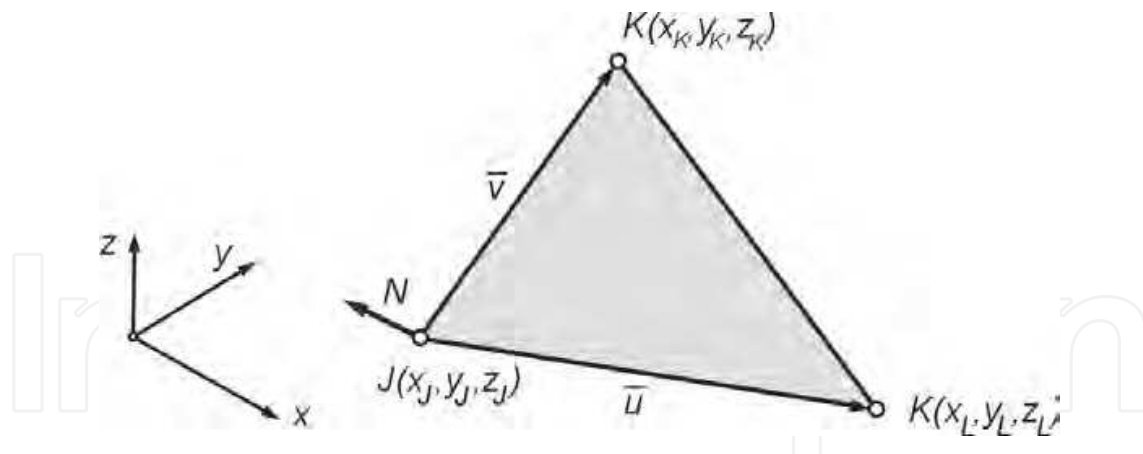
Fig. 8. Single flat triangular unitary surface of STL format

3.2 The accuracy of the model mapping in the STL format

The process of converting the 3D-CAD model into the 3D-CAD-RP form (STL format) is called tessellation. It is a process in which three-dimensional model geometry is approximated by means of triangular surfaces (Budzik et al. 2007). The size and shapes of the triangles can be regulated by setting the proper parameters of data export. The accuracy of the approximation depends on the model surface shape Flat surfaces are fully mapped by triangles (Campbell, 2008). The mapping of curvilinear surfaces causes the emergence of the so-called chord error, which occurs between the model surface and the triangle net which approximates it . The error is measured perpendicularly to the triangle surface, and its value depends on the assumed approximation parameters (fig. 9a).

The error of the f chord is also responsible for the accuracy of the construction of convex and concave surfaces having different radii of curvature. The accuracy of approximation can also be described by means of the approximation angle - α (fig. 9b).
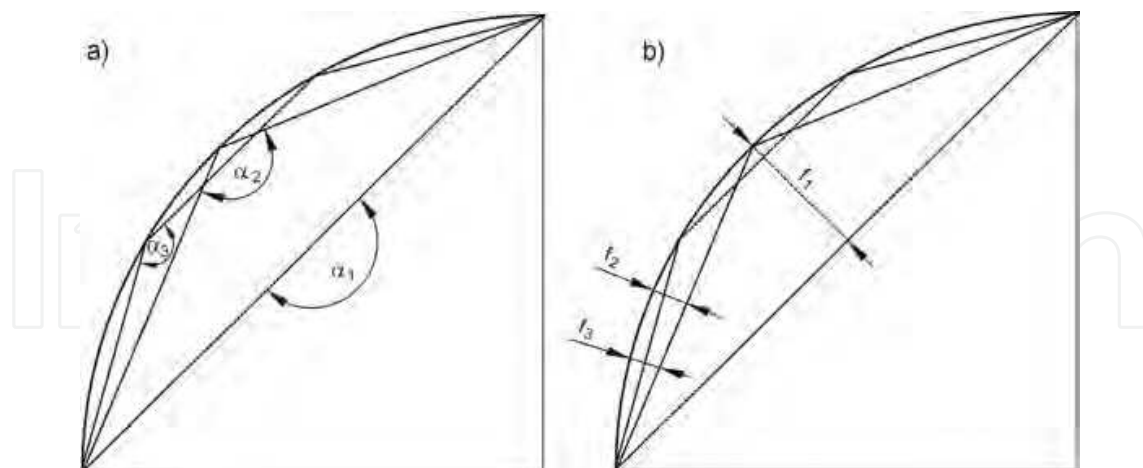

Fig. 9. Mapping error between CAD model spherical surface and approximating triangle:
a) angle deviation, b) chord deviation

The parameters of geometric data export from 3D-CAD systems should be dictated by the assumed accuracy of mapping the physical model built by the RP device. Increasing the surface approximation accuracy in the process of tessellation causes an increase in the number of triangles describing the model surfaces (fig. 10) and a greater size of the STL file.
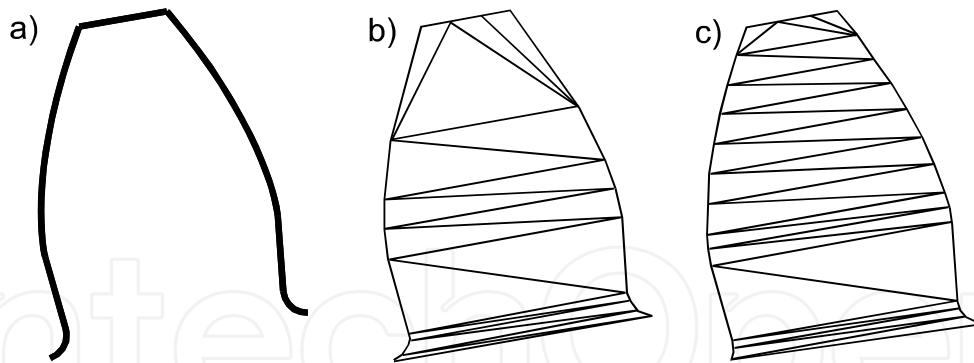
Fig. 10. Gear wheel model tooth profile: a) nominal profile (theoretical – CAD), b) STL model profile (2540 triangles of the whole gear), c) STL model profile (2724 triangles)

In the case of simple geometric models, the size of the generated STL file is not large. It is much greater for models of complex curvilinear surfaces , such as e.g. gear wheels.

The production of accurate RP gear wheels models necessitates the application of the proper tolerance of data export to the STL format. The tessellation parameters are defined in 3D-CAD systems by means of various algorithms, which determine mapping accuracy and are responsible for the occurrence of geometry mapping errors. The STL format is also a format of saving data received in the 3D scanning process. In this case, the geometry of the model saved in the STL format virtually always contains errors in the form of noises, missing surface fragments or surface discontinuity.

3.3 Mapping errors in the STL format

During the conversion of 3D-CAD files into the STL format, there may occur geometry description errors. These errors result from the inaccuracy of the model processing by tessellation algorithms in the translators of CAD systems. The most common STL model errors include: the reversal of normal vectors, gaps and interspaces between the triangles describing the surface, warped surface, losses of whole surfaces or their fragments, overlapping triangles, the assignment of a single edge to more than one triangle.
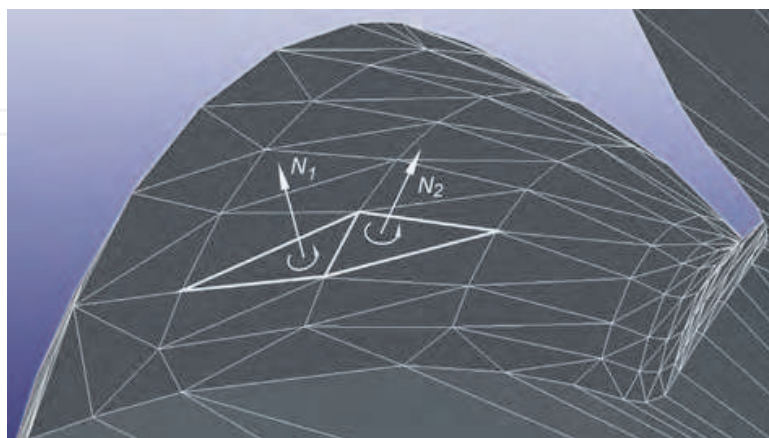

Fig. 11. Correct triangles with normal vectors oriented outwards (STL pinion model)

The correct geometry description with the use of the STL format must meet the condition of all normal vectors of unitary surfaces being directed outside the approximated solid. In some CAD systems, errors occur during the export to the STL file, involving the reversal of

the normal vector. The most common source of the error is the wrong order of providing the triangle vertexes. The sequence depends on the sense (turn) of the normal vector, defined by the right-handed screw method (fig. 11). Such an error may apply to whole surfaces or individual triangles.

