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Finite element simulation of roller burnishing in crankshafts

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Abstract

Roller burnishing is a very commonly used industrial process. It involves a local plastic deformation on surfaces that permits the fatigue strength of structures to be increased. Crack propagation is indeed delayed by the introduction of compressive residual stresses. In this way, this process is particularly useful in the presence of stress concentrators like in the fillets of crankshafts or in notched shafts for instance. In the present work, a three-dimensional finite element analysis is carried out with the commercial software ABAQUS in order to model roller burnishing in the fillets of crankshafts. The contact between the workpiece and the tool is simulated and the latter is subjected to a pressure. Thus, all the residual stresses and strains can be calculated after unloading. The outputs are compared to experimental profiles of residual stresses measured by X-ray diffraction and a good agreement between experimental and three-dimensional numerical results is obtained. Unfortunately, this analysis is costly and the effects of roller burnishing can only be observed in the vicinity of the contact between the tool and the piece and not on the whole circumference of the shaft since neither the tool nor the piece rotates. However, our investigations show also that a simple axisymmetric model may approach experiments, not considering residual stresses as unknown quantities but as inputs of the problem. The three-dimensional field obtained by revolving the two-dimensional one will then make it possible to study, by the finite element method, crack propagation in such residual stress fields.

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1 Introduction

Roller burnishing is a very commonly used industrial process. It was introduced for the first time in railroad industry in the thirties. Thanks to its profitability, it then became widely used in mechanical machining.

This process consists in applying a load by contact of a rotating tool to a workpiece (see Fig. 1). According to the load intensity, this process may be used to enhance the surface finish of the piece (at low load levels), to improve dimensional margins (at intermediate loads) or to increase the fatigue strength of structures (under large loads).

In the present work, we particularly focus on this last point. Indeed, roller burnishing is very attractive in the presence of stress concentrators like in the fillets of crankshafts or more simply in notched shafts for instance (see Fig. 2). It has been observed that pieces submitted to roller burnishing had higher fatigue lives than pieces with no treatment (see Fig. 3). Cracks, which occur preferably at stress concentrators, have even stopped propagating in some cases. The underlying mechanism is surface plastic deformation which generates compressive residual stresses which hinder crack initiation and propagation.

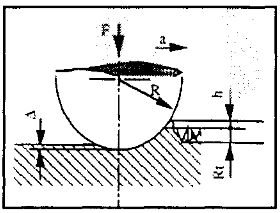

Fig. 1 : roller burnishing process [1]

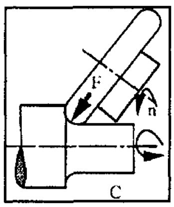

Fig. 2 : strengthening of a shaft [1]

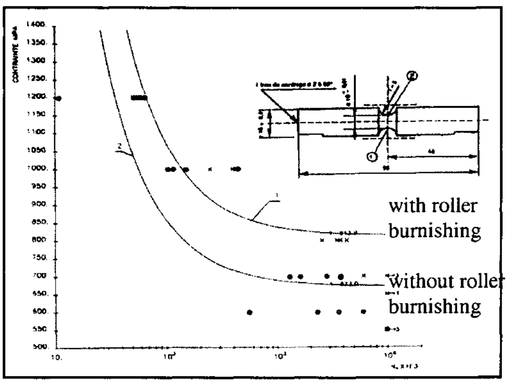

Fig. 3 : influence of roller burnishing on fatigue strength [2]

The experimental informations about residual stresses can be obtained by two kinds of methods. The first one consists in removing layers of material and measuring stresses gradient. The other is an optical one. It uses X-ray diffraction and presents also the advantage to be non destructive. However, for both

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methods, it is necessary to be careful with results because measurements remain difficult and can just give an approximation of the level of residual stresses.

Even though roller burnishing is well implanted in the mechanical industry, its use and development rely essentially on an empirical knowledge. Many experiments have been carried out to determine the right values of the different parameters of the process of roller burnishing to obtain the best results for each case. Indeed, investigations have showed that this is a complex process and each parameter (pressure, rolling speed, duration of the process or number of tool passes for instance) has its own influence on the surface roughness and hardness and on the level of residual stress generated [1, 2, 3 ,4].

