

# METHODOLOGY OF INCREASING ACCURACY OF GEAR MODELS MANUFACTURED USING ADDITIVE FDM METHOD

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## Summary

The paper presents methodology of increasing the accuracy of models of gears made applying additive methods. As a part of activities related to this subject, it was necessary to develop 3D-CAD research gears, which were the basis for producing physical models made using incremental FDM manufacturing technology. The created models were verified in order to determine the accuracy of resulting geometry. Then modifications were introduced to models so as to increase their accuracy. On this basis, in an iterative process, compensation coefficients were calculated to ensure reduction of defects in geometry with respect to a nominal 3D-CAD model.

**Keywords:** gears, 3D-CAD, RP techniques, FDM technology, optical measurement, accuracy analysis

## Metodyka poprawy dokładności modeli kół zębatych wytwarzanych z zastosowaniem addytywnej metody FDM

### Streszczenie

W artykule przedstawiono sposób poprawy dokładności modeli kół zębatych wytwarzanych z zastosowaniem metod addytywnych. Opracowano model 3D-CAD badawczych kół zębatych. Stanowiły podstawę do wytworzenia modeli fizycznych wykonywanych z zastosowaniem przyrostowej techniki wytwarzania FDM. Modele poddano weryfikacji w celu określenia dokładności ich wykonania. Wprowadzono modyfikację tych modeli dla podwyższenia ich dokładności. W procesie iteracyjnym ustalono wartości współczynnika kompensacji odkształceń. Zapewniono zmniejszenie błędów wykonania modelu w porównaniu z nominalnym modelem 3D-CAD.

**Słowa kluczowe:** koła zębate, 3D-CAD, techniki RP, technika FDM, pomiary optyczne, analiza dokładności

## 1. Introduction

The accuracy of physical models created using Rapid Prototyping (RP) techniques in an additive process is largely dependent on parameters of a given

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device. However, additional factors which define it are deformations resulting from processing distortions of a material and from an incremental way of building a prototype.

In order to increase the accuracy of prototype gears it is necessary to develop deformation compensation coefficients of models made by means of selected incremental techniques. These coefficients are defined based on studies that consist in iteration of a combination of CAD-RP-CMM processes. To carry out the research process it is necessary to develop 3D CAD models of test specimens, making them applying selected RP techniques and carrying out a measurement process. The developed methodology for modelling and introducing modification was based on Autodesk Inventor software environment. A manufacturing stage enclosed making physical models using industrially applied representative incremental techniques. The obtained models of gears were subjected to measurements and to analysis of accuracy.

At the current stage of development of additive methods technological improvement of manufacturing accuracy is extremely costly and difficult to implement. The suggested methodology based on the process of increasing the accuracy of gear prototypes does not require interference with the production equipment, which does not increase manufacturing costs. The methodology is based on processing compensation of geometry of a product. Therefore it is possible to get a prototype of higher dimension- shape accuracy than that resulting from technological assumptions of a given additive process. The obtained deviation maps for prototypes of gears can be the basis for development of libraries dedicated to specific manufacturing systems for other product groups.

## **2. Modelling process of the research gear pairs – making a nominal model**

The development that has been made in the field of rapid prototyping system allows for producing prototypes of complex geometry, even those whose execution by machining methods is impossible. However, the geometry in a form of a solid model needs to be initially developed in CAD system.

Autodesk Inventor system was used to create the research models. Although the applied system has a specialized tool to make solid models of gears, it was decided to use a method of solid simulation of machining to make the research models. The choice was dictated by the fact that the models prepared using special tools are generated in nominal dimensions and a user cannot modify them locally. Aforementioned possibility of modifications is necessary to carry out the research work [1].

The first stage of the work was creating parametric nominal models of research gears. As already mentioned, a solid machining simulation was applied to make them. This method involves two parameterized solids: a solid reflecting the tool and a solid shell of the workpiece (Fig. 1) [2].

Both of presented solids were made on the basis of parametric sketches made in accordance with applicable standards on the geometry of gears. A sample sketch relating to the solid of tool is shown in Fig. 2.

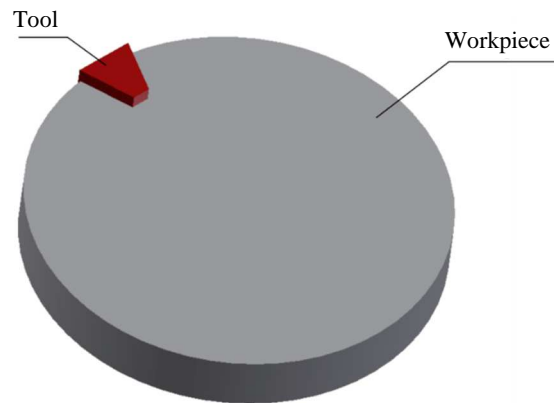


Fig. 1. Solids involved in the simulation

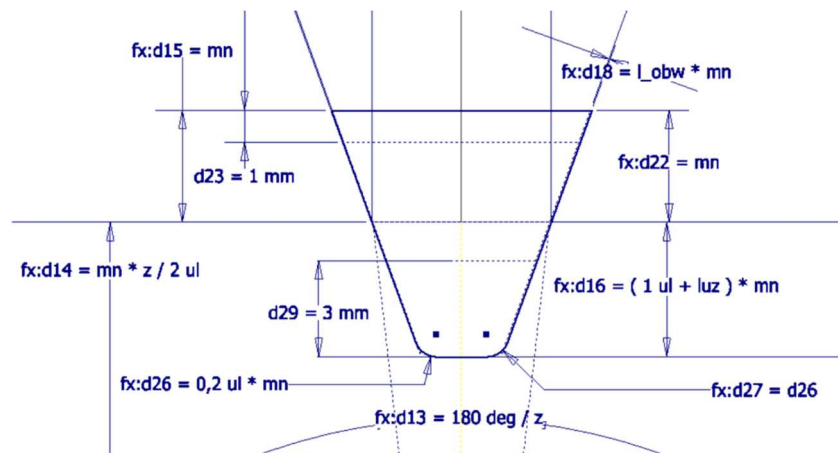


Fig. 2. Parametric sketch of the tool solid

The machining simulation method consists in iterative execution of the difference between the tool solid and the workpiece in successive positions resulting from the kinematics of the actual machining process. A method consisting in generating subsequent insertions of the tool solid in relation to the immobilized workpiece solid was used to simplify the model (Fig. 3) [3].

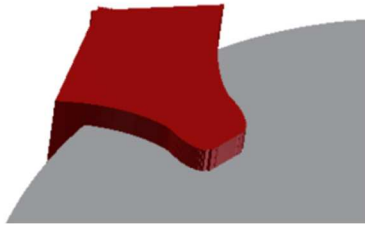


Fig. 3. A solid of tool placed in successive discrete positions

Subsequently, a number of operations of solids subtractions was made and one space was received as a result (Fig. 4).

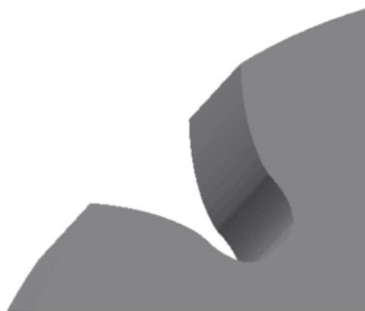


Fig. 4. The tooth space obtained by machining simulation

After one space was made, it was arranged in a circular pattern to make a complete toothed wheel rim (Fig. 5). After adding constructional elements in a form of a hub, a hole and a splineway, a solid model of the research gear was obtained. After changing parameters, the second gear of transmission was generated automatically to form the pair of research gears (Fig. 6).

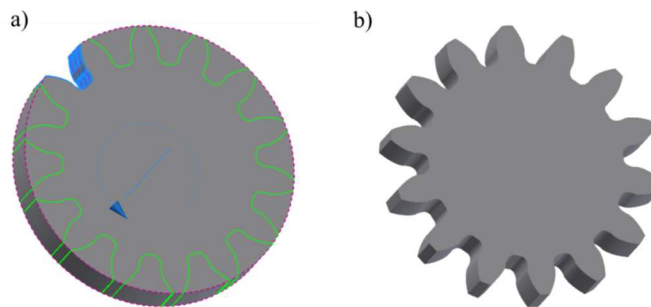


Fig. 5. Creating a complete toothed wheel rim: a) performing a circular pattern, b) a solid model of the rim of the gear



Fig. 6. Solid models of gears

### **3. The process of printing and measuring a nominal models of a gear pair made in FDM technology – a nominal model**

On the basis of developed 3D-CAD models, two pairs of spur gears were made using FDM method (Fig. 7). Research gears of the first series were based on nominal models whose geometry is to be modified in subsequent iterations of the process of improving accuracy. Then the models were subjected to geometry measurement using Atos II TripleScan optical scanner (Fig. 8).



Fig. 7. A pair of gears formed in FDM technique – a nominal model

Results for the pair of nominal gears obtained from the measurement were subjected to accuracy analysis. After getting geometry from the measurement process, it was bound with geometry of the nominal 3D-CAD model (Fig. 9, 10) [4, 5]. In the received measurement results mainly teeth flanks were analyzed and main activities of correcting geometry were focused on them. Such an action resulted from the previously conducted studies, which indicated that main areas of geometry errors lie in these zones. Moreover, the area of teeth flanks is largely responsible for a correct cooperation of a gear pair.

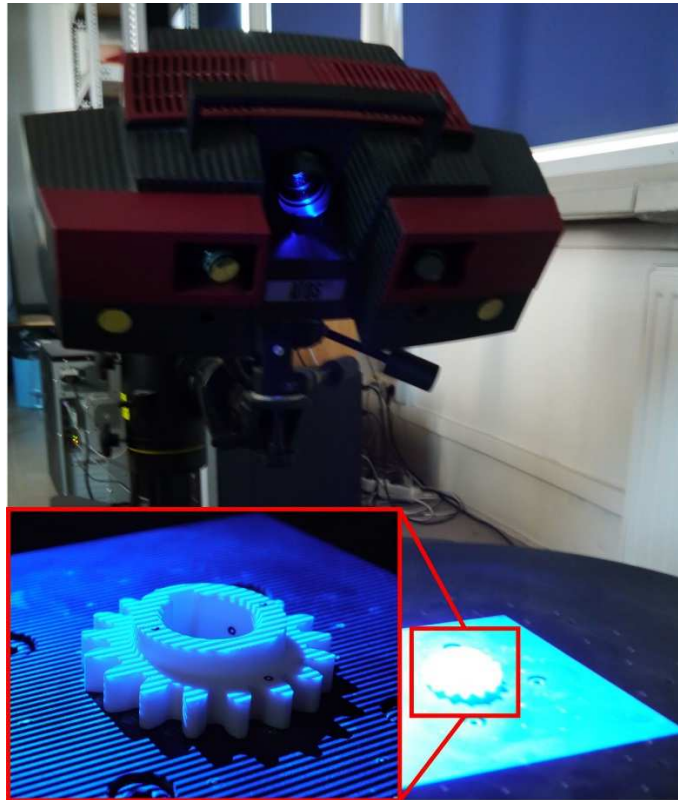


Fig. 8. Sample measurement of a gear formed in FDM technique – a nominal model

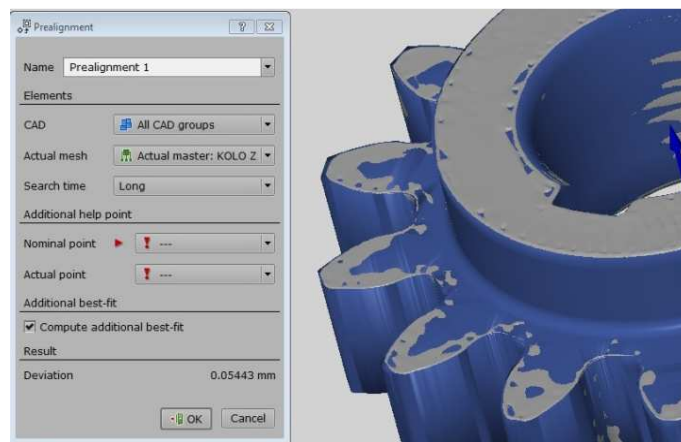


Fig. 9. Adjusting the measured geometry to 3D-CAD pattern – FDM pinion (a nominal model)

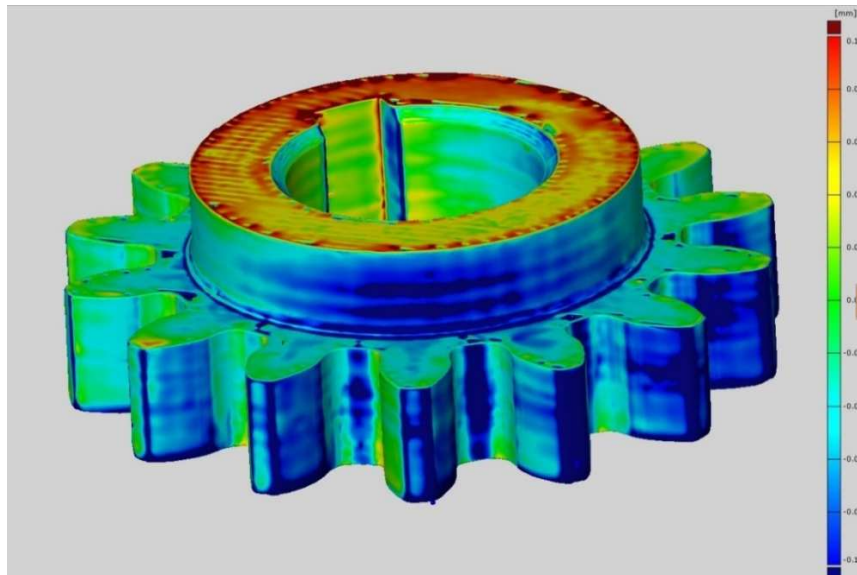


Fig. 10. A global analysis of deviations in geometry – FDM pinion (a nominal model)

Error values obtained on the basis of geometry measurements were used to develop compensation coefficients of geometry changes for an incremental shaping process. The coefficients were introduced to geometry of 3D-CAD models which were modified and then re-created taking into account their values.

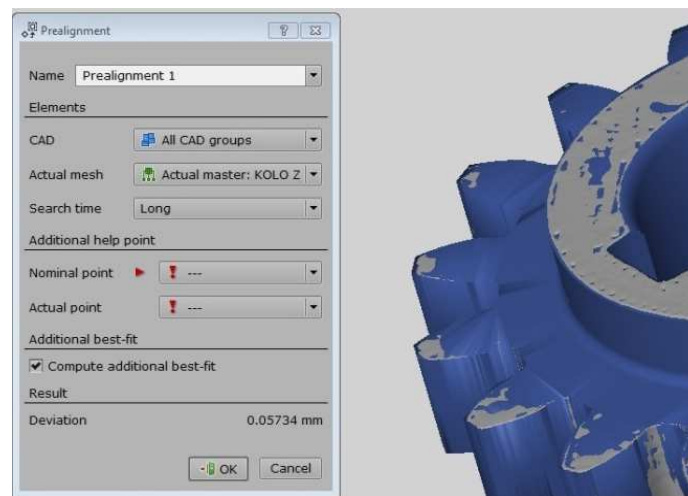


Fig. 11. Adjusting the measured geometry to 3D-CAD pattern – FDM gear (a nominal model)

Working out an analysis of geometry for the gear pairs made by FDM technique for nominal research models showed that both for the pinion and for the cooperating wheel in the area of tooth flanks there was contraction of material (Fig. 11, 12). Maximum values of deviations on tooth flanks ranged from  $-0.1$  to  $-0.18$  mm. These results were used to make adjustments in the first step of the iterative process.

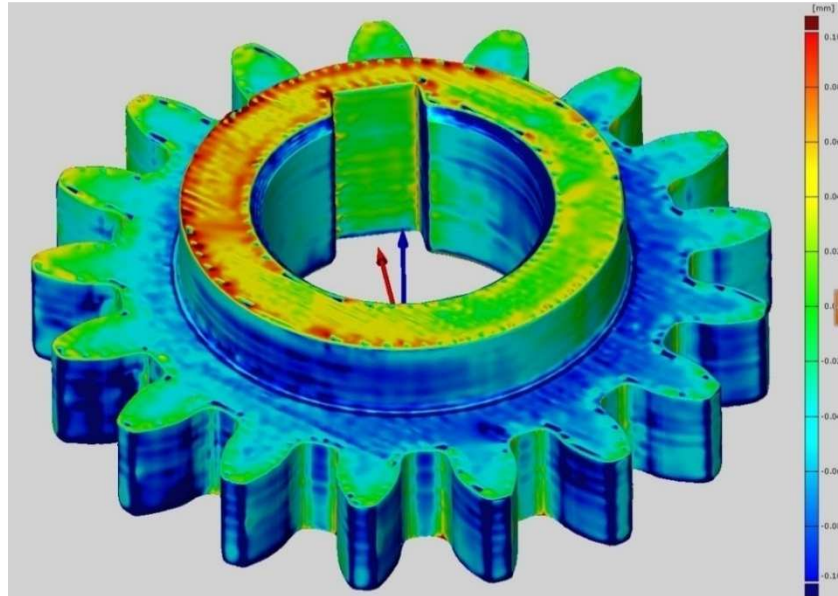


Fig. 12. A global analysis of deviations in geometry – FDM gear (a nominal model)

#### 4. The first iteration of geometry of gears

During ongoing work we concentrated on tooth flanks. After analyzing deviations of nominal models we found that their distribution on flanks is uniform, and therefore assumed modifications were introduced by modifying the profile of the tool. In case when it was required to increase tooth thickness, edges of the profile of the tool were moved inwardly by a predetermined value (Fig. 13).

If it was necessary to reduce the width of tooth, the profile modification consisted in shifting the edges to the outside. Comparison of gear models before and after introducing modifications is shown in Fig. 14.



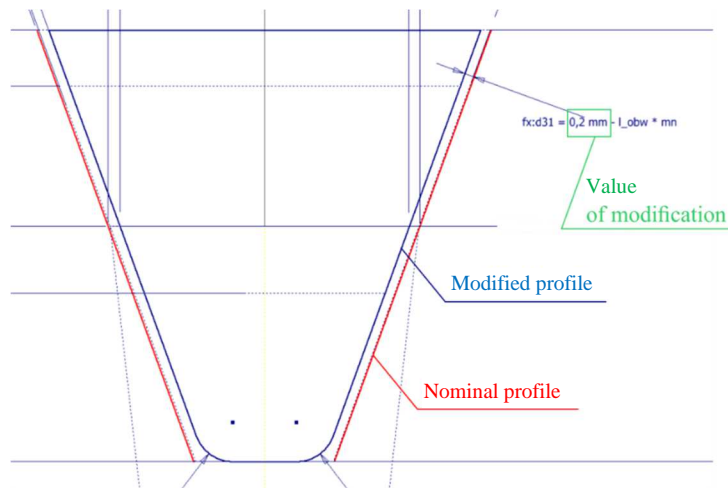


Fig. 13. The method of introducing modifications

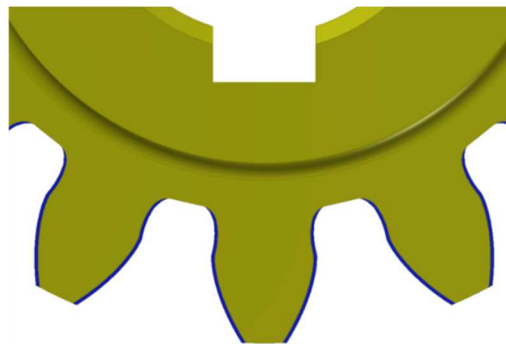


Fig. 14. Comparison of models before (yellow) and after introducing modifications (blue)

### 5. The process of printing and measuring nominal models of a gear pair made in FDM technology – the first iteration

Research models of gears were made again on the basis of measurement results and introduced adjustments to geometry of tooth profiles. The nature of deviations for FDM method caused that the geometry of toothed wheel rim was increased by the offset value of + 0.2 mm. As in the case of nominal models, they were subjected to geometry measurements and an analysis of deviations was carried out [6, 7].

The pair of gears after the first stage of iteration was again subjected to accuracy analysis using Atos II Triple Scan optical scanner. After acquiring

geometry in the measurement process, it was bound with nominal geometry of the 3D-CAD model (Fig. 15 and 17).

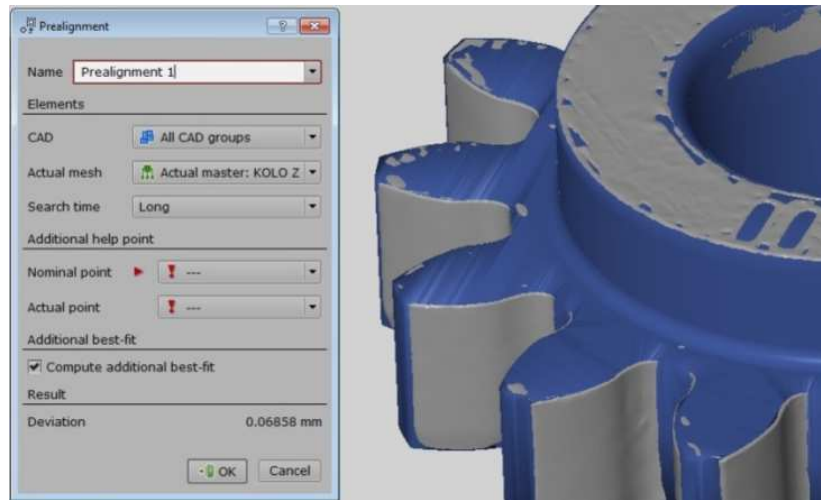


Fig. 15. Adjusting the measured geometry to 3D-CAD pattern – FDM pinion (first iteration)

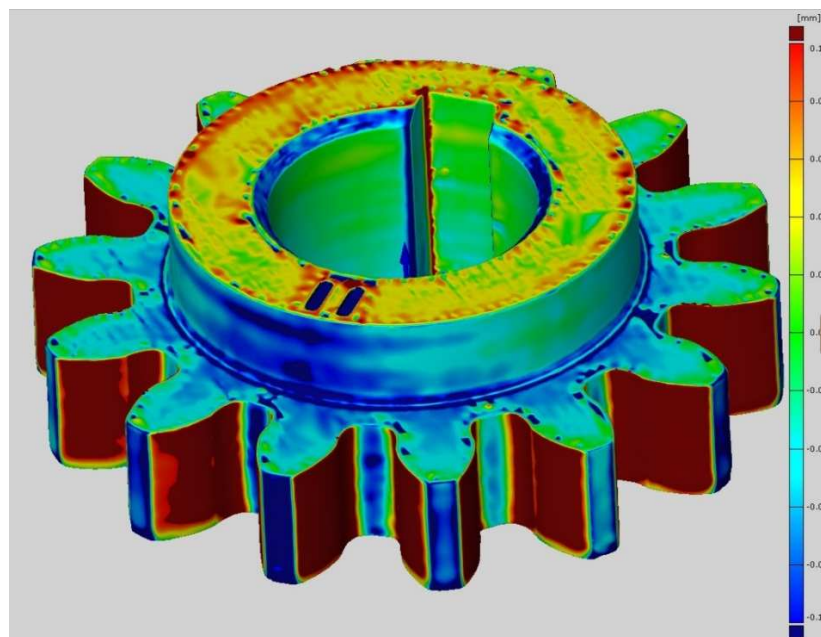


Fig. 16. A global analysis of deviations in geometry – FDM pinion (first iteration)

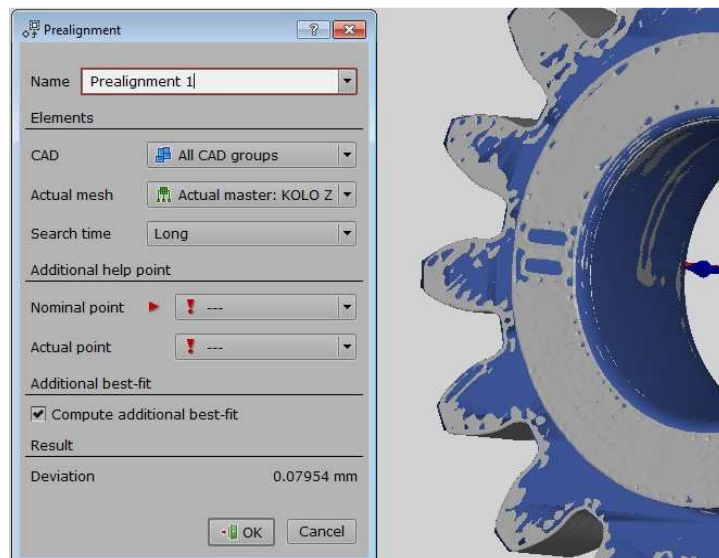


Fig. 17. Adjusting the measured geometry to 3D-CAD pattern – FDM gear (first iteration)

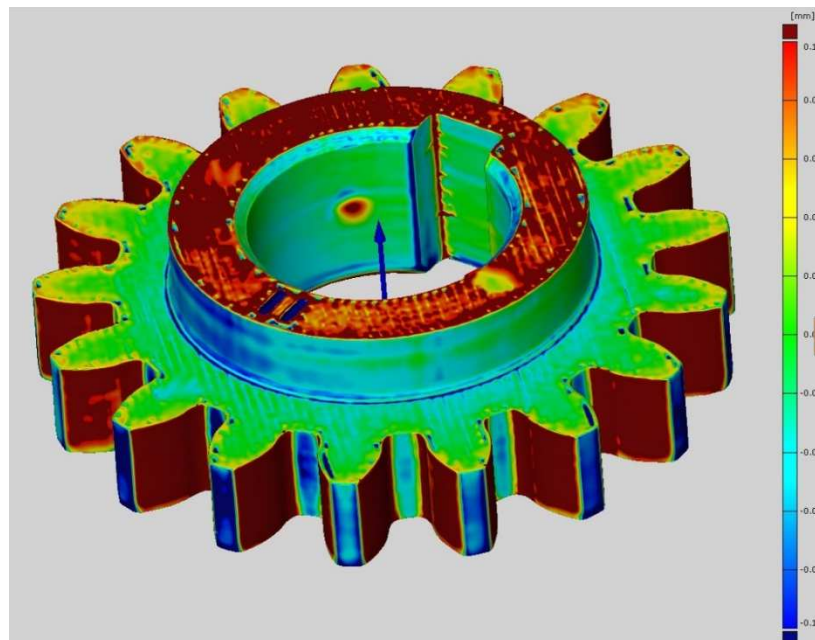


Fig. 18. A global analysis of deviations in geometry – FDM gear (first iteration)

The geometry analysis for the pair of gears for the first stage of iteration for research models showed that both for the pinion and for the cooperating wheel there was an excessive increase in tooth thickness in the area of flanks (Fig. 16 and 18). Specified values of maximum deviations on teeth flanks were in the range of + 0.1 to + 0.16 mm. These results were used to make adjustments in the second stage of the iterative process.

## 6. The second iteration of geometry of gears

In the following stage of ongoing work, after analyzing deviations in models after the first iteration, it turned out that it was necessary to make further modifications. A similar course of action was assumed as in case of making models in the first iteration (Fig. 19).

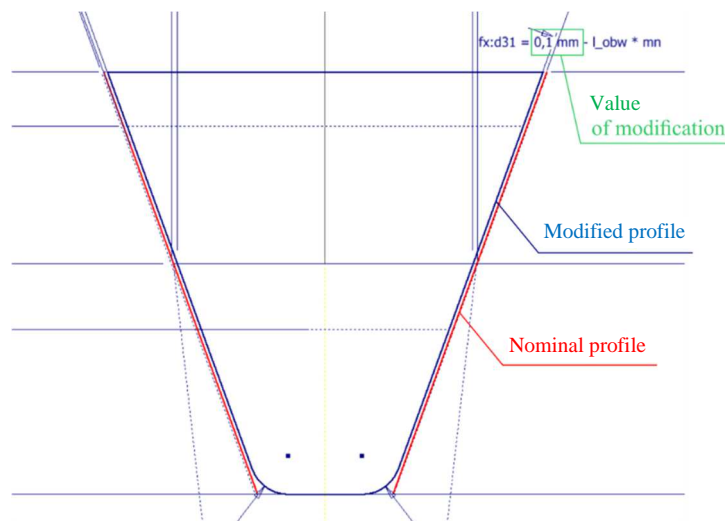


Fig. 19. The method of introducing modifications

Comparison of gear models before and after introducing modifications is shown in Fig. 20.

## 7. The process of printing and measuring nominal models of a gear pair made in FDM technique - the second iteration

The measurements results and adjustments made to teeth profiles showed that geometry deviations are too great. Therefore, we carried out the second step of the iterative process. As a result of it research models of gears were made again. The

nature of deviations for FDM method caused that the geometry of the toothed wheel rim was increased by + 0.1 mm in relation to the nominal model. Similarly to the previous models, they were subjected to measurement of geometry and an analysis of size of deviations was conducted.

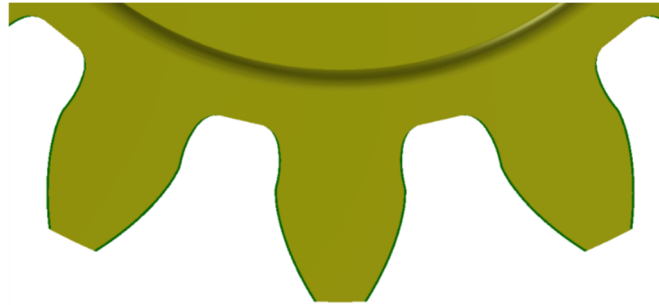


Fig. 20. Comparison of models before (yellow) and after introducing modification (green)

The pair of spur gears made in FDM technology after the second stage of iteration was one more time subjected to accuracy analysis. After acquiring the geometry in the measurement process, it was bound with a nominal geometry of the 3D-CAD model (Fig. 21 and 23).

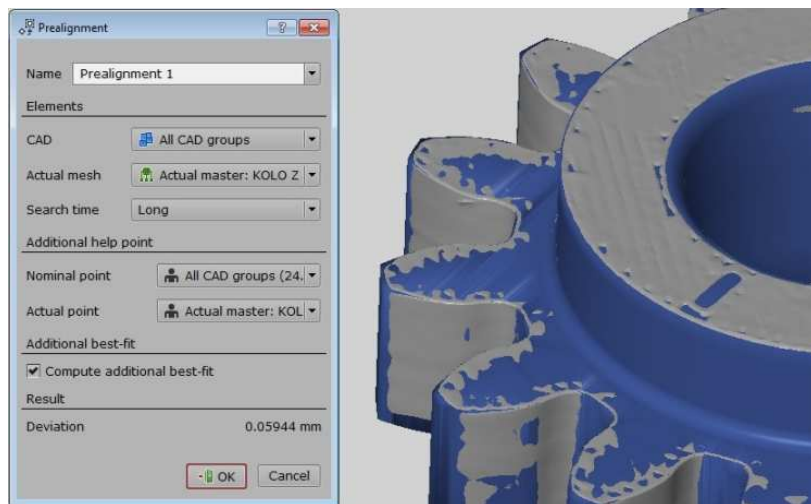


Fig. 21. Adjusting the measured geometry to 3D-CAD pattern – FDM pinion (second iteration)

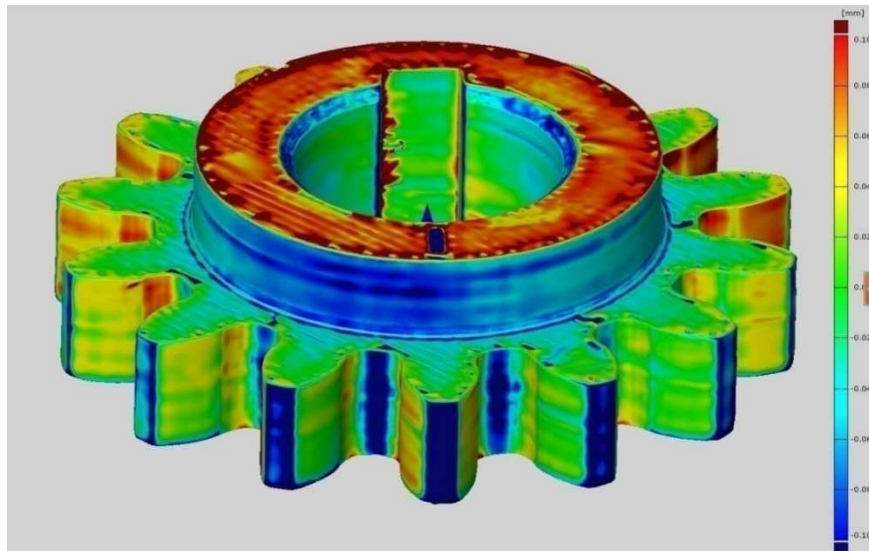


Fig. 22. A global analysis of deviations in geometry – FDM pinion (second iteration)

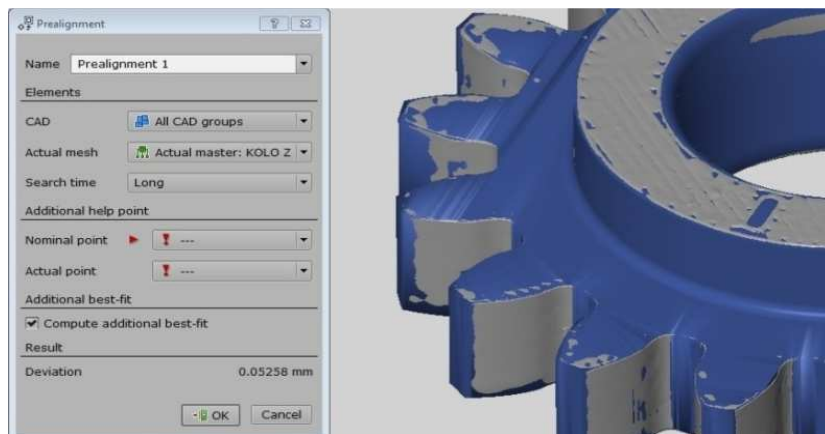


Fig. 23. Adjusting the measured geometry to 3D-CAD pattern –FDM gear (second iteration)

The geometry analysis for the pair of gears for the second stage of iteration for research models showed that both for the pinion and for the cooperating wheel there was an increase in tooth thickness in the area flanks (Fig. 22 and 24). However, increasing the thickness of teeth by values determined in the iterative process caused that geometry deviations were within 85% in the range of 0 to + 0.04 mm. Specific values of maximum deviations on teeth flanks were in the

range of + 0.04 to 0.08 mm and it was a 15% share. Therefore, the correctness of the applied method of increasing accuracy for FDM technique used in manufacturing gears can be confirmed.

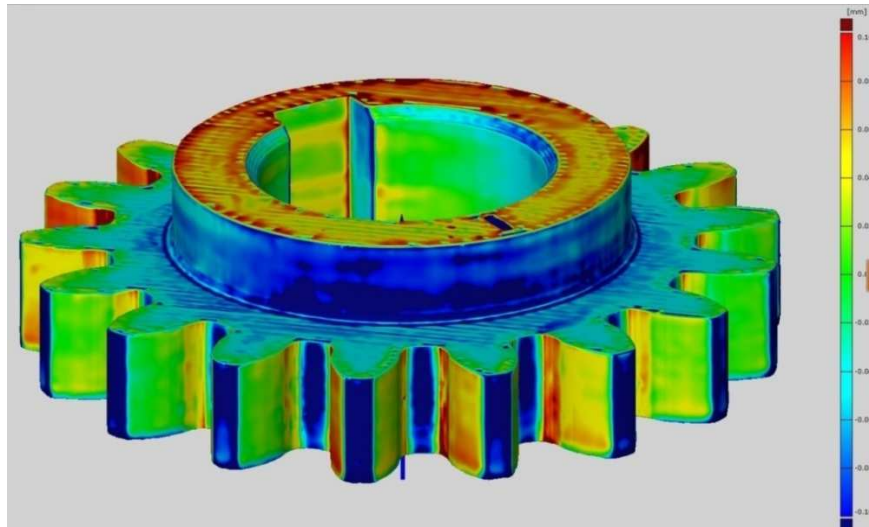


Fig. 24. A global analysis of deviations in geometry – FDM gear (second iteration)

## 8. Conclusions

The aim of the research was to develop methodology of increasing the accuracy of gear models made by means of FDM additive method. The carried out research made it possible to create functional prototypes of gears, where the accuracy mapping CAD geometry was improved by using a feedback loop between the modelling stage, manufacturing and accuracy inspection.

Based on the carried out research and tests, deformation compensation coefficients were developed for analyzed methods for producing models of gears using additive techniques. As is apparent from the presented iterative process for FDM manufacturing method, it is necessary to increase the amount of material in selected areas of a model. However, the size of modifications cannot be equal to the value of obtained geometry errors. In order to achieve a proper distribution of deviations, it is necessary to excess (for FDM method) material by about 50% of the value of geometry deviations.

As a result of geometry corrections performed as presented above, it is possible to create models of gears with twice as high accuracy as errors of manufacturing accuracy declared by producers of individual devices.

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