Another error is the 'loss' of a triangle or triangles. Blanks (triangles) can occur individually or as combinations of a few triangles. Empty triangles can also appear when the radii of curvatures are changed, e.g. in the area (fig. 12).
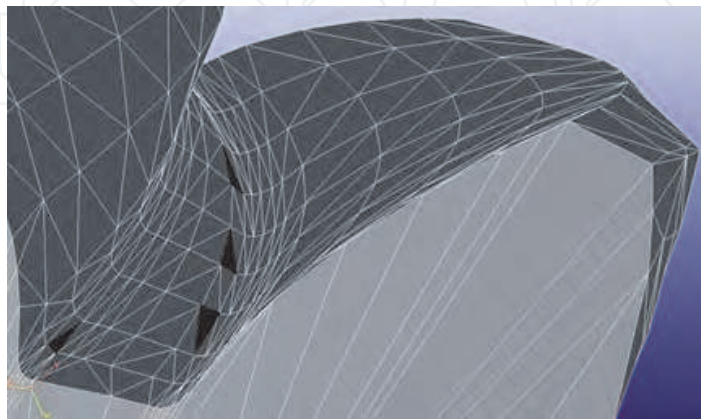
Fig. 12. Empty triangles of gear wheel STL model (marked in black)

Having surface discontinuity, such a model is impossible to build by means of RP devices. This kind of error is most often generated by low-quality modelers of CAD systems. The correction of such an error, i.e. 'patching' the gap created by the 'lost' (not generated) flake of surface geometry requires the application of geometric program operations. In such case, the STL file should be opened in a program supporting STL formats (e.g. Magisc RP), the coordinates of the vertexes of the surface flake should be read, the normal vector N to the surface should be determined and such a surface should be saved in the STL file.

In the case of models of complex shapes, geometric errors can occur, which are not allowed for by the algorithms used for tessellation. These phenomena are the source of errors of STL models. These errors usually emerge in the places of joining surface flakes into one object fig. 13). Such an error may result in the lack of a common edge of the surface flakes being joined.
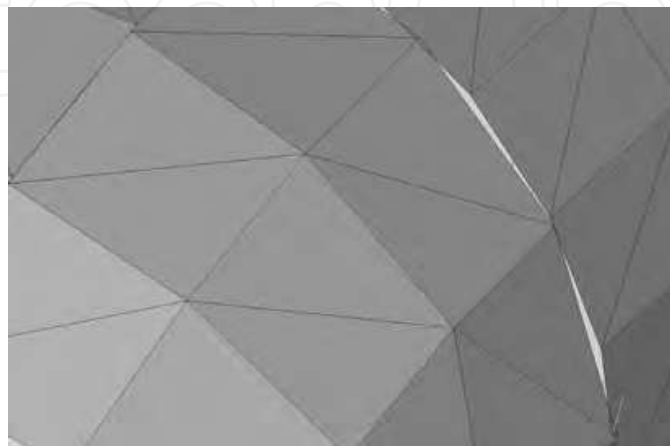

Fig. 13. Warps at the joint of surfaces in STL model

It is possible to correct some of the errors in CAD programs, using program options. If the surfaces of the model are built with the use of parametric curves and surfaces, the correction of the error comes down to the modification of the values of curves and surfaces parameters.

In the case of free surfaces modeling, the correction is possible through the modification of the control points of curves or surfaces.

There are also mapping errors in the form of disappearance of whole surface flakes (fig. 14). Errors of this type usually occur during geometric data export from the IGES to the STL format when there is no source file in the format of the program in which the 3D-CAD model has been created. Such errors can be corrected with the aid of specialized software (Magics RP) equipped with a module of data export in the IGES format.
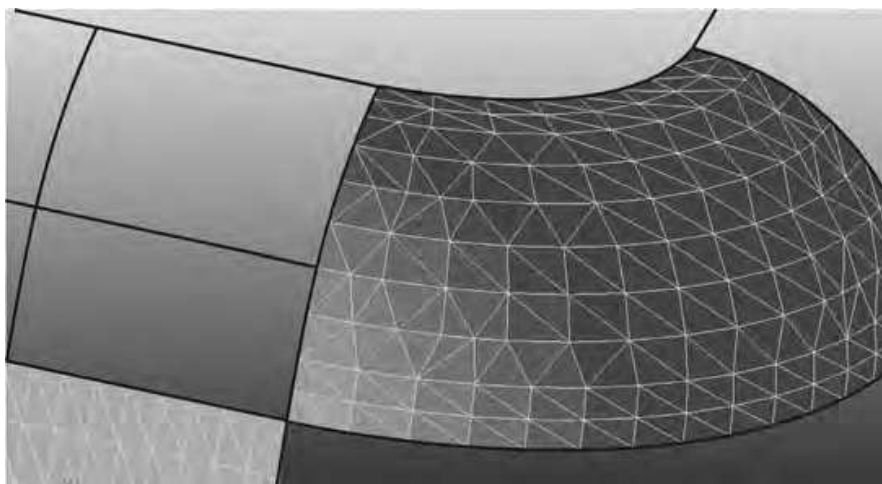
Fig. 14. Lost surface flakes in STL model

The model geometric data in the STL file is described by triangles with x, y, z coordinates for each of the triangle vertexes. The coordinates are described in the global system of Cartesian coordinates. Errors of data generated during the creation of the STL file result from the tessellation process. Program correction of errors is based on mathematical transformations of the triangular surfaces in 3D space.

3.4 Data processing in CAD systems

Most programs for three-dimensional modeling have a module of data export to the STL format. Depending on the program, the modules make it possible to receive data of different degrees of accuracy. Some programs do not have the possibility of determining the parameters of the STL file accuracy, others limit the scope of the defined accuracy to e.g. merely providing the length of the side of the triangle describing the solid surface or specifying a general accuracy level (Inventor).

Just like Inventor, Mechanical Desktop (MDT) is a program available in the software package of AutoDesk. However, it offers much greater possibilities in terms of creating elements of complex shapes and saving them in the STL format. The MDT program has a separate command for data saving in the STL format: AMSTLOUT. The options of this command make it possible to set the accuracy of the STL model mapping by means of four parameters, defined as: angle tolerance, constant of proportionality, intervals between vertexes, surface tolerance (fig. 15).
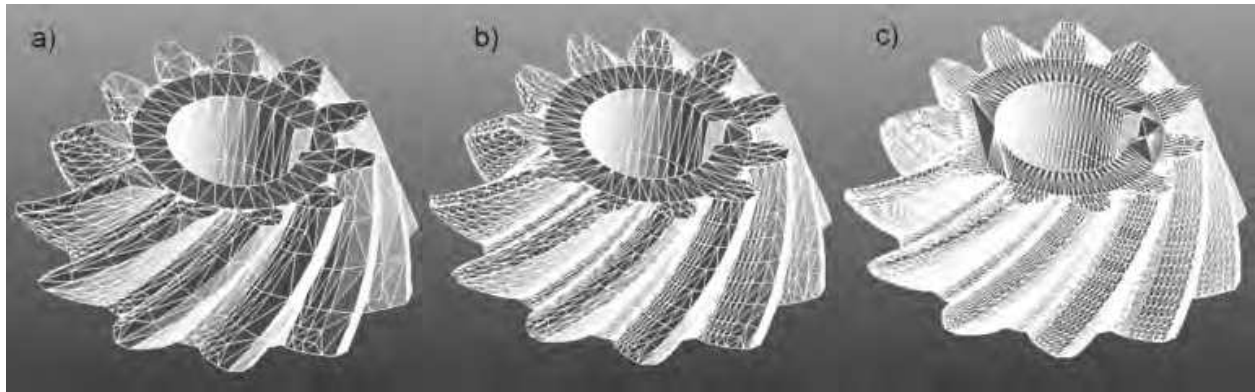
Fig. 15. STL model being exported from Mechanical Desktop with defined surface accuracy:
a = 0,5mm, b = 0,1 mm, c = 0,05mm

In CATIA V5R18 it is possible to save a file in the STL format in the Part Design module.
However, the geometric parameters of such a model of standard settings cannot be used for
the manufacture of accurate gear wheels. In order to increase the accuracy of the STL model,
the Machining → STL Rapid Prototyping module should be activated in CATIA. Next, in
this module, the Tessellation command should be selected and the accuracy of the STL
model should be defined by specifying two parameters: sag and step (fig. 16).
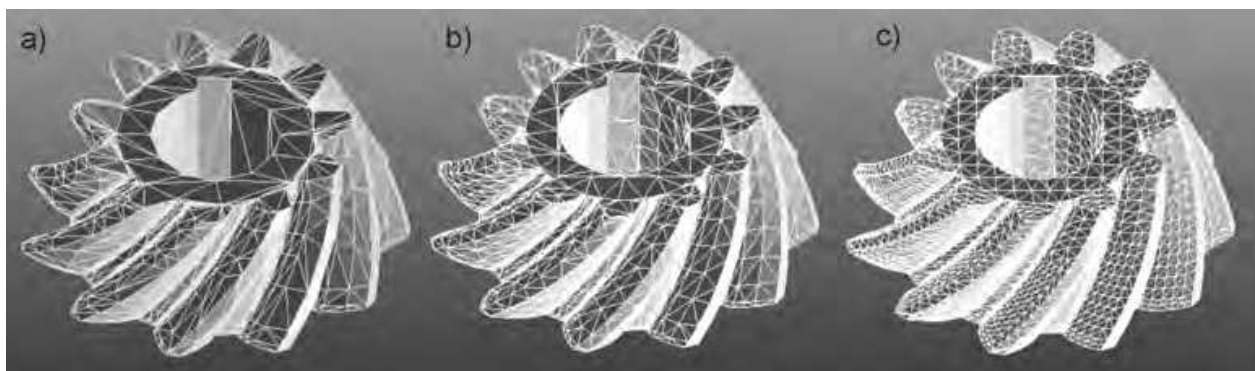
Fig. 16. STL model being exported from CATIA: a) sag = 10mm, step = 6mm,
b) sag = 0,2mm, step = 6mm, c) sag = 0,2mm, step = 3mm

The accuracy of data depends on its source. The CAD model has an accuracy determined by
the accuracy of the system in which the model has been created (for CATIA the linear accuracy
is 0.001 mm). The constructor has an influence on the model accuracy at the stage of file export
into the format of RP devices (e.g. STL). Depending on the program capabilities, the
constructor can define the export parameters (e.g. angle tolerance, surface tolerance, constant
of proportionality, intervals between triangles vertexes – MDT). Some programs make it
possible to define (assume) the length of the triangle side in the STL format.