Nevertheless, during recent last years, some numerical models have been proposed to determine the residual stress field of roller burnishing. S. Braham [5] used the simplified analysis of inelastic structures [6] and K. Dang Van and H. Maitournam developed a direct stationary method [7]. Both show a good agreement with experimental data. However, these methods require complex numerical tools developed by a few laboratories and they are not easily usable.

This explains why, in the present work, the aim is to obtain the residual stress field entirely by the finite element method using the commercial software ABAQUS. Considering the complexity of the process, we will choose to simplify the phenomenon and just take pressure or driving in of the tool in the workpiece as parameter. The friction will not be taken into account in our model and the analysis will be a static one.

The workpiece is a notched shaft whose groove is supposed to resemble the fillet of a crankshaft. When we will have obtained the residual stress field near this stress concentrator, crack propagation in such kinds of fields will be studied, in the next future, still by the finite element method.

In a first step, we will consider a three-dimensional analysis and compare our numerical results with experimental data obtained by X-ray diffraction method. Then, we will try to simplify the problem to a two-dimensional one and in a third part, we will explain how to obtain the three-dimensional residual stress field through a simple two-dimensional analysis.

2 Three-dimensional analysis

Our work is purely numerical. No experiments have been performed by the authors. Thus, in order to evaluate the accuracy of our finite element modeling, we will use the experimental results of the PhD thesis of M. Bennebach [8]. This work studies notched shafts in nodular cast iron and measurements of residual stresses are carried out by CETIM (Centre Technique des Industries Mécaniques) with the X-ray diffraction method. The only parameter of roller burnishing that we will consider is the force applied on the tool : 7800 N.

The nodular cast iron has the mechanical characteristics given in table 1. The material of the tool is unknown. In this work, the behavior of the tool will be chosen purely elastic and more rigid than the piece (see Tab. 1). The corresponding stress-strain curve of the workpiece used in ABAQUS software is plotted in figure 4. To be in good agreement with the experimental results, our model has the exact geometry of the notched shaft (see Fig. 5).

Table 1: mechanical characteristics of the piece and the tool

	Young modulus (GPa)	Poisson's ratio	yield stress (MPa)	tensile strength (MPa)	elongation at tensile strength (%)
piece	165	0.275	400	760	5
tool	210	0.3			

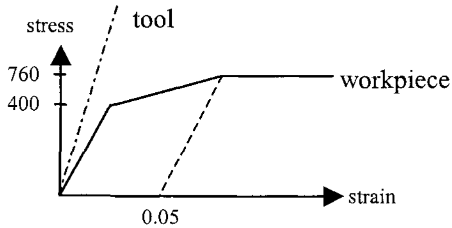

Fig. 4 : Stress-strain curve of the nodular cast iron used in ABAQUS

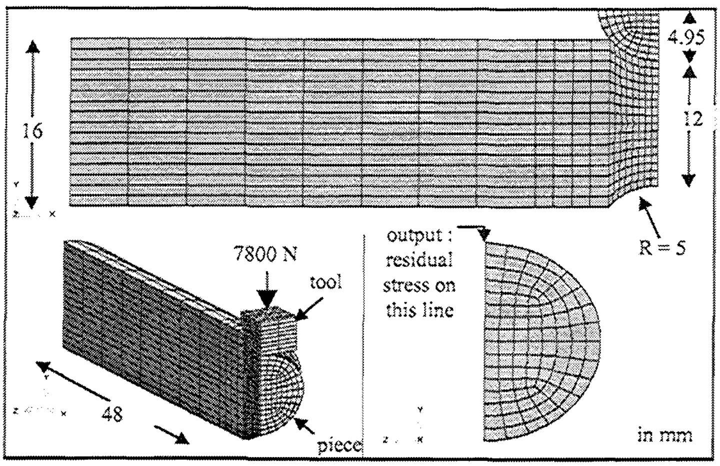

Fig. 5 : Three-dimensional model

Of course, the model has been simplified thanks to the symmetries of the shaft. The tool is considered as cylindrical since its curvature radius in the plane (Y,Z) is very large compared to the one in the plane (X,Y) (4.95 mm). Besides, we have chosen to cut the tool in a plane parallel to the plane (X,Z) to apply a surface load corresponding to the experimental force of 7800 N.

