FE impact model and simulation of the shot peening effect on cylindrical gear topland and profile edge rollover

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Introduction

When mechanical current production transmissions are subjected to a load increase by product upgrades or additional functionalities, usually the envelope and working environment of the transmission is already restricted by other elements of the machine where it is used. For those cases, or wherever the space constrains force us to have high power and torque transmitted in a relatively small space, the shot peening can be applied as an additional improvement for the existing or new gears. If the design of the gear to be improved by shot peening is already in production and its manufacturing process does not take into account any preparation for the shot peening, some issues with sharp edges can be found.

The bending fatigue improvement is achieved when the shot peening is extended from the bottom of the root fillet past the tangent point between the root and flank. The pitting fatigue improvement is required on the active profile area where the maximum contact pressure is reached [1]. Although the topland of the gear is not the objective of the shot peening treatment, in reasonable volumes of part production, the shot peening cannot be localized to the area of the gear tooth that is desired to be treated. So, profile geometry, root and topland of the gear are evenly treated.

In a standard shot peening process of a gear, any sharp edge is prone to present issues. The general recommendation by the shot peening industry is to avoid functional areas with sharp edges to be treated [2]. That is the case of the gear tip edges where the impact of the shots can produce a small protrusion on the side of the tooth active profile. This protuberance generated on the active profile near the tip edge is known as profile edge rollover. The dimension of the generated protrusion can be taken into account as a deviation from the perfect shape of the involute profile, that eventually will result in a wrong contact between the tip of the shot peened gear tooth and the contact area of the mating gear tooth. The effect of the edge rollover is directly affecting the behaviour of the gearmesh in the EAP (End of Active Profile) of the shot peened gear and the area close to the SAP (Start of Active Profile) of the mating gear in mesh with it. If microgeometry corrections, such as tip relief, have been performed during the manufacturing process prior to shot peening, the effect of the edge rollover can be less critical, but should be evaluated for any specific case.

The problem of profile edge rollover can be minimized before or after the shot peening with manufacturing processes additional to the normal steps to produce a gear. One of the used methods in the industry, that can partially or totally remove the edge rollover, is the isotropic superfinishing, where the surface finish of the gear is enhanced and the edge rollover is worn during the process. Furthermore, it can also be mitigated by special gear shot peening processes, such as the method proposed by N. Hamasaka et al. in a dedicated patent [3]. The mentioned special processes increase the final cost of the part and add more complexity to the complete manufacturing process.

Objectives

There are many factors on the shot peening process of a gear and they have complex influence on the resultant microgeometry and residual stresses of the part. The numerical simulation of the process is therefore complex and costly. The aim of the present study is to provide a method to get a simplified analysis model in order to predict and analyze the generation of the edge rollover. The required simplifications and assumptions will be validated by experimental results on different gears with measurements of the gear profile before and after the shot peening process.

There are no scientific publications available for the relationship between the gear profile finishing operations and the shot peening effects on the gear microgeometry. In this study, it is also given an overview of possible contributors to the edge rollover formation, that are caused by the parameters in the gear finishing operations. One of the particular cases analyzed consists of a production part without shot peening that is wanted to be shot peened, but the finishing process must be modified or adjusted to avoid operations to remove the edge rollover after the shot peening process.

Methodology
Finite Element Analysis is used to obtain the local plastic deformation of the tooth tip edge and experimental parts produced under specific process conditions are measured to validate the FEA model. The aim of the analysis is to solve the nonlinear dynamic response of the model over time for the interaction of the shots impacting the gear tooth. The nonlinearities of the system stem from the material properties of the gear and the high-speed impact. To perform the analysis in an efficient way, the transient explicit dynamics Workbench application of Ansys® software has been used. The momentum exchange between the shot body and the stationary gear tooth is an important aspect of the analysis. This type of analysis is efficiently simulated for the time duration event of less than one millisecond. With time increments on the order of one microsecond, the solution offers the accuracy required during the impact event [4].

3D geometry is used. The theoretical profile of the gear subjected to study has been used to generate the representative portion of the tooth to be analyzed. A portion is used small enough to minimize the number of nodes of the mesh, but wide enough to avoid having issues of edge effect. The model mesh is generated using the meshing tool of the ANSYS mechanical application. The mesh settings are defined for patch conforming mesh sweeping. Local mesh controls are used to define the required mesh refinements of the impact zone. The total tooth geometry is included, so it can be further used to analyze the residual stresses in the root or flank areas, in addition to the edge rollover study, using more complex analysis methods like multiple random impact models [5]. The system analyzed consists of two nozzles separated a fix distance with respect to the root of the gear and oriented with an angle of 60° between them, pointing to the root diameter of the gear. From each nozzle, half of the shot media flow is projected to the gear. No flow or shot interaction have been considered.