3.5 Data processing in RP systems – magics RP software
Magics RP is a universal program for the processing of files used in processes of data
preparation for rapid prototyping. The basic version of the program makes it possible to
read and process STL and MGX files.
Additionally, the program capabilities can be expanded by modules for the export of data
saved in the following formats: MGX, IGES, VDA, VRLM, Catia V4, Catia V5, STEP, NX,

ProE and Pointcloud. During the import, the source file should be selected and the accuracy of the STL model mapping should be defined in the window of parameter settings. In the course of the import, a window pops up showing the progress of the performed operation.

Magics RP enables the edition of models, the correction of geometry errors of the model saved in 3D-CAD and 3D-RE formats, such as overlapping edges, missing triangles or surface fragments occurring in the triangulation process (fig. 17).
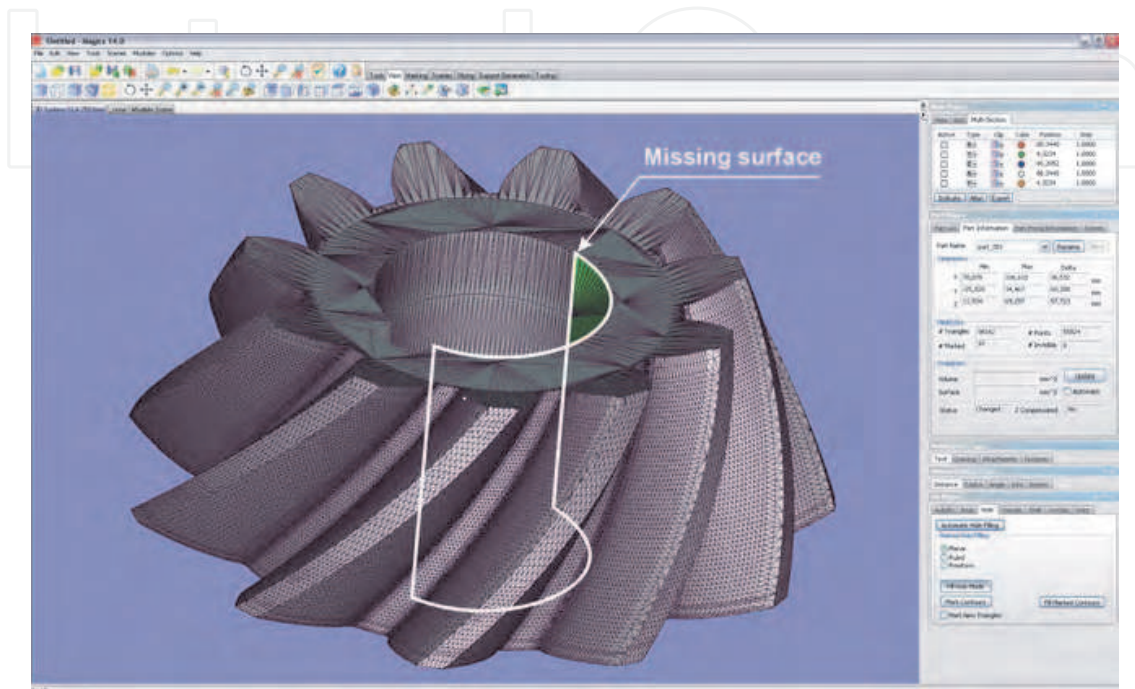

Fig. 17. View of missing surface – error generated during triangulation of STEP model

Some of STL models errors can be corrected with the aid of program tools (fig. 18a) by using automatic options. This, however, can lead to further errors in the form of the model shape change on the reconstructed surface and, sometimes, on the adjacent surfaces (fig. 18b).
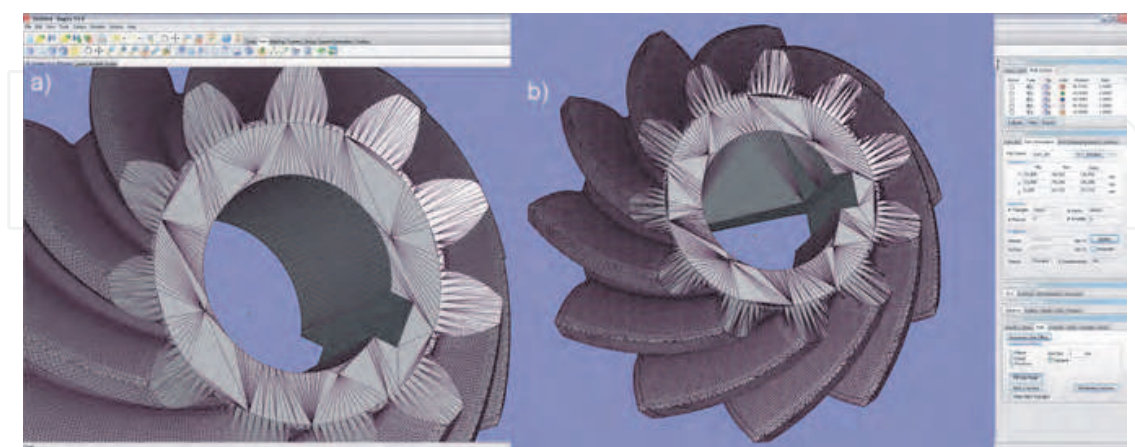

Fig. 18. Correction of model error: a) correct model, b) wrongly corrected model

In order to obtain a correct STL model, it is recommended that an individual approach be adopted towards the process of correction of geometry errors for each processed object (fig. 19a). The program allows for the optimization of the STL model by changing the parameters

of the triangles mapping the object geometry. One of such operations is the reduction of the number of the triangles (fig. 19b). However, in this case, it should be ensured that the reduction of the triangles has not caused a change in the model geometry, which will affect the manufacture of the prototype.
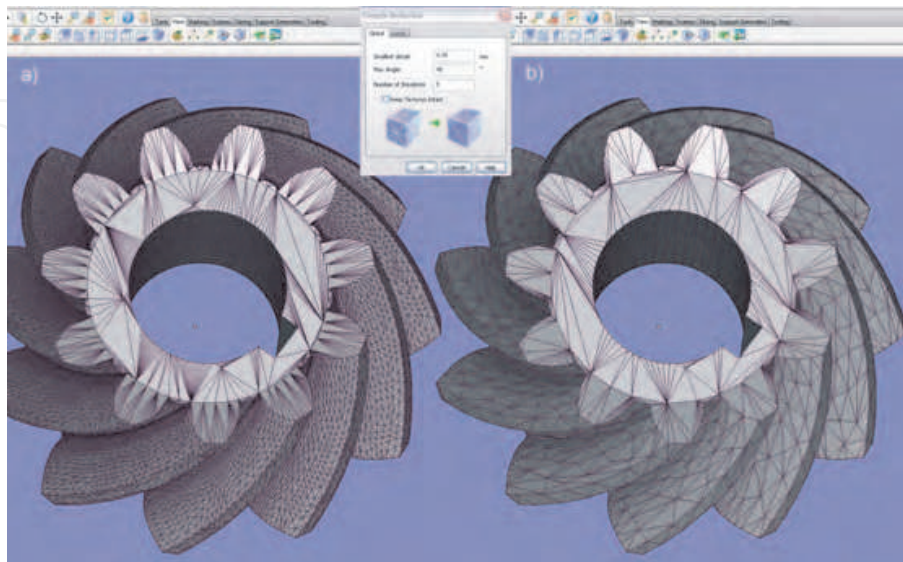

Fig. 19. Reduction of the number of triangles describing STL model surface: a) gear wheel starting model, b) model after reduction

Magics RP also makes it possible to process data coming from 3D-CAD systems as well as geometry received in the process of 3D scanning (fig. 20a). The program also enables the performance of simple 3D modeling operations (e.g. making holes or closing the scanned surfaces - fig. 20b). Thanks to this, it is possible to quickly generate the STL model, on the basis of which the physical prototype can be fabricated.
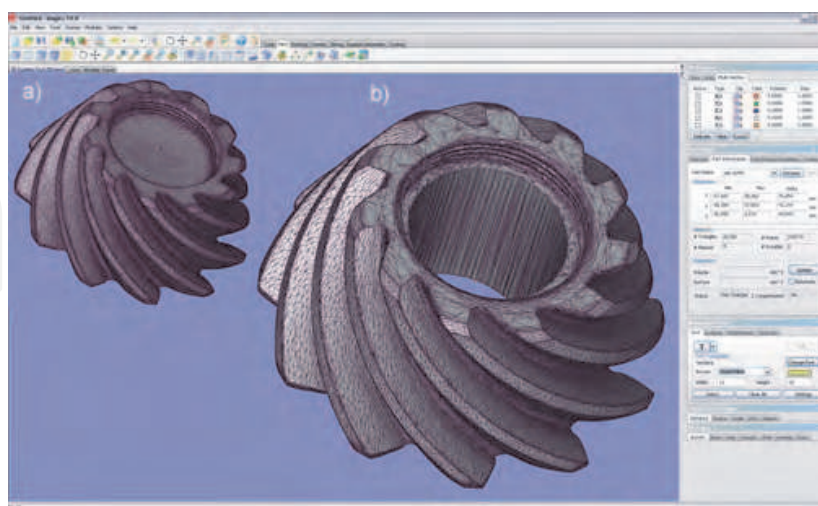

Fig. 20. Data processing in Magics RP: a) surface of scanned gear wheel received in scanning process, b) gear wheel STL model after program processing

Another important benefit of the program is a library of rapid prototyping devices. It is here that data can be prepared for the processes of most RP devices manufactured by companies,

such as 3D Systems, Stratasys, OBJET, ZCorporation. The library of devices is expanded as new machines and technologies are introduced into the market.

Magics RP is a supplementation of programs sold together with rapid prototyping devices. It allows for data processing in the process of technology preparation for rapid prototyping systems, and, above all, makes it possible to correct some errors of the model, difficult to eliminate when there are no original 3D-CAD files.

Magics RP also enables the division of large models into parts, the size of which does not exceed the dimensions of the RP device working chamber. During the division, the program makes it possible to insert elements joining the individual fragments of the model.

4. An analysis of geometric accuracy of gear wheels models

Test prototypes of cycloidal gear wheels have been generated by incremental rapid prototyping methods (JS, SLA, SLS, FDM, 3DP), on the basis of the same 3D-CAD model. In order to eliminate the impact of errors of data processing on the physical prototype, the CAD model was exported to the STL format and a high accuracy of the parameters of the model geometry mapping was assumed. Test models were also used for studies of the determination of the real geometric accuracy of gear wheel prototypes made by the analyzed RP methods.

4.1 The measurement of test prototypes with the use of CMM

The objective of the tests was to make an analysis of the geometric accuracy of gear wheels models produced by the rapid prototyping techniques described above with reference to the CAD model (fig. 21a). The measurements were conducted with the use of the coordinate measuring machine - WENZEL LH 87 (fig. 21b). The measurements were carried out in the scanning mode along the measuring path. The shape of the path, the direction of measurement direction and the starting point are shown in figure 21c.
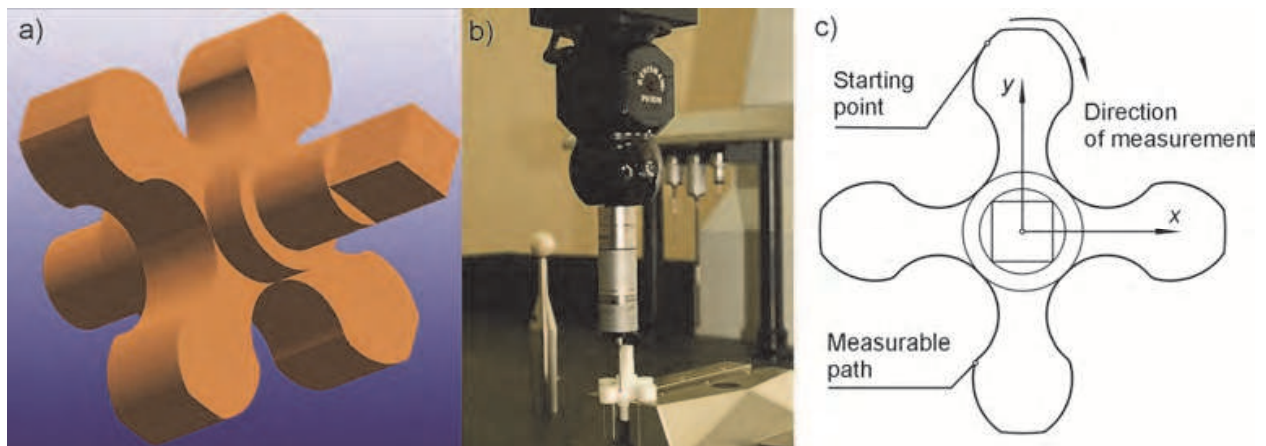

Fig. 21. Measurement preparation: a) gear wheel CAD model, b) measuring machine - WENZEL LH87, c) measurable path

The preparation of the coordinate measuring machine involved actions typically performed in compliance with the coordinate measurements procedure. Measurements were conducted on crude (not having been subjected to the finishing abrasive machining) prototypes built by means of incremental RP methods: JS-PolyJet, SLS, SLA, FDM and

3DP. The results of the measurements in the form of selected protocols have been presented in figures 22-24 respectively.

The fabrication of gear wheels prototypes requires the most accurate rapid prototyping methods. An analysis has been made of models of test blades produced by the JS-PolyJet, SLS, FDM and 3DP methods. In the first place, a gear wheel produced by the JS-PolyJet technology was measured. This model has a high accuracy in the majority of the measuring points, the deviations having a positive value, which does not go beyond the assumed tolerance range of 0.1mm or only slightly exceeds it (fig. 22a).
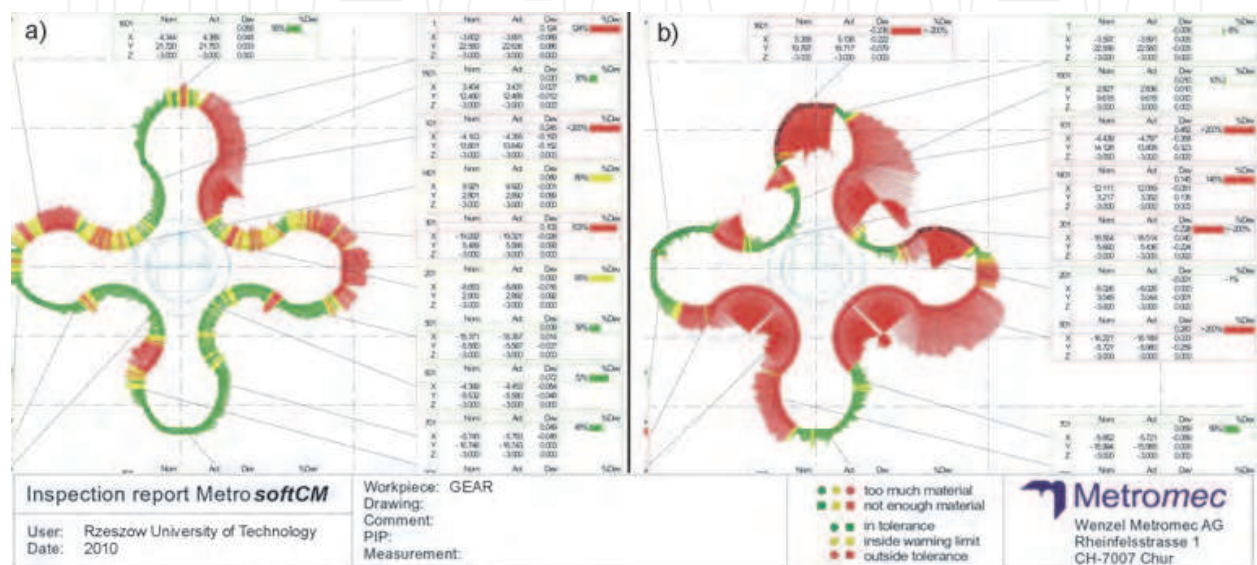

Fig. 22. Measurement protocol of gear: a) JS–PolyJet (Vero material), SLS (PA 2200 material)

Often the geometric accuracy of models also depends on the material the model is made from. The SLS model has been made from polyamide, which exhibits considerable (for RP techniques) processing shrinkage reaching 3%, causing deformations of the model which exceed the assumed tolerance range (fig. 22a).

The highest accuracy is presented by the SLA model (fig. 23a). In the case of the FDM models, gear wheels made from the ABS material have been measured, with a layer thickness of 0.254mm. The model has a fairly high accuracy (fig. 23b). As a result of the measurements, the accuracy of the 3DP model has also been determined (fig. 24). For this technique, the model geometry immediately after the print-out may differ from the model geometry after the infiltration process. The difference value will be dependent on the shrinkage of the applied infiltrator and the depth of the infiltration.

4.2 The measurement of test prototypes with the application of ATOS GOM system

The coordinate measuring technique enables the measurement of gear wheels by means of contact measuring machines, with the application of advanced specialized measuring software. Gear wheels of any gear tooth forms and profiles manufactured in the RP technology can be measured with the use of optical coordinate scanners, for which the accuracy of identification of the measuring points depends on the applied optical system, i.e. measuring field (Budzik et al 2010).

The application of optical scanners as well as the methodology and algorithms devised for the needs of the measurement of gear wheels allows for the metrologically correct

measurement of the characteristic geometric qualities determining the accuracy of the fabrication of the measured elements (fig. 25a). A gear wheel and a pinion made in the FDM (ABS) and SLA (SL5170) technologies have been measured. An analysis of accuracy has been made with the use of the same CAD models (fig. 25b), which served as the basis for the manufacture of example wheels of the bevel gear of a circular arc line of Gleason's tooth. The results of the analyses discussed above are presented in figures 26 and 27.
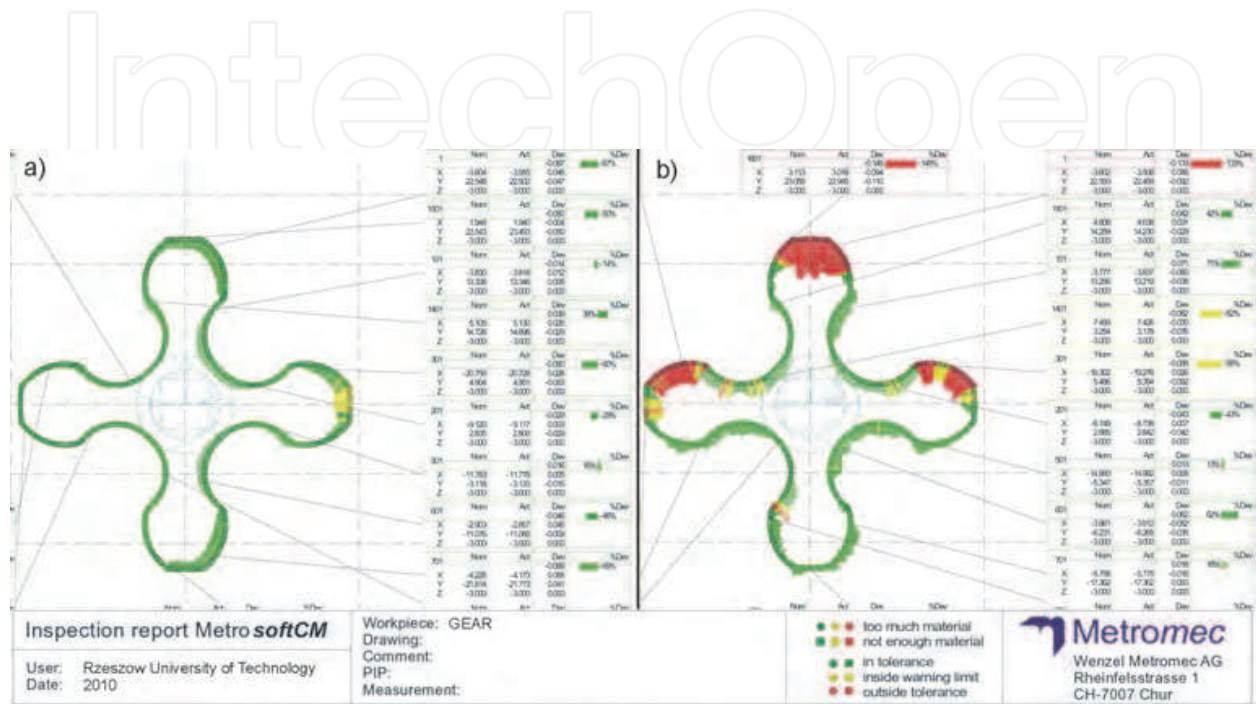
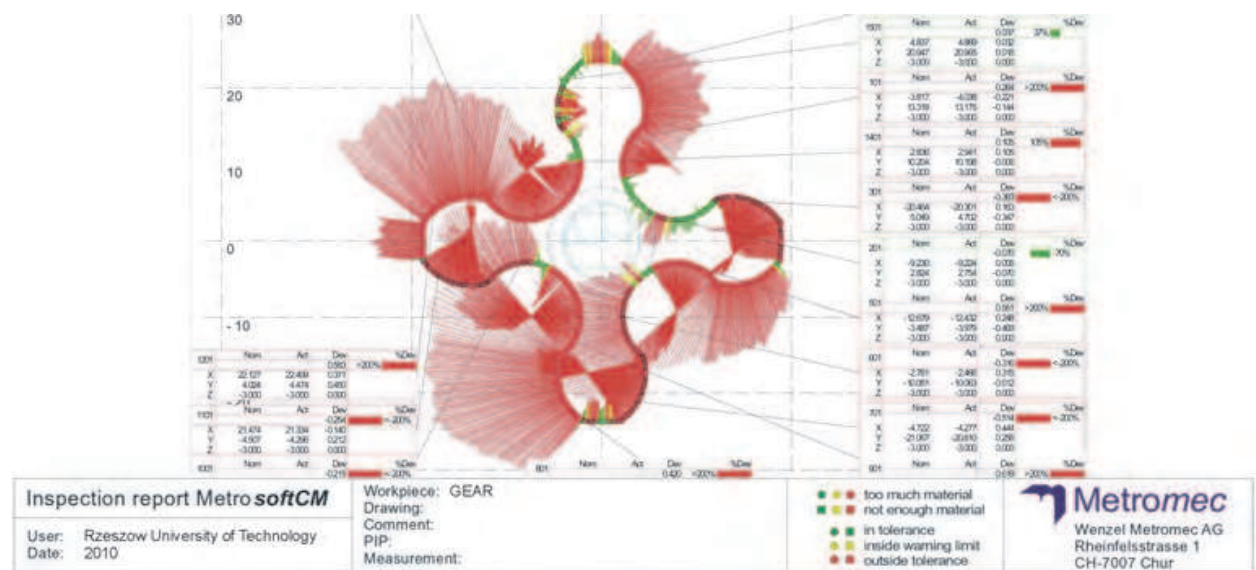Fig. 23. Measurement protocol of gear: a) SLA (SL5170 material), b) FDM (ABS material)

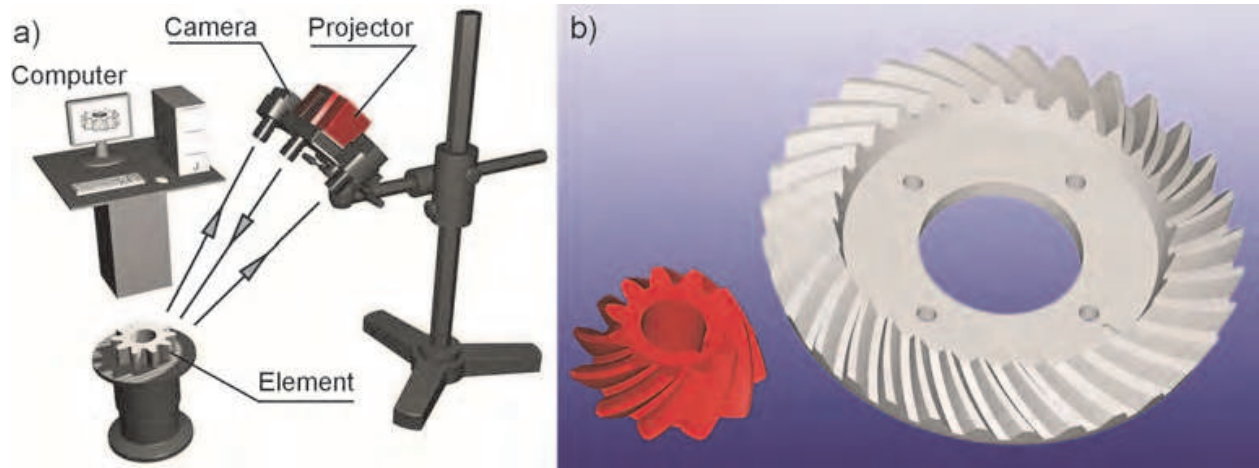Fig. 24. Measurement protocol of 3DP gear wheel (ZP131 + Z-Max Epoxy material)

Fig. 25. Measurement of prototypes by means of ATOS GOM system: a) test stand,
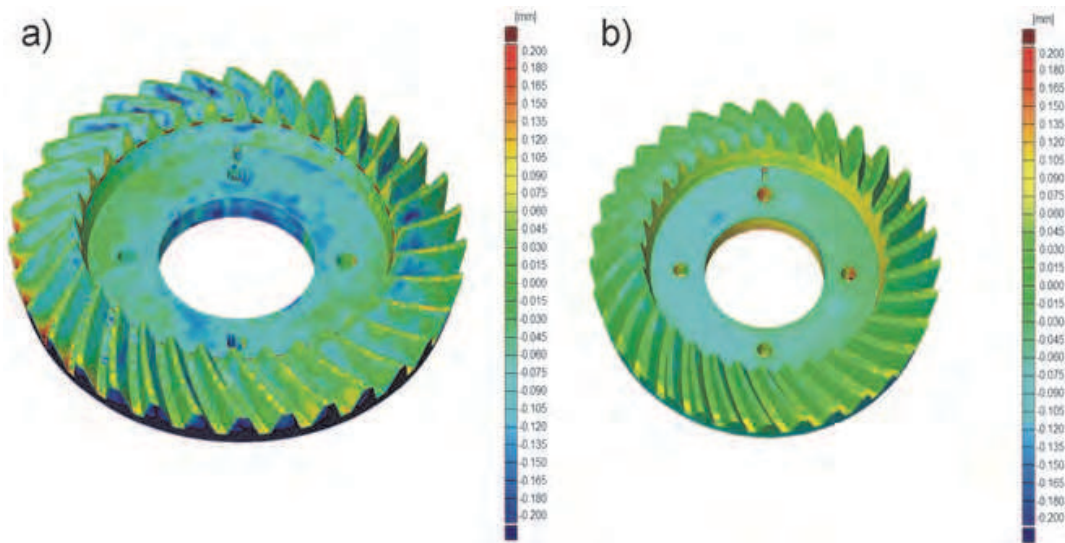b) 3D-CAD models of measured gear wheels

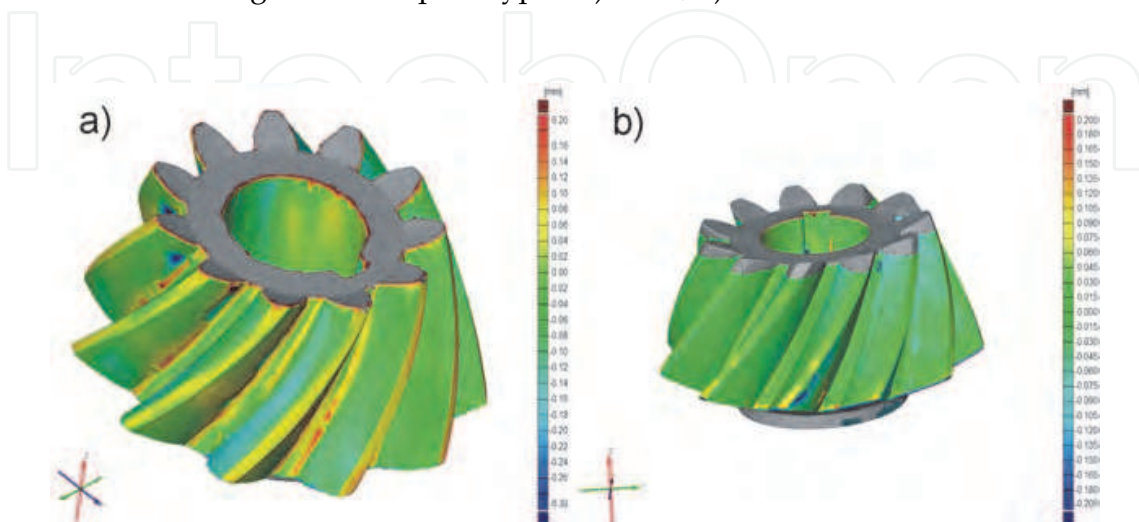Fig. 26. Deviations of gear wheels prototypes: a) FDM, b) SLA

Fig. 27. Deviations of pinion prototypes: a) FDM, b) SLA

Based on the analysis of the deviation values of the gear wheel and the pinion in all the measured points, in comparison with the CAD model, it can be observed that gear wheels made in the SLA technology (SL5170) are characterized by low values of limit deviations. Local deviations of positive values are caused by discontinuity, lack of measuring points or too few measuring points in the places of occurrence of very small radii of transition surfaces.

An analysis of the real deviation values of gear wheels made from different materials, by means of various rapid prototyping technologies, and especially their characteristic distribution, may serve a the basis for the creation of correction maps of the gear wheel CAD model to obtain an element corresponding to the assumed model in very narrow tolerances.

The measurements of gear wheels conducted with the application of two incremental RP methods (SLA and FDM) allowed for the determination of the real accuracy of the manufacture of the bevel gear prototype.

The models of the gear wheels were oriented on the working platform in such a way that the axis of rotation was parallel to the axis of the RP device. This made it possible to increase the accuracy of the produced gear wheels. The primary source of geometric deviations and surface roughness (especially in the direction of the axis of the RP device) is the layer structure of models in incremental methods.

The accuracy of fabrication of gear wheels and their tests remain a major technological problem. The application of the coordinate measuring techniques in combination with the CAD/CAM/RP methods in the manufacture of gear wheels aims at improving the process of design, construction and technology (Oleksy et al. 2010).

The production of gear wheels prototypes with the application of RP methods is based on the 3D-CAD model. Therefore, it was possible to determine the values of deviations with reference to the nominal 3D-CAD model. In the case of measurements with the use of coordinate optical methods, the shape of the gear wheels or the tooth form are not particularly significant for the measuring process.

Coordinate measuring methods make it possible to determine the real accuracy of models made with the application of rapid prototyping techniques. The measurement and analysis of the geometric parameters of gear wheels allow for the compensation of errors and the determination of the correction value for RP devices.

The accuracy of RP models can be corrected at various stages of the technological process. First of all, the correction can be made during the construction of the model, the processing of numerical data and the export of data to one of the RP formats, e.g. STL or SLC. This is particularly important for gear wheels, the tooth forms of which are generated in the process of processing simulation. The numerical model errors may occur at this stage of modeling. Such errors are impossible to determine for the STL model. They emerge at the last stage of the manufacturing process, while the layers of the mesh profile are being built. It is especially visible in the stereolithography method, the software of which (3D Lightyear) is sensitive to this type of program errors.

5. The possibility of RP systems application for gear wheels testing

Rapid prototyping methods are increasingly applied in the manufacture of test prototypes (Liou, 2008). In the case of gear drives tests, RP techniques can be employed for the production of gear wheels used for mating area analysis, resistance (including photo-elasticity) and fatigue tests. For tests of the mating area, its observation is possible through

the transparent structure of the prototype (e.g. SLA or PolyJet). Tests of photo-elasticity are also based on the use of transparent materials. Here, prototypes can be prepared directly by incremental methods or indirectly through transparent resin casting by means of the Vacuum Casting technique, for example. Resistance fatigue tests can be conducted for models made by any RP method, with the proviso that the criteria of model similarity are earlier specified with the application of e.g. the FEM analysis (Pacana et al. 2010).

5.1 Tooth Contact Analysis (TCA)

The design of gears with new atypical profiles is a complex process, requiring a lot of geometric and strength computations. The production of atypical gears frequently requires the making of expensive and atypical tools. Launching new types of gears, especially those with gears of atypical profiles, requires also adequate research into the transmission stand test. The process of designing may become significantly reduced with such aids as the computer aided design (CAD), the finite elements method (FEM) and rapid prototyping methods (RP). Thanks to the CAD technique application, it is possible to model a gear geometrically, the FEM technique allows for initial verification of strength, whereas preliminary testing may be carried out on gears made with a rapid prototyping method, e.g. stereolithography (Sobolak & Budzik 2008).

Instantaneous contact area is one of the determinants of correct gear mating. Instantaneous contact area is the area on the tooth flank, which contacts the mating surface of another tooth at a specific moment in time. The shape and size of that instantaneous contact area, as well as its changes as the gears turn, affect the correctness of gear mating and the kinematical precision of any gearbox (Sobolak & Budzik 2008).

The contact between tooth surfaces in an ideally geometric gearbox occurs in a point or line but, because of deformability of the mating teeth flanks, in reality, it is always a certain surface.

At a specific moment in time, a contact area may exist between several pairs of teeth. It is the so-called total instantaneous contact area. In experimental studies, the mating area, which is a Boolean sum of instantaneous contact areas on tooth flanks, is usually determined. The mating print determination is frequently used in industrial practice, while that of the instantaneous contact area in not practiced because of the inherent difficulties.

The transparency of the gear material is of key importance for the determination of contact area in the method described here. The idea of contact area determination consists in the observation of the contact area between mating surfaces through a transparent material. Among other materials, the SL5170 resin has transparency characteristics suitable for the stereolithography method, but other transparent materials can also be used for such testing. Stereolithography requires a 3D geometrical model of the produced object. It also possible to cast gear models from transparent materials in silicon molds (Vacuum Casting method). Silicon molds may be made on the basis of existing gears. Such a method allows for the determination of the cause of abrasion and damage in the existing gearbox.

The tested gearbox may become loaded with torque, properly selected to suit a specific plastic it is made of (using the model similarity rule (Sobolak & Budzik 2008), or may be tested without load with the use of a specially selected liquid. The liquid shall create meniscus that facilitates observation.

The meniscus that is created depends on the type of liquid whereas the liquid layer thickness, δ, may be determined experimentally with the use of suitable stereolithographic

models. The meniscus thickness may be determined from the formula (1). The thickness of the liquid layer, δ, may be determined using fragments of two spheres (Fig. 28):

$$\delta = r_1 + r_2 - \sqrt{r_1^2 - \frac{a^2}{4}} - \sqrt{r_2^2 - \frac{a^2}{4}} \qquad (1)$$

where:
δ – thickness of liquid layer (meniscus),
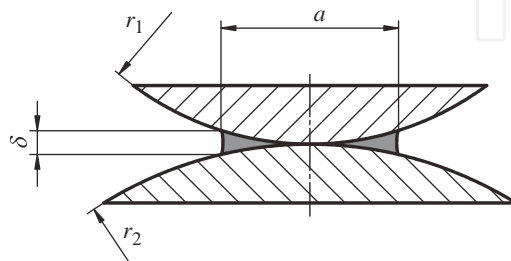a – diameter of observed contact area,
r1, r2 – radii of spheres.

Fig. 28. Diagram for determining approximate thickness of liquid for the sphere-sphere case

In both cases (with loading or with liquid) the distance, δ, equivalent to the gear deformation value in the contact area is determined.

Tests that were carried out with fragments of spheres of various radii showed that the thickness of meniscus, δ formed for stereolithographic models depended on the type of the liquid used only. Quite importantly, it does not depend on curving radii. In gearboxes, especially those of complicated gear geometry, gear teeth have variable curvature (e.g. involute tooth profile, arc-wise tooth line).

5.1.1 The making of stereolithographic model of gears

Geometric CAD models of Gleason SGM bevel gears with a circular arc tooth line, as presented (Sobolak & Budzik 2008), are used in this example (Fig. 29a). Gears were made with tool mapping by the simulation technique. Thus, they are representative of gears made as a result of actual machining. Among others, they contain machining marks left by the tool. The technique of tool mapping simulation in the CAD environment consists in the simulation of machining, wherein both the tool and the workpiece are 3D models. The tool
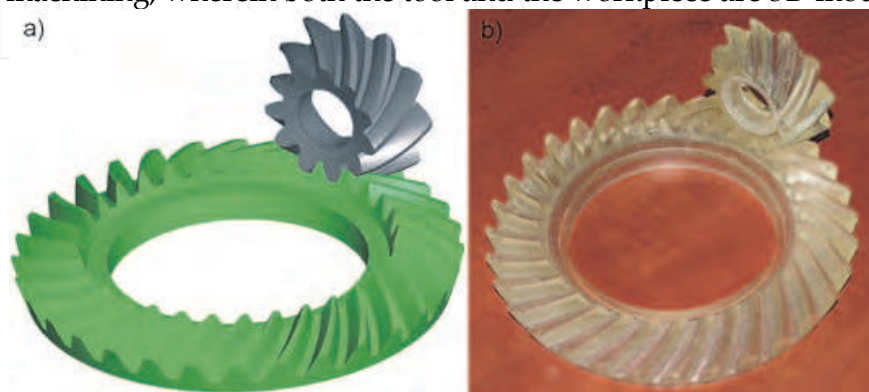

Fig. 29. Test models: a) 3D-CAD model, b) SLA model

performs discrete motions in respect to the workpiece in accordance with the kinematics of actual machining. In each of the consecutive positions from a workpiece-representing body, a common part (interference) of tool and workpiece is removed.

The CAD models were prepared in a manner which enables direct observation of the mating area. For this purpose, suitable recesses were made with CAD system in 3D gear models, so as to facilitate a constant observation of the contact area.

CAD models of gears and fixture were created using the Mechanical Desktop software, from where they were exported to the STL format. In the STL format the 3D bodies are described with the use of flat, triangular surface flakes. Compared to CAD, the surface precision of the STL model is assumed as 0.001 mm. This is dedicated accuracy for the export of CAD to the STL file for the gear tooth. Then, the process of stereolithographic model making on the 3D Systems SLA-250 apparatus was prepared (Fig. 29b).

5.1.2 Stand tests of the contact area

Gear wheels were compared in a special test stand (fig. 30), which enables the examination of pairs of gear wheels in various configurations. Static as well as dynamic determination of the mating area is possible. The stand is equipped with elements fixing gear wheels (1), a powder brake for imposing a load on the gear (2), a torque meter (3), a stepper motor (4) for propelling the gear and a steering console (5) with a computer.

The contact area is visible on the inside of the pinion through transparent resin (fig. 31a). Its shape is somewhat similar to an extended ellipse. Noticeable irregularities of the contact area contour are caused by machining marks, as would be left by a real tool on tooth flanks (in fact the analyzed gears are machined by gear generating, as it was duly taken into account in building the CAD models of pinion and gear wheel – fig. 31b).

Observation-facilitating conical recess inside the pinion is also visible. In order to visualize the contact area, the gears were moistened with distilled water with detergents added. The
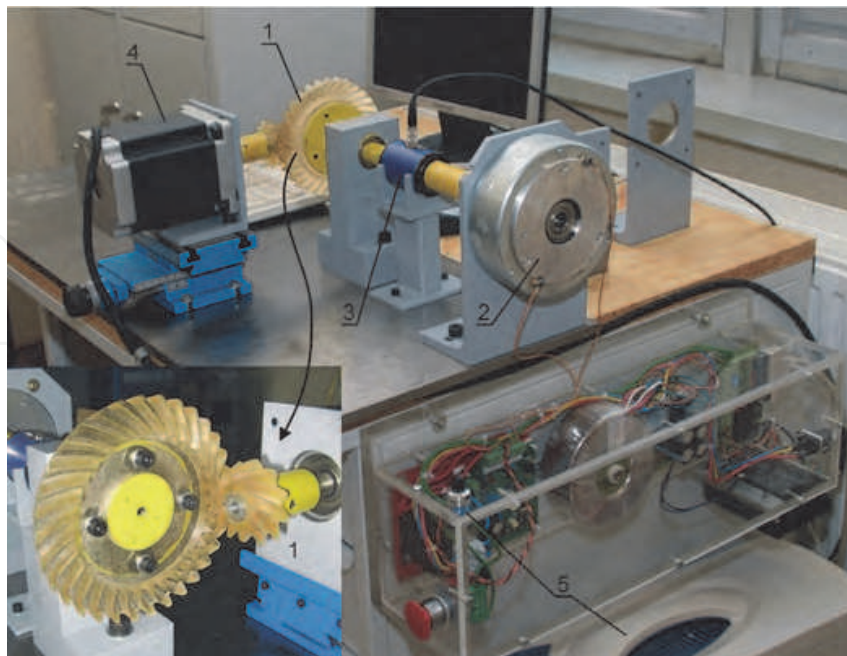

Fig. 30. Stand for testing the contact area: 1-gear, 2-brake, torque meter, 4-stepper motor, 5-sterring console

detergents were selected experimentally so that they form meniscus of thickness similar to the typical thickness of the layer of ink used in gear inspection machines, i.e. 0.00635 mm. The contact area obtained corresponds well with that geometrically determined with the use of 3D models in the CAD system. The determination of the geometric instantaneous contact area in the CAD system consists in a mutual gear infeed by a preset amount equal to, say, the thickness of the layer of ink used in gear inspection machines and in the determination of interference. The spatial curve that defines the interference volume is treated as the instantaneous contact area of mating gears.
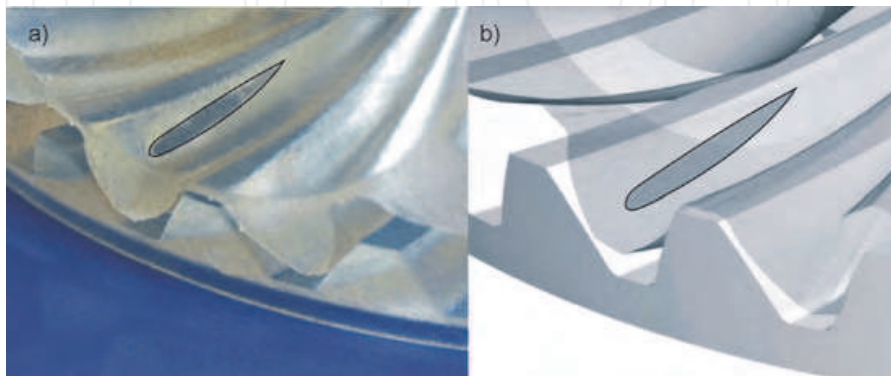
Fig. 31. Contact area: a) visible on internal side of SLA model, b) visible on CAD model

The deliberate application of stereolithography and the use of the suitable polymer (e.g. transparent resin, SL5170) produced a test gearbox, in which the instantaneous contact area may be determined through direct observation. The determination of the instantaneous contact area and, in particular, its changes as the gears turn by one division of graduation, enables conclusions to be drawn about the correct gearbox designing. The application of the ink method is also possible for mating marks determination.

The application of rapid prototyping techniques, (such as stereolithography, applied in the example) allows for a considerable acceleration of research into new designs of gears and gearboxes, as there is no need to make a real gearbox of metal, which would require an extended time for design as well as testing, and would involve a higher cost. The results of the stand testing correspond with the analyses performed in the CAD environment and with analytical methods.

5.2 Fatigue tests of non-involute gear wheels

In the engineering design of toothed gears, the need often arises to verify the correctness or accuracy of solutions achieved by means of analytical methods.

The design and implementation of new tooth profiles of gear wheels require a long calculation and testing process. It is possible to speed up the process by verifying the results of analytical calculations with the aid of the CAE/FEM numerical analysis and experimental tests of prototypes made by RP methods (Pacana et al. 2010).

The subject of such tests were the objectives of numerous projects, including R03 021 02 and POIG.0101.02-00-015/08). During the realization of the assignments of the research projects, a wide range of innovative tooth profiles of gear wheels were designed. The designed wheels were subjected to analysis with the application of FEM. As a result of the analysis, tooth profiles were selected for the construction of test prototypes by RP methods and stand tests (fig. 32).

The selection of the proper profiles for gear wheels intended for tests was also preceded by calculations and analysis of bending stresses at the tooth base for four consecutive teeth in the mesh. Thanks to the juxtaposition of graphs depicting the successive teeth in one chart and their determination in time, it is possible to define the work character and the load course for the whole gear. These graphs can be used to observe the mutual locations of one-pair and two-pair mating areas for consecutive tooth pairs in the mesh.

Once the FEM analysis was completed, test prototypes of selected pairs of gear wheels were produced with the application of the SLA and FDM methods.
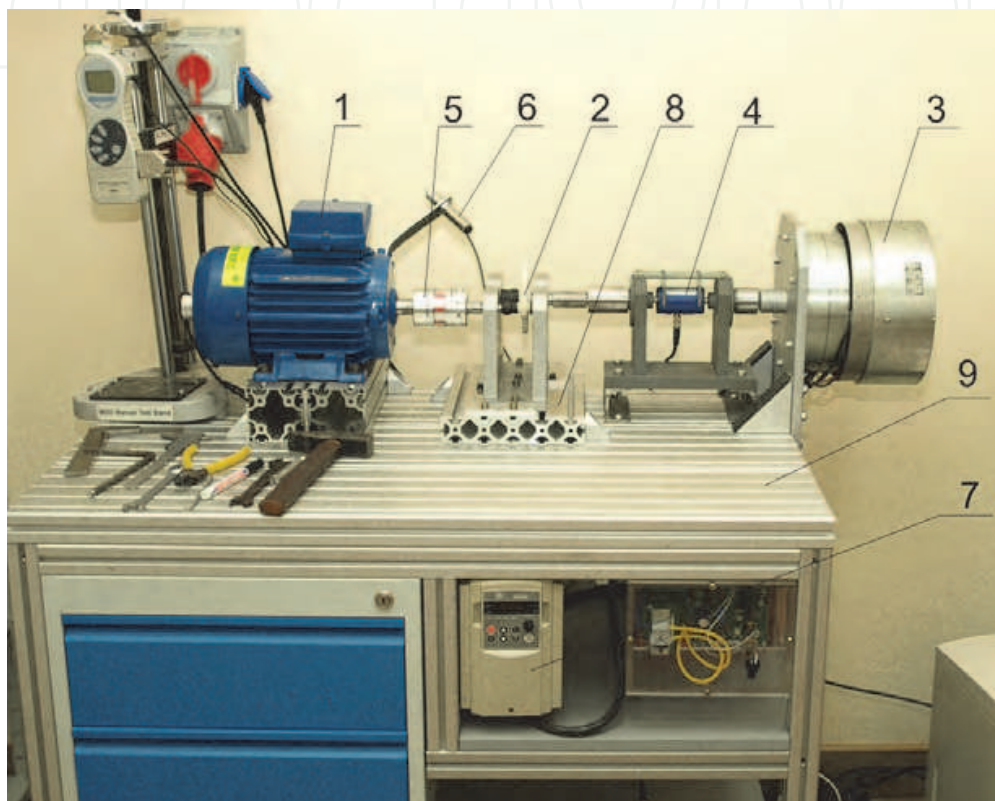
Fig. 32. Stand for gear tests: 1-Motor, 2-Reducer, 3-Brake, 4- Torque meter, 5- Clutch,
6- Pyrometer, 7-Inverter, 8-Base, 9-Stand table

A three-phase induction motor (1), controlled by an inverter (7) through a clutch (5) drives the tested stand gear. The gear is loaded with a brake (3), which introduces into the system a stressing moment, measured by means of a torque meter (4). The position of the gear shafts is digitally determined by location converters. The gear temperature is measured with the application of a contactless method, utilizing temperature radiation, by means of pyrometers (6). All data obtained during the fatigue tests are read by the measuring system and transferred to the computer.

The stand is universal, with the possibility of changing the configuration of the test system, and its modular structure enables the examination of single units and pairs of gear wheels of the individual pair of gears. For this reason, the stand base was designed in such a way as to allow for the mounting of individual components in various configurations.

The conducted quality analysis of various tooth profiles was aimed at determining the values of bending stresses at the tooth base for gear wheels having different parameters of the toothed wheel rim. Calculations were made for gear wheels of the following tooth

profiles: involute, arc, sinusoidal and BBW circular arc. For all of the analyzed profiles, the same boundary conditions were adopted for calculations and tests. This allowed for the verification of the correctness of the received calculations results with the aid of stand tests of real gears with wheels made by means of RP methods.

Based on the realized tests, it can be concluded that non-involute gear wheels have the highest resistance. Minor differences were observed between the MES analysis and the stand tests of prototypes. This confirms the validity of the adopted research assumptions and the assumptions of the model similarity criteria. The slight discrepancy between the results of the FEM calculations and the findings of the stand tests may further be reduced by entering the data obtained in the research process into the FEM model in the course of the next approximations.

6. Conclusion

Rapid prototyping methods are widely applied in many fields of technology. One of the essential benefits of RP techniques is the possibility of generating prototypes of complex, virtually unlimited internal and external geometry, such as gear wheels. This article discusses selected aspects of the manufacture and testing of gear wheels with the application of rapid prototyping methods in the theoretical and practical aspects.

The analysis presented in chapter 1 has a general nature and concerns selected RP techniques, most commonly used in practice. Chapter 2 describes the practical aspects of one of the most significant stages in the rapid prototyping process – program data processing. This phase has a major influence on the geometric accuracy of prototypes irrespective of the applied RP system. The next chapter discusses the tests results of the geometric accuracy of gear wheels prototypes produced with the application of coordinate measuring methods. The last part demonstrates the possible applications of prototypes manufactured by means of incremental techniques in laboratory and industrial tests.

The subject of the application of RP methods for the production and testing of gear wheels goes beyond the scope of this article. Therefore, the information presented herein includes selected issues of research work realized at the Department of Machine Design of Rzeszow University of Technology as part of many projects, such as "Modern Material Technologies in Aerospace Industry", No POIG.0101.02-00-015/08.

7. Acknowledgment

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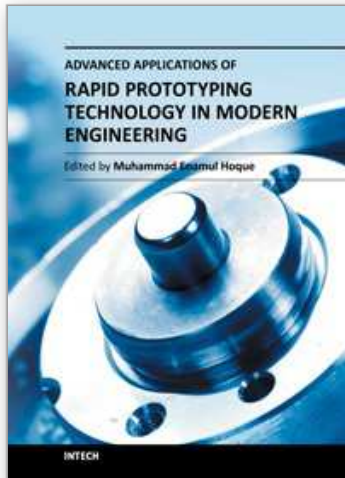
Advanced Applications of Rapid Prototyping Technology in Modern Engineering

Edited by Dr. M. Hoque

Rapid prototyping (RP) technology has been widely known and appreciated due to its flexible and customized manufacturing capabilities. The widely studied RP techniques include stereolithography apparatus (SLA), selective laser sintering (SLS), three-dimensional printing (3DP), fused deposition modeling (FDM), 3D plotting, solid ground curing (SGC), multiphase jet solidification (MJS), laminated object manufacturing (LOM). Different techniques are associated with different materials and/or processing principles and thus are devoted to specific applications. RP technology has no longer been only for prototype building rather has been extended for real industrial manufacturing solutions. Today, the RP technology has contributed to almost all engineering areas that include mechanical, materials, industrial, aerospace, electrical and most recently biomedical engineering. This book aims to present the advanced development of RP technologies in various engineering areas as the solutions to the real world engineering problems.

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