Thus, the principle of our simulation is to press the tool that will come into contact with the piece and compress it. When we unload, we can then obtain the residual stress field. However, it must be noticed that it is just a static analysis: the tool and the piece do not rotate. The results of roller burnishing are localized in the vicinity under the tool on the symmetric axis of the shaft as it is pointed out

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in figure 5 and not on the whole circumference of the shaft as it is observed experimentally.

The mesh is refined in the fillet where the contact is automatically managed by the code ABAQUS. The tool is considered as the master surface and generates contact pressure on the slave surface, the workpiece. Different types of meshing have been subject of investigations and the best results have been obtained with linear pressure hybrid 20-node quadratic brick using reduced integration (C3D20RH in ABAQUS) .

Just one cycle of load and unload is done. After unloading, the whole residual stress field is accessible. Experimental measurements just give axial and tangential residual stresses whereas, by this method, one can also obtain other stresses or strains. So, by collecting the numerical outputs on the straight line under the tool, it is possible to compare our results for two different meshings (meshing 2 being much refined on the workpiece surface) with experimental data giving axial and tangential residual stress versus depth (see Fig. 6).

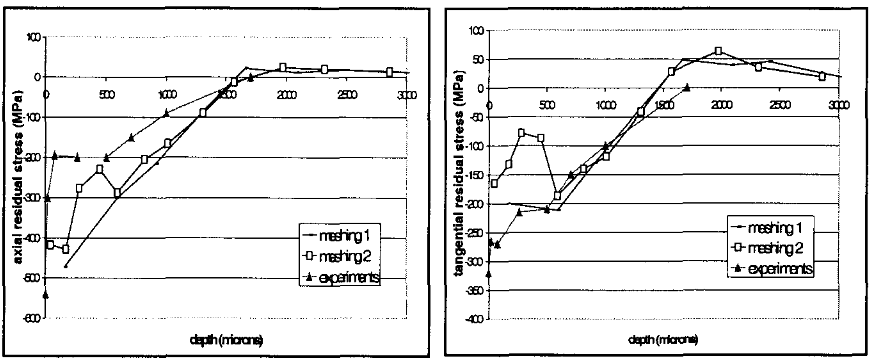

Fig. 6 : comparison between 3-D numerical results and experiments : axial and tangential residual stresses vs. depth

Considering the inaccuracy of the experiments and the different numerical simplifications that we have done, it can be said that there is a good agreement. The surface compressive residual stresses that are typical of roller burnishing are found numerically. This finite element method is reliable to obtain residual stress field generated by roller burnishing.

Some slight differences can be noticed very superficially (for depth below 500 microns). Meshing 1 seems to better approach axial residual stresses while meshing 2 gives better results for tangential residual stresses. That may be explained by the numerical singularity of the contact that attaches great importance to meshing.

However, three-dimensional calculations are very long because phenomena of plasticity and contact are staked. Moreover, as it is above-mentioned, roller burnishing is not simulated on the whole circumference of the shaft but just in the vicinity of the contact with the tool. That is why we will try now to simplify the problem to a two-dimensional one.

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3 Simplification to a two-dimensional analysis

The three-dimensional model has given good results. Nevertheless, one cannot obtain the whole residual stress field generated by roller burnishing by this way and calculations are very long. So, in a first time, the aim of this part will be to recover three-dimensional results just by a two-dimensional analysis.

The comparisons will not be based on experiments but just on differences between three-dimensional and two-dimensional numerical results. The geometry of the shaft is not modified, the roller burnishing force is still the same but material of the specimen changes to better approach the case of crankshafts (see Tab. 2) and the tool is still taken purely elastic and more rigid. Then, three-dimensional calculations have been performed with this new material.

Table 2: new mechanical characteristics of the piece

	Young modulus (GPa)	Poisson's ratio	yield stress (MPa)	tensile strength (MPa)	elongation at tensile strength (%)
piece	195	0.3	500	770	5

In a first step, plane strain and plane stress elements have been tested : they have led to great differences with three-dimensional results. Therefore