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The Effects of Blank Geometry on Gear Rolling for Large Gear Modules: Experiments and Finite Element Simulations

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ABSTRACT Gear rolling is a forming process to produce gear wheels by plastic deformation. The advantage of the process is to eliminate the chip formation during production and also to improve the product properties since the non-metallic inclusions will be oriented along the cog surface and not perpendicular to it. The method has been developed in the past years for gear production for automobile application with modules up to 3 mm. The successful application of gear rolling in those cases raises the question regarding the feasibility of using cold rolling to manufacture gears with larger modules which can be used for heavy vehicles. In this paper, a gear wheel with normal module of 4 mm has been studied in order to investigate if such large modules can be manufactured by gear rolling. One of the issues in rolling of gears is the design of the blank geometry in order to obtain the right gear geometry after the rolling process. Blank shape modifications are necessary to control and to reduce the undesired shape deviations caused by the large plastic deformations in rolling. The blank modifications also help the process designer to control the forming force and torque. In this paper, the process has been modeled by finite element simulation and the influence of different blanks has been simulated. The validity of the FE model has been checked through several experiments. Both the numerical and experimental results revealed favorable blank modifications to apply for further developments of the gear rolling process.

INDEX TERMS Accuracy, gears, geometry, modeling, manufacturing processes.

I. INTRODUCTION

Gear wheel production is currently dominated by cutting technologies. Using forming techniques such as gear rolling to fabricate gear wheels still has scientific and technical novelty. Significant developments in these techniques have been reported during the last decade [1]–[11].

Gear rolling as a ‘‘tooth generating’’ process can be performed by two different methods [3]. The first method is called ‘‘flat rolling’’ and the gears are formed between linear gear racks. The main problem with this method is that the process of tooth generation should be completed in one cycle of tools moving against each other. This limits the application of the flat rolling to smaller gear modules otherwise it will require racks with large sizes to produce a gear with large tooth height and module [4].

The second method is called ‘‘round rolling’’ and the gears are formed by round forming tools. Using round tools has some advantages. One is that this process can be performed in several rounds of tool rotational cycles that will let the process progress with small deviations in formation of the pitch which is one of the sources of the geometrical errors in gear rolling. Also considering the case of large gear wheels, the size of equipment will be a limiting factor and it is easier to realize with a finite number of rolling cycles with round tools rather than performing it in one cycle with very large flat tools [4]. Therefore in order to investigate the case of gear rolling for a gear wheel with normal module of 4 mm, gear rolling with round tools is studied in this paper.

The main steps of gear rolling with round tools are illustrated in Fig. 1. As it is shown, the process will start with an initial rolling phase which is used for engaging the tools and the blank together. This phase is required to divide the blank into the required number of teeth. The second step starts when both penetration speed and rotational speed of the tools cause plastic deformation of blank material and the shape of the gear teeth gradually evolves. Finally when the full depth of

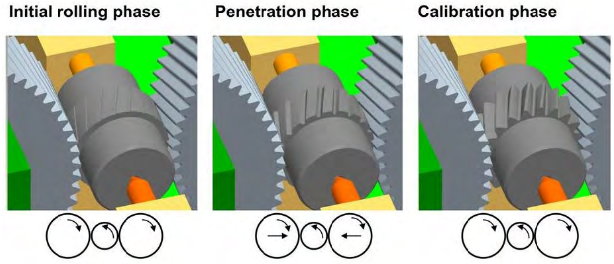

FIGURE 1. Gear rolling process steps for round rolling.

gear teeth is reached on the blank, the penetrating movement of tools stops and the tools just roll the gear blank. This last step is a calibration step which will equalize the deformation of the material over all of the formed teeth.

The process kinematics is a key to a successful rolling process as it is shown by [5]. The loads and torques during gear rolling has a direct relation to the amount of penetration. Therefore it is necessary to design the process to prevent overloading the rolling machine. Many reversal points of rotation direction are applied during the process to keep the symmetry in material deformation. The reversal points are also helpful to keep the position of the so called ''rabbit ears'' in the middle of the formed teeth on the blank. Importance of process kinematics and reversal points has been discussed in the literature to a great extent [6], [7]. An illustration of the process path for rolling of gears is given by Neugebauer *et al.* [3], for a gear with normal module of 1.6 mm. Similar process kinematic planning will be used for the investigations in this paper.

A few researchers have reported the possibilities of application of gear rolling for higher normal modules than 2 mm [8]–[11]. No evidence and in depth study has been provided about such applications for gear rolling except the results published by Kretzschmar *et al.* [2] in where they presented development on a case with normal module of 3.45 mm for a rounded tool design numerically. In addition to this point, the excessive axial material deformation and opened rabbit ears are among the major issues caused by gear rolling in the current state of the research. When the tooth height is relatively high, as for instance for gears used for heavy vehicles, such problems can be even more pronounced than those discussed in the literature previously. A few suggestions and recommendations to avoid the problems are given by the previous publications in this field. They are mainly to reduce the size of the rabbit ears and improve the shape of teeth formed by the rolling process but they have not been tested in practice. The possibility of rolling of a gear wheel with the normal module of 4mm is investigated numerically previously by the present authors but it has not been verified experimentally until now [9]–[11].

The goal of this paper is to develop and investigate the gear rolling method for producing gears with a module of 4 mm which is larger than reported previously by other researchers. This is primarily done by focusing on blank shape modifications. The effects of some modifications on the forming force and torque as well as how they can reduce the geometrical errors in the produced gear wheels are presented. Such errors are evaluated based on measurements on the rabbit ears and shape deviations along the axial direction of the gear wheel.

In this paper one initial FE simulation was performed with a simple geometry of the tool/blank set up. Based on the results from that simulation three modifications of the blank geometry were proposed to improve the gear wheel geometry. The degree of success of these three modifications was evaluated by studying different measures of deviations of the final gear geometry compared to the intended geometry. After the FE study an experimental study was performed. This was partly used to verify the accuracy of the predictions of the FE simulations and partly to draw general conclusions for process modifications based both on FE simulations and experimental trials.

II. GEOMETRIES, KINEMATICS AND MATERIALS

In the following part of this section the geometrical specifications for the intended gear geometry, the initial blank geometry, the tool geometry and the process kinematics are described.

The specifications of the gear studied in this work are shown in Fig. 2. The gear has a normal module of 4 mm and 21 teeth. The addendum diameter is 100 mm, the root diameter is 81.7 mm and the tooth depth is 9.15 mm. These three values are used as the reference values and are used to evaluate the results of the FE model as well as the experimentally produced gears.

Normal module m_n [mm]	4.0
Number of teeth z	21
Normal pressure angle α_n [°]	20
Helix angle β [°] / direction	20 / right
Addendum mod. factor x	0.3261
Tip diameter d_a [mm]	100.0 ± 0.1
Root diameter d_f [mm]	81.7 ± 0.1
Tooth height h_z [mm]	9.15
Tooth height factor y	2.2875

FIGURE 2. Specifications for the gear used for investigations.

In order to be able to roll a gear wheel with the intended dimensions a blank shape with the right design must be used. The shape of this blank can be found by FE-simulations through an iterative procedure. To create the blank and tool geometries for an initial FE model, it is required to first calculate the initial blank diameter (dv). This calculation is done according to the constant volume principle. It is possible to calculate the volume of the gear shown in Fig. 2 by using any available CAD software and then use it as the reference volume to calculate the cylindrical blank diameter with the same height and volume [12]. For this specific gear $d_v = 92.2$ mm is obtained from such a procedure and is used to create the blank geometry in the FE model. The blank geometry for the initial simulation is shown in Fig. 3a.

A set of modified blank geometries will be studied additionally to the initial geometry shown in Fig. 3a.

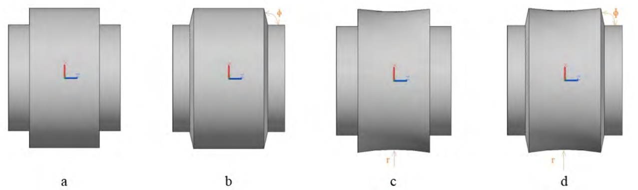

FIGURE 3. a) initial blank geometry calculated based on constant volume principle in gear rolling (blank #0), b) blank shape modified with inclined surface angle (blank #1), c) blank shape modified with outer surface radius (blank #2), d) blank shapes modified with both inclined surface angle and outer surface radius (blank #3).

The alternative blank geometries are presented in Fig. 3b, Fig. 3c and Fig. 3d. The value for outer surface angle (ϕ) modification and the value for outer surface radius (r) modification in each of the blank designs are given in Table 1. The definitions of ϕ and r can be found in Fig 3.

TABLE 1. Parameter values for modification of blank geometry.

Symbol	Modification type	Unit	Blank #0	Blank #1	Blank #2	Blank #3
Φ	Surface angle	°	90	121	90	121
r	Surface radius	mm	-	-	148	148

By knowing d_v it is possible to calculate the tip diameter of the tool (d_a). Using d_a and with the help of any gear calculation software the specifications for the tool geometry can be calculated. Generally the larger the tool is, the smoother the gear rolling process will be, but the high costs of the special tool material, as well as the limitation in space for mounting large tools in the gear rolling machine, restricts the tool geometry to be within certain limits. For the machine that was available in the lab where the experimental tests in this research were performed, a tool with the specifications shown in Fig. 4 is designed to roll the blank into a gear wheel. As it is given by Fig. 4, the tool has 59 teeth and the same normal module as the specified gear in Fig. 2 which is 4 mm.

Transverse module m_n [mm]	4.0
Number of teeth z	59
Normal pressure angle α_n [°]	20
Helix angle β [°] / direction	20 / left
Addendum mod. factor x	0.4012
Tip diameter d_a [mm]	264.36 ± 0.03
Root diameter d_f [mm]	246.07 ± 0.03
Evolv. tip radius r_a [mm]	0.4
Evolv. root radius r_f [mm]	0.4

FIGURE 4. Specifications for the round rolling tool used for investigations.

The gears blanks are manufactured in the steel grade 16MnCr5 which is traditional steel for gears used in automotive transmissions. Tension and compression tests were performed to calibrate the material plastic flow curve from experiment into the FE model. To keep execution times of simulation low, a rigid/plastic behavior is defined for the blank material in the FE model.

The tools used for the gear rolling experiments were made of the high strength powder metallurgical steel ASP 2012 with a tensile strength of 2500 MPa in the hardened condition. Due to the high strength of the tools it is assumed that they behave as rigid material in the FE model. This assumption reduces the computational times.

In order to obtain the intended gear geometry after gear rolling, it is necessary to design the right process kinematic plan for the tools to roll the blank and at the same time penetrate into it which will result in formation of the gear teeth around the blank. Under the applied force and torque the material of the blank will yielded and starts to flow. The plastic flow of the blank material will gradually change its shape from a cylinder into a gear wheel. It is important that the process kinematic does not cause over loading on the rolling machine. In practice overloading will result in unfinished rolling process which is not desired. Therefor the process kinematic is very important in running the experiments of gear rolling. In this work a process with 200 rolling cycles and 13 reversal points for change of direction of rotation has been used experimentally in order to reach the final depth of penetration without overloading the machine. The applied process plan is shown in the Fig. 5. The process design could be realized by means of the simulation and parallel monitoring and optimizing of the penetration curve per each rolling cycle in a combined numerical-experimental setup. For this purpose the first test were performed with a constant amount of penetration per each rotation of the blank in simulations. This setup led to forces higher than machine limits after few revolution where just half of the required penetration was reached. Therefore when it is needed to keep the number of revolutions low (<200 revolutions in this investigations) such constant penetration per revolution cannot be the right process setup to be used. The plastic hardening of the material during cold rolling will require to apply higher forces and torques for deforming the material into the final shape which at some point will result to overloading of the available machine. In order to keep the number of revolution cycles low and at the same time to reach the final required depth of penetration a repetitive try and error loop is required until the process penetration curve

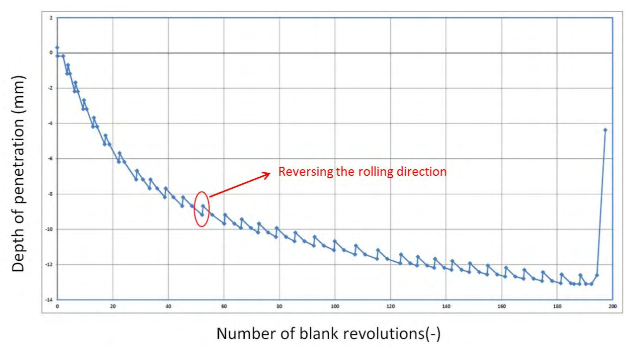

FIGURE 5. Specifications for the round rolling tool used for investigations.

which meets the required final depth of penetration with force and torques lower than machine limits is reached. To reach this design higher amount of penetrations are used in initial steps of the gear rolling while the material is softer, and when the material starts to be hardened, with reducing the penetration feed we could control the force and torques and keep them lower than the machine specifications. In this work an acceptable setup which is shown in Fig. 5 reached after three sets of optimization of the process curve. Obviously the proposed process design is very dependent on the available machine and also the process requirements. But the rule of the thumb is that the decided process should be comparable with the traditional cutting processes with respect to the time (which is defining the number of revolutions to reach the final penetration as a design parameter) and also to not result in overloading the gear rolling machine.

III. EVALUATION METHODS

As it is mentioned earlier it is needed to measure the effect of the proposed blank modifications on the final shape of the rolled gear to evaluate the influence of modifications. In this section the used method to evaluate the effects of modification on the gear rolling

No standard measurement routine has previously been defined for such evaluations. Therefore the parameters shown in Fig. 6 are used to compare the results. Fig. 6 shows a FE simulation result as an example. The material displacement in Z direction, which is the axial direction of the gear wheel, is given in the Fig. 6. The excessive material deformation length (Δb) is calculated as $\Delta b = b_{tot} - 40$, where btot is the total face width including the excessive distortions and 40 mm is the desired gear face width, see Fig. 2. Our goal is that by introducing modifications on the blank shape, modifications will result in $\Delta b \rightarrow 0$ mm as an indication of improvements.

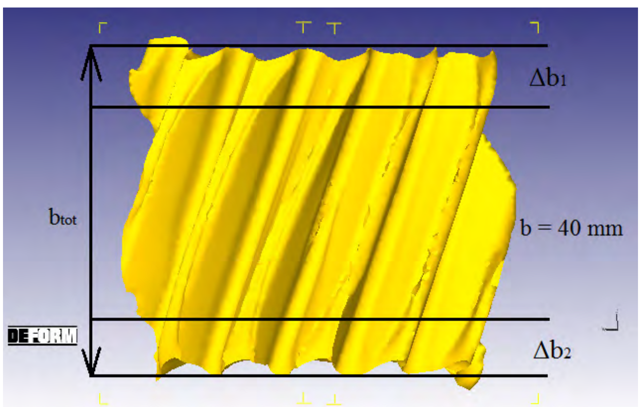

FIGURE 6. The measurement routines for excessive material deformation.

Additionally the crowning of the gear tooth is evaluated through measurement of the maximum outer radius, R_{max} and minimum outer radius, R_{min}, see Fig. 7. It is desired that both R_{max} and R_{min} are as close as possible to 50 mm which is half of the tip diameter (d_a) for the gear studied in this paper, see Fig. 2.

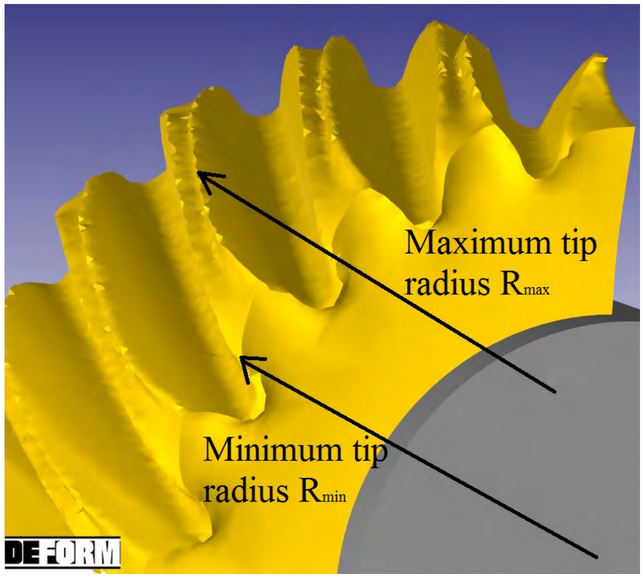

FIGURE 7. The measurement routines for the outer radius of the formed tooth.

The aim is to reduce the excessive material deformation Δb, and reduce the difference between R_{max} and R_{min} as presented with ΔR in the results.

IV. FINITE ELEMENT SIMULATION

When the geometrical specifications are designed with the CAD software it is possible to export them to the FE model. The FE model is shown in Fig. 8. The cylindrical solid shaft in the model is used to fix the center of the blank and has no effects on the results of the plastic zone on blank. As it is shown in Fig. 8 the FE model is made using one tool, and by modelling a sector of the blank instead of the full geometry. All is to reduce the size of the model and consequently decreasing the time and cost of calculation without losing any important details about the process. The given process kinematics in Fig. 5 is translated into a FE software to define the motion of the tool and blank respectively. A reduced kinetics scheme with 20 rolling cycles to reduce simulation time is used for investigations. This was one tenth of the experimentally defined numbers of cycles. The software DEFORM 3D was used in this research to run the simulations for gear rolling [13]. The material behavior is modelled as rigid/plastic for the blank by using power law and as rigid for the tool to reduce the computational costs. The Columb friction model, with a friction factor of 0.4 is used to take into account the friction effects during the rolling process in contact area between the tool and the blank [12].

First a simulation of the process based on initial blank shape in Fig. 3a is performed. This simulation is referred to as sim #0 in the FEM results. The result of this initial simulation #0 is shown in Fig. 9.

Running the FE model leads to the formation of gear teeth over the blank. The final shape of the blank after running

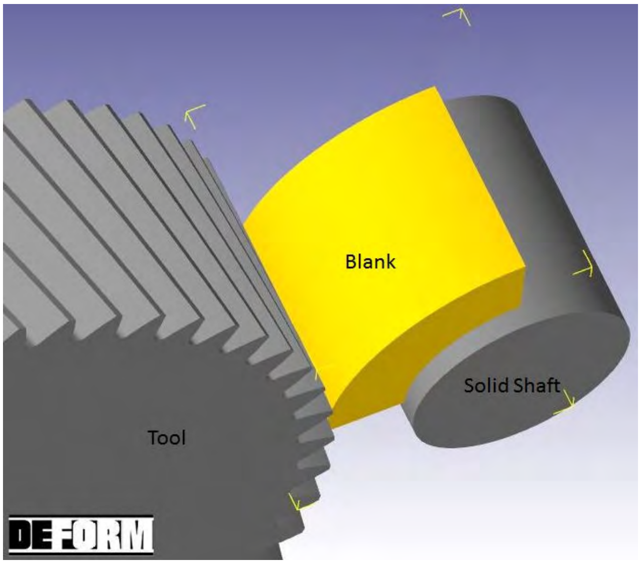

FIGURE 8. FE model to simulate the gear rolling of the selected gear geometry.

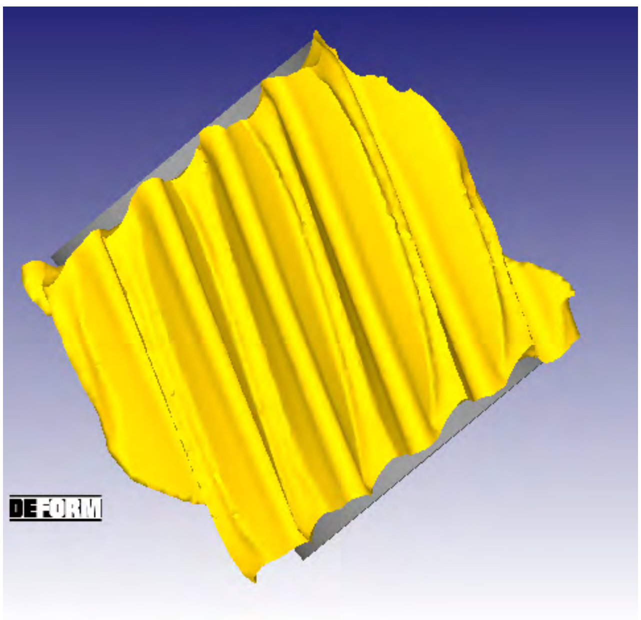

FIGURE 9. FE simulated gear teeth formed on blank after gear rolling.

the simulation is shown in Fig. 9. As can be seen in Fig. 9, when the tool reaches its full depth of required penetration into the blank, the rabbit ears on top of the teeth still remained open. Also a large amount of material deformation has occurred in the axial direction of the blank which is not desired. This excessive deformation leads to crowning of the tooth in the middle of face width as it can be seen in Fig. 9.

The FE simulation results of simulation #0 showed that a blank design as in Fig. 3a will result in a gear wheel with open rabbit ears, with significant crowning and a high amount of widening in the axial direction. Therefore it is necessary to modify the blank geometry in a way that close the rabbit ears, reduces crowning and reduce widening during the rolling operation.

To study the effects of blank shape on the final gear quality and rabbit ear shape, additional simulations were performed. Two different design parameters were considered for modifications of the blank shape in this paper.

The first modification is adding an inclined surface angle (Φ) in the blank shape as shown in Fig. 3b. It is expected that this modification reduces the amount of excessive axial deformations since there exists less material nearby the two ends of the face width of the gear.

It was shown by the initial simulation that material deformation occurred more in the middle area of the blank compared to the two ends. To reduce this effect a second modification is introduced in the form of a surface curvature of the outer surface blank shape as shown in Fig. 3c. Finally one case was studied with the two variants of #1 and #2 put together in one case #3. That geometry is illustrated in Fig. 3d. The results of the FE simulations are presented in Fig. 10 and in Fig. 11a, b and c.

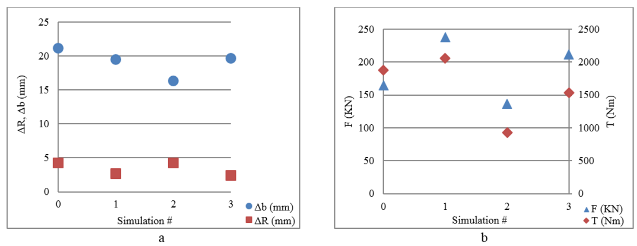

FIGURE 10. a) The results of simulations based on different blank shapes as predicted changes in Δ b and Δ R, b) maximum F and T predicted for gear rolling from simulations.

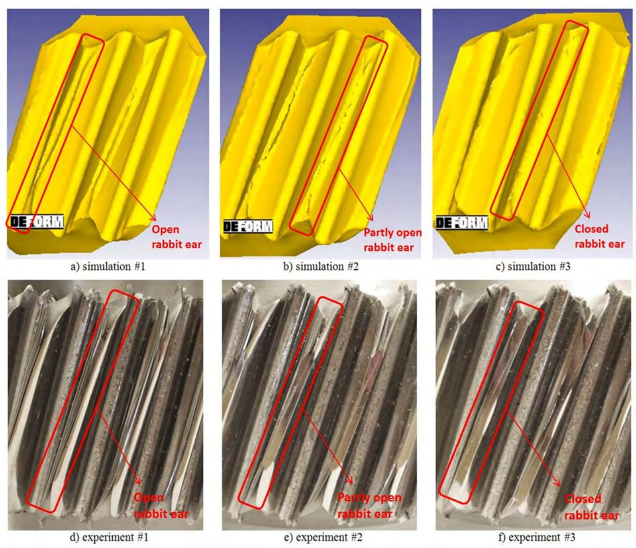

FIGURE 11. Simulation and experimental results.

The evaluations of the FE simulations show that the proposed modifications have effects on the deviations of gear geometry after gear rolling process. For instance, based on sim #1 adding the inclined surface angle caused a reduction of Δb and ΔR while it increased the force and torque. Sim #2 showed that the addition of the surface curvature cause reduction in Δb, but it in fact increases ΔR in comparison to the sim #0. On the other hand the addition of the surface curvature showed a good effect on the required force and torques during the rolling process. The combined modifications in sim #3 resulted in a minimum in ΔR and T. Each modification has its advantages with respect to which measure is most important.

The simulated gear shapes are illustrated in Fig. 11 a, b and c. They are viewed in the radial direction of the gears. Simulation #1, Fig. 11a, shows a gear tooth with open rabbit ears along the full face width. Simulation #2, Fig. 11b, presents semi closed rabbit ears along the face width. In simulation #3, Fig. 11c, with the rabbit ears are fully closed along the full gear width.

The three blank shape modifications #1- #3each leads to different effects on the final gear shape. The cases #1 and #3 lead to the lowest values of ΔR. The case #2 leads to the smallest value of Δb. The case #2 gives the smallest Force and Torque. And finally the case #3 leads to the most fully closed rabbit ears. So depending on which parameter is most important for a particular application process designer should chose modification accordingly. The parameter ΔR is the most important since that shape deviation must be modified with milling or grinding or both afterwards. It is thus more complicated and costly to adjust than the other parameters which can be adjusted mainly with turning. For that reason cases #1 and #3 are in general most favourable designs for blank.

V. GEAR ROLLING EXPERIMENTS

Fig. 12 shows the gear rolling machine used for this research. Based on the process modifications studied by FEM in the previous section of the paper three sets of experimental trials were performed based on the geometries taken from simulations #1, #2 and #3. These trials will be used to verify the accuracy of the FE simulations and to discuss general suggestions for process modifications based on FE simulations and experimental trials.

The process kinematic needs to reach the final depth of penetration without overloading the gear rolling machine. The process kinematics for the experiments was shown in Fig. 5. With this kinematics it was possible to reach full gear depth within 200 revolutions. The reversals are necessary to improve the forming symmetry as well as preventing one sided rabbit ears [10]. Fig. 13 shows one of the rolled gear wheels. The gear shapes in the different cases are illustrated in Fig. 11d, e and f. Double tests were performed for all cases #1- #3.

To validate the FE-model a series of interrupted rolling trials are performed with 3.25 mm, 6.5 mm, 9.75 mm and 13 mm of penetrations depth and the load and torques recorded in the rolling machine are compared with the predicted loads and torques from the FE model at the same depth of penetration. The results are shown in Fig. 14 and Fig. 15. The simulated forces are within 23% of the experimental ones and the torques within 16%.

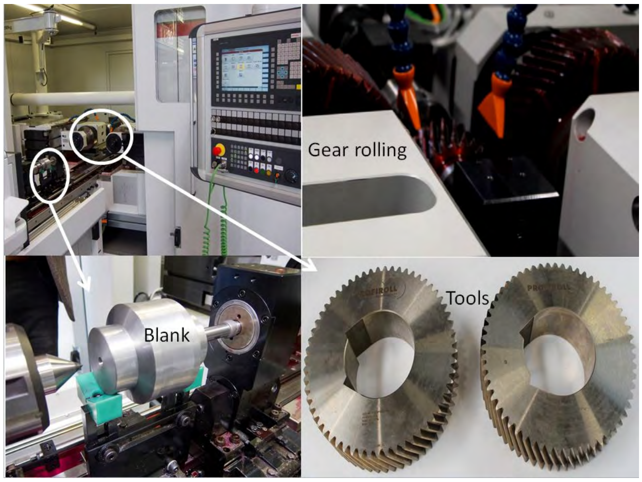

FIGURE 12. The experimental setup for gear rolling.

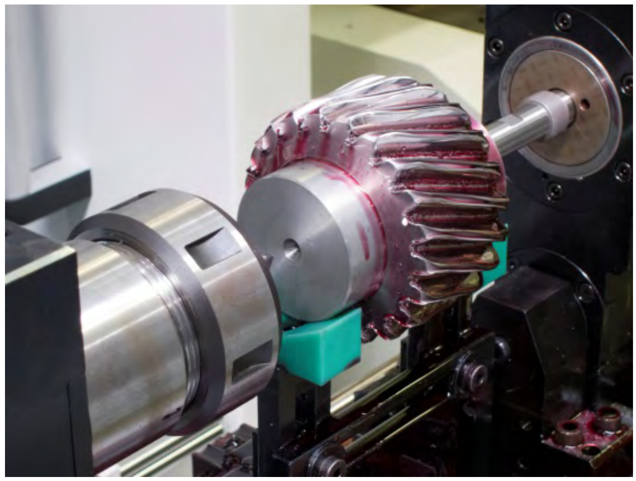

FIGURE 13. The gear formed by rolling process after experiment #3.

Fig. 16 shows the comparison between the FE prediction for Δb on the vertical axis and the experimentally measured Δb for each of three cases on the horizontal axis. As can be seen for all the three cases, the predicted values from the FE model slightly was higher than from the physical tests. The maximum difference between simulation and experiment is 16%. It is of course important that a recommendation to adjust geometry goes in the same direction for both simulation and experiment. This is true for Δb with one exception and that is cases #1 and #3. These cases give similar values of Δb in simulation but case #1 shows a lower value experimentally.

Fig. 17 shows the results obtained from experiment with respect to the measurement of difference between R_{max} and R_{min} as illustrated previously in Fig. 7. The maximum

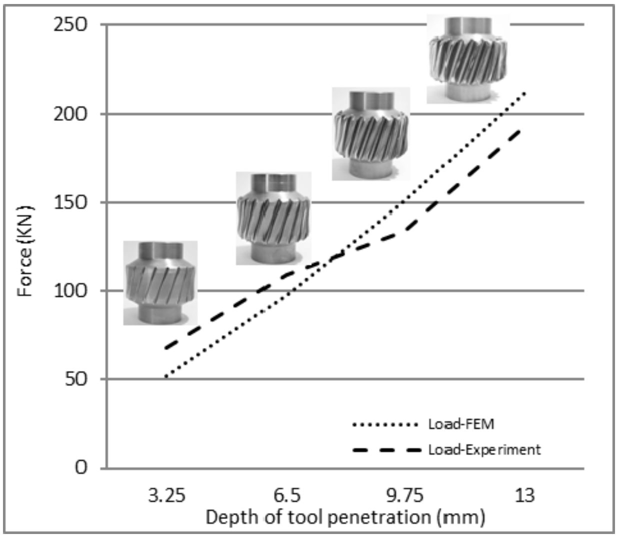

FIGURE 14. Comparison of predicted rolling force by FE model and the experimental rolling force recorded from interrupted tests on experiment #3.

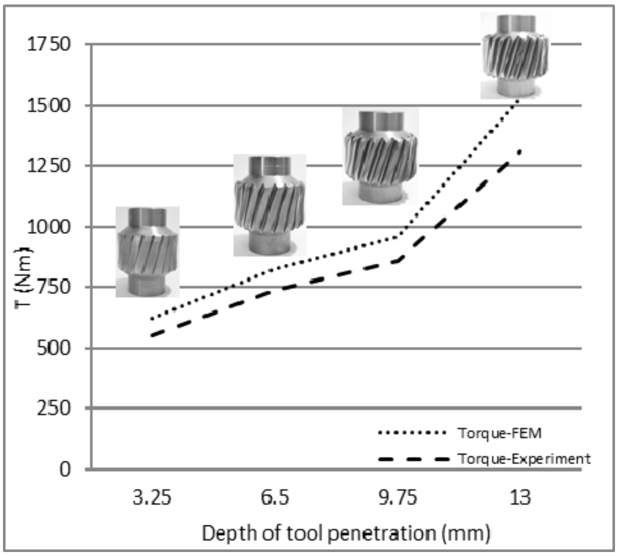

FIGURE 15. Comparison of predicted torque by FE model and the experimental rolling force recorded from interrupted tests on experiment #3.

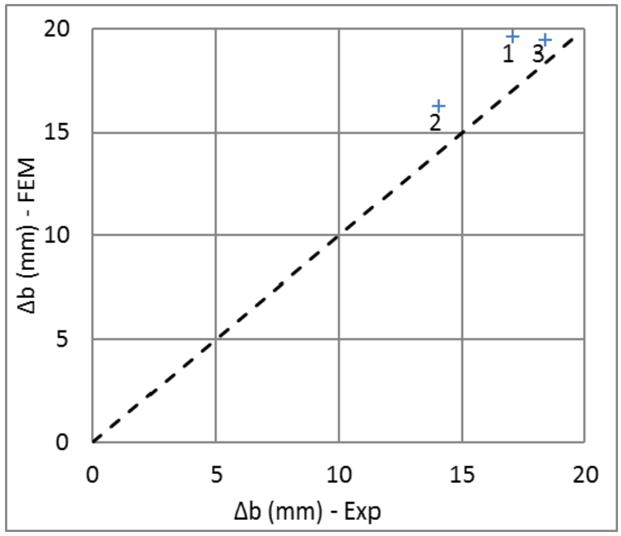

FIGURE 16. Comparison of measured Δ b from experiments and predicted value by FEM.

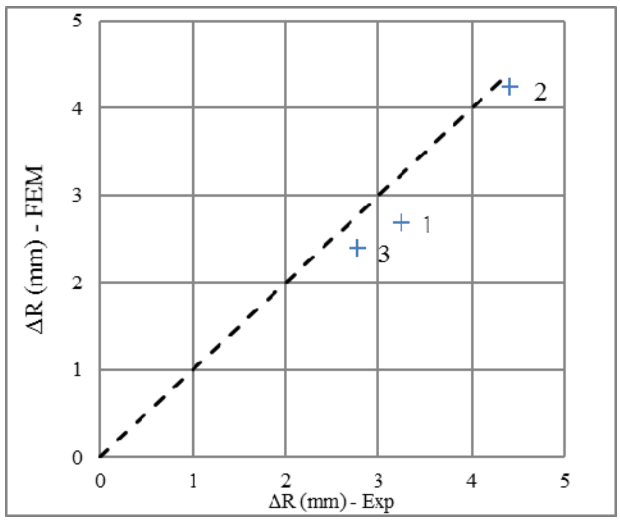

FIGURE 17. Comparison of measured Δ R from experiments and predicted value by FEM.

deviation between simulation and experiment is 17%. Both experiment and simulation place the different cases in the same order which is very satisfactory.

Fig. 18 and Fig. 19 are showing the comparison between the measured maximum force and torque for rolling of each blank shape on the horizontal axis while the predicted maximum force and torque from simulation of corresponded blank is mapped on the vertical axis. As it is can be observed for both force and torque the predicted amounts were higher than the physical tests. The maximum deviation is 10% for force and 16% for torque. Predictions from simulation and experimental observations are in the same order.

Considering the rabbit ear shapes, as also it was predicted by FEM simulation experiment #1 resulted to a fully open rabbit ears on the rolled gear, see Fig. 11d. Experiment #2 resulted in a gear with almost closed rabbit ears Fig. 11e. Finally the experiment #3 has fully closed rabbit ears as presented in the Fig. 11f, also these predictions in FE fall in the same order as the experimental observations.

The conclusion is that there is a good agreement between simulations and experiments. The simulations are capable of ordering the different cases in the same order as the experimental trials which is very satisfactory. It means that the recommendations made in the simulation section still stands after seeing the experimental results.

For future studies looking primarily for the modifications suggested in blank #1 and blank #3 is suggested. Out of those two designs the blank #3 has advantages by having slightly

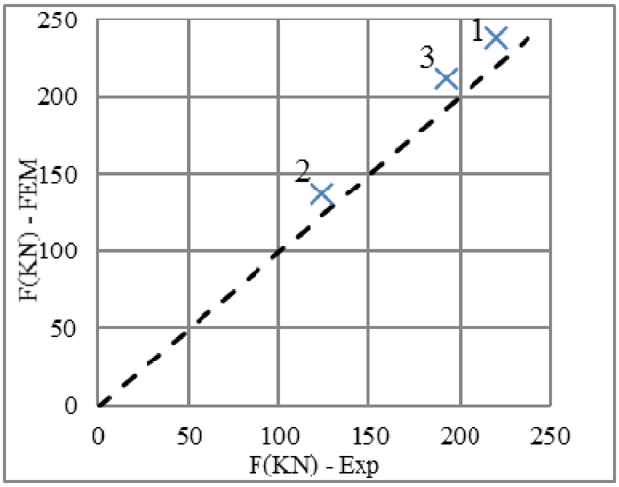

FIGURE 18. Comparison of measured force (F) from experiments and predicted value by FEM.

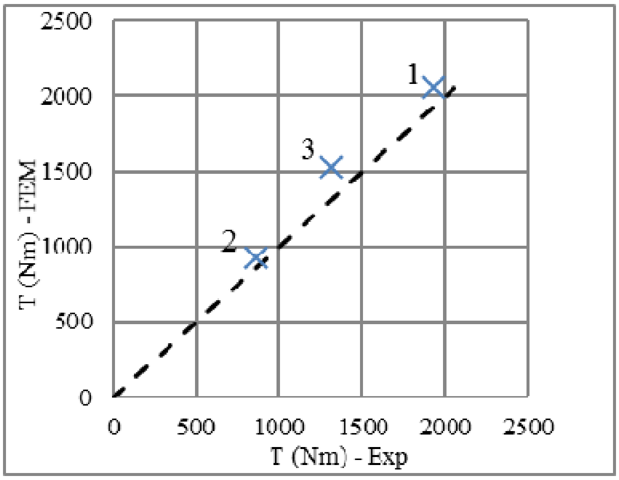

FIGURE 19. Comparison of measured torque (T) from experiments and predicted value by FEM.

lower force and torque at the same time as it could result in better closed rabbit ears.

VI. CONCLUSIONS

Three different geometrical modifications of the blank geometry were studied for gear rolling with a normal module of 4 mm. One width parameter as Δb and one crowning parameter as ΔR, are defined to measure the geometrical deviations on the gear after the rolling process. Additionally forces, torques and rabbit ear closure were recorded. Experimental test were performed to validate the FE model results as well as checking the accuracy of the FE predictions. The following conclusions are made:

1) The comparison of FE model predictions and the results obtained from the experiments showed high correlation between numerical and physical tests, which shows that FE simulation can be used for optimization of blank geometry in similar cases.
2) In order to reduce the amount of shape deviations compared to the nominal standard of the gear wheel after gear rolling it is necessary to use some geometrical modifications of the blank shape.
3) Addition of an inclined outer surface angle (ϕ), to the blank shape, resulted in the lower Δb and lower ΔR but it increases the force and torque required for rolling and rabbit ears are still partly open.
4) Addition of outer surface radius (r), to the blank shape reduced the amount of Δb but increased the amount of ΔR. The rolling force and torques were reduced to a low level. The rabbit ears were more closed than in the previous case.
5) Using both modifications together (ϕ and r), resulted in no improvement in Δb but the minimum crowning, the minimum ΔR, almost unchanged levels of force and torque and fully closed rabbit ears.
6) The modification including both ϕ and r seems most promising for future studies.

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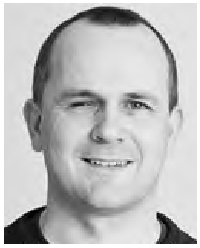

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