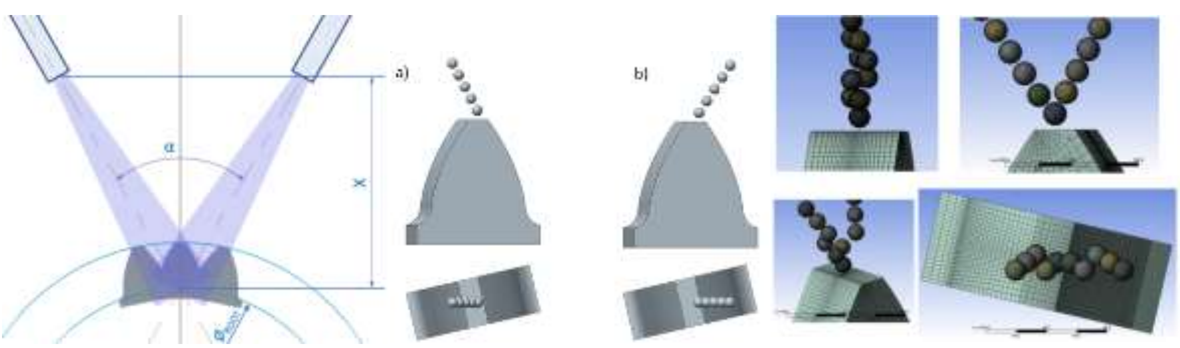


Fig. 1 – Layout of the shot peening system used, 3D input geometry and model mesh for multiple impacts

The material of the gear is 18CrNiMo7-6 (EN 10084). The gear heat treatment is case carburize, quench and temper. Surface hardness is 59 to 63 HRC and the effective case depth (50 HRC - SAE J423) of the gear teeth is 0.9±0.13 mm. As the gear tip tooth thickness is 1.2 mm, the material properties considered for the analysis model have been only the case properties. The properties for this material were included in the FE model as a non-linear steel with isotropic hardening, which during plastic deformation, causes a uniform increase in the size of the yield surface that results in an increase in the yield stress. For simplicity, the material constitutive model includes bilinear isotropic hardening assuming a von Misses yield criterion.

The machine that has been used is a Wheelabrator, 2 TR4 – 7V S2 in a gear production line. In order to have a complete study and not limiting it to a fix value of shot velocity, three different speeds are used to perform each of the analysis cases: 40, 55 and 70m/s. For a more realistic simulation a CFD (Computational Fluid Dynamics) analysis and DEM (Discrete Element Method) simulation can be used to determine the shot stream velocity distribution and mean impact velocity value as well as energy dissipated due to the interaction of both nozzles [6]. The assessment for the impact location, orientation and velocity was done by performing a series of analysis. Same configuration for the tooth and shot geometries, materials and meshes and same configuration for restrictions and body interactions is used. The effects of the variation of the shot velocity and distribution on the gear topland are studied. For each of the three different shot velocities selected, several iterations have been run. The aim of this series of analyses is the development of a method to get the maximum edge rollover possible for a given gear tooth geometry.

The ISO system of accuracy for cylindrical gears, that is described in the ANSI/AGMA standards [7], has been used for the evaluation of the results and the measurement of the gears. The profile K-Chart is a widely used technique to evaluate the measured involute profile with respect to the allowable tolerance limits [8]. The prefect involute shape is represented as a vertical straight line from SAP ① to EAP ② and the trace of the measured tooth profile must fit between the perfect involute and the limits of max. tip relief ⑥ and max. root relief ③, which are determined from the total profile error band delimited by ④ and ⑤. Moreover, if it is correct and the profile lays in between the limitations the total error must be also separated into the slope and form components. In order to compare the results obtained from the FEA with the actual measurements, the obtained profile shape must be translated to the K-Chart. The deformed mesh from Ansys Workbench can be directly exported and measured accurately in a CAD application for any section selected. The selection of the section to measure has been done based on the max deformation for the plane of the shot movement, where the impact is generating the biggest edge rollover.

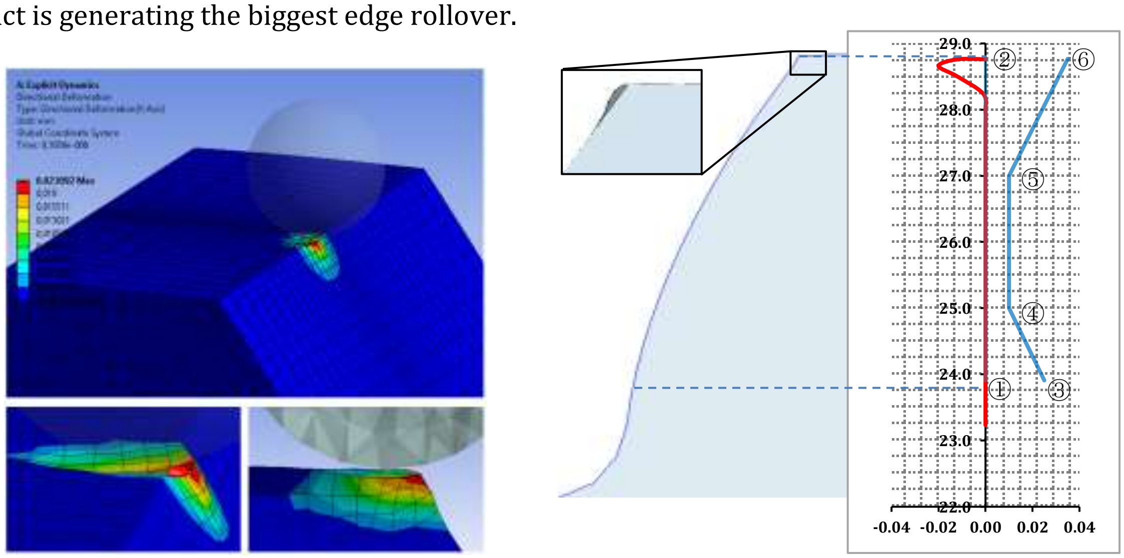


Fig. 2 – Directional deformation results from FEA and profile K-Chart for the resultant geometry

Results and analysis

Direct comparison between the FEA results and the measured profiles is done to correlate the analysis. The correction factor proposed to calibrate the model is the coefficient of friction (COF), which is applied in the body interactions of the FEA model when the contacts are defined. So, at the beginning of the iterative process, frictionless contact is selected and the results of edge rollover values are smaller than the measured ones. The adjustment of this coefficient is done to match the measured mean edge rollover values and it is not only representing the COF, but it is also taking into consideration other imperfections of the analysis as a global correction factor of the model.

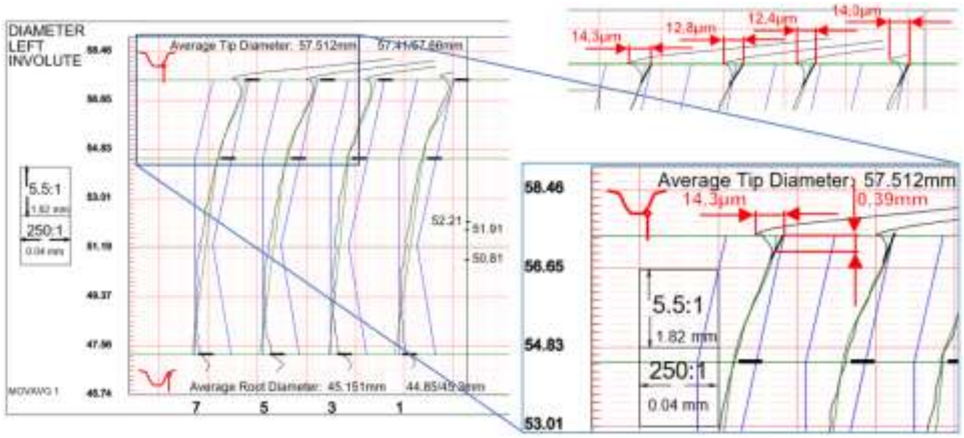
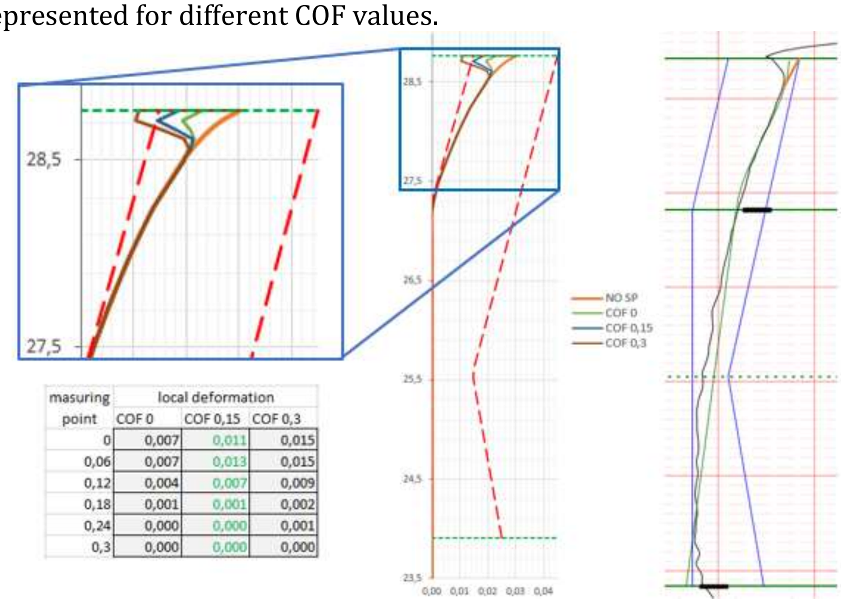


Fig. 3 –Edge rollover values and shape obtained from measured gears

The profile traces of several samples have been measured and, from these measurements data, the edge rollover values are obtained. The mean value for each gear is calculated from the measured teeth and compared to the results from the analysis. The measurements of the directional deformation of the FEA are translated to the profile K-Chart and both are compared as shown in Figure 4, were three iterations are represented for different COF values.



masuring point	local deformation		
	COF 0	COF 0,15	COF 0,3
0	0,007	0,011	0,015
0,06	0,007	0,013	0,015
0,12	0,004	0,007	0,009
0,18	0,001	0,001	0,002
0,24	0,000	0,000	0,001
0,3	0,000	0,000	0,000

Fig. 4 – Comparison between measured profile and FEA results translated to K-Chart

A compilation of the main values from the FEA solution is organized in the graphics shown in Figure 5. There are five curves obtained for each shot velocity. The orientation of the gear with respect to the nozzles has been defined for the maximum contribution to the edge rollover generation. The shot stream with respect to the gear tooth, pointing from the topland to the active profile, is generating the maximum deformation values. Each value represents the deformation caused at six measuring distances from the edge on the active profile (from 0 to 0.3 mm), that have been caused by a single shot impacting at a certain distance from the edge in the topland direction (0.20, 0.15, 0.10, 0.05 and 0.00 mm).

The biggest deformation is reached for the highest velocity values as the kinetic energy of the shot balls impacting the surface is bigger. The combination of highest velocity and impact location closest to the edge, produces the greatest deformation up to 0.024 mm of material projection to the active profile side.

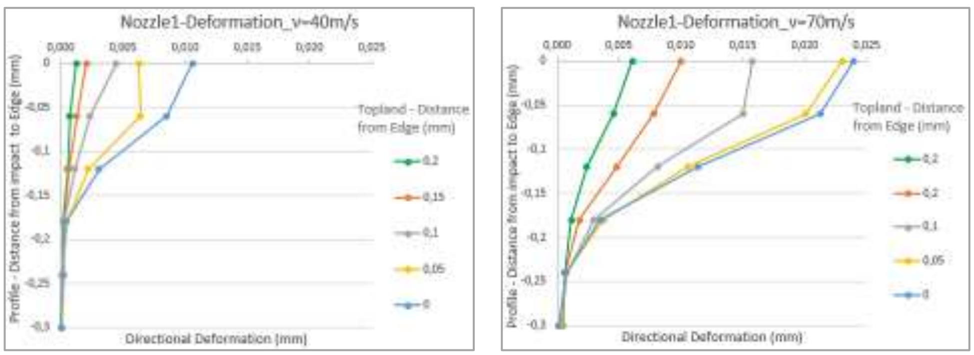


Fig. 5 – Directional deformation for two of the three velocity cases studied for edge rollover assessment

The finishing operation of the gear tooth flank can have an impact on the gear tooth tip. Two different profile finishing operations are compared: profile grinding and shaving. For the ground gears analyzed, the sharp edge is showing values of edge rollover similar or smaller to shaved gears. However, the difference of the initial diameter where the edge rollover is starting is different. For the shaved gear studied, it is observed that the topland of the teeth is presenting some material that has flowed from the profile surface to the outside diameter, generating a small burr along the facewidth. This burr generation depends on the parameters used during the shaving operation, the amount of material removed and the shaver disc used.

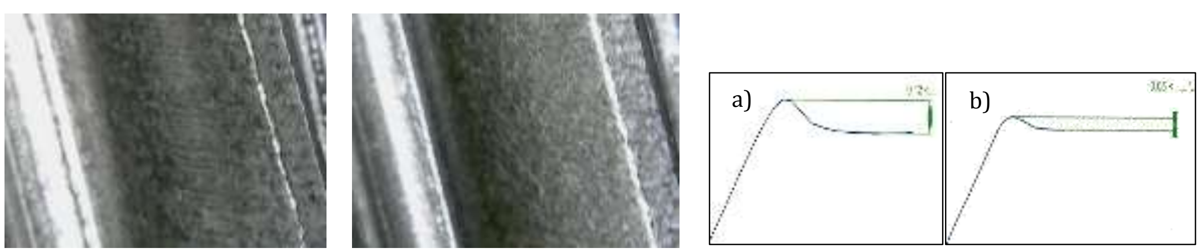
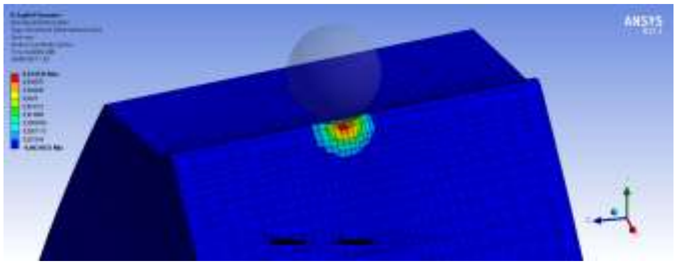


Fig. 6 – Gear flank before and after shot peening and measurements: a) before and b) after shot peening

The geometry of the burr generated during the shaving process has been measured with a contact profilometer. The height of the burr is reduced during the shot peening process due to the plastic deformation of the edge. Values of 0.07 to 0.12 mm are measured for sample parts before shot peening. After the shot peening of the samples the same teeth are measured, getting height values from 0.03 to 0.05 mm. When the material protruding from the outside diameter of the gear before shot peening is deformed, it is contributing to the formation of a continuous bulge in the tip of the gear towards the active profile side. The tip geometry measured with the profilometer has been included in the model and the results obtained show an increase of the edge rollover compared to the parts without the defect from shaving and they match with the measurements of the gears presented in Figure 6.



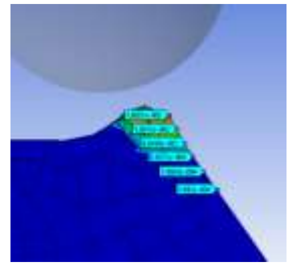


Fig. 7 – Analysis results for the shot impact including the tip defect from the shaving operation

Conclusions

The edge rollover of the gear tooth tip is studied for cylindrical gears. A simplified FE model is proposed to simulate the impact and analyze the deformation of the tooth profile. Several iterations of the FEA are run to obtain a series of results to be compared to real tooth profile measurements.

As concluding remarks, the results of the analysis reveal the following:

- The results from a simplified FEA of the shot impact, near the tip edge, can be used to replicate and predict the edge rollover formation, with an acceptable accuracy according to the cylindrical gear accuracy standard systems.
- Shot impact velocity and distance to the tip edge are the major contributors to the dimension of the profile defect studied.
- The correlation of the analysis results with a productive shot peening machine design have been presented and the values predicted are equivalent.
- The simplifications of the FEA proposed can cause a difference in the magnitude of the effective deviation from the perfect involute profile. The coefficient of friction is one of the FEA configuration parameters that can be used to calibrate the model, knowing the boundary conditions and the measured deformation of the part.
- The gear manufacturing processes of shaving and generative profile grinding, prior to shot peening, are compared regarding the edge rollover formation. A defect generated during the shaving process is a contributor to the edge rollover generation. Future work can be done to differentiate these processes with the edge rollover tendency for a similar gear tooth geometry. The optimization of the process prior to shot peening is important to avoid or minimize the edge rollover formation.

References

[1] AGMA, "AGMA 938-A05: Shot Peening of Gears." 2005.
[2] Metal Improvement Company, "Shot Peening Aplications," 2005.
[3] N. Hamasaka, C. Nakao, and T. Kuse, "Gear Shot Peening Method," US5911780A, 1999.
[4] ANSYS Inc., *ANSYS Explicit Dynamics Analysis Guide*, vol. Release 17. 2016.
[5] A. Gariépy, S. Larose, C. Perron, and M. Lévesque, "Shot peening and peen forming finite element modelling - Towards a quantitative method," *Int. J. Solids Struct.*, vol. 83, p. 183, 2016.
[6] T. Honga, J. Y. Ooia, and B. Shawc, "A numerical control simulation to relate the shot peening process parameters to the induced residual stresses," 2002.
[7] AGMA, "ANSI/AGMA IS0 1328: Cylindrical Gears - IS0 System of Accuracy," vol. 2, 1997.
[8] AGMA, "ANSI/AGMA 2000-A88 Gear Classificaction and Inspection Handbook," 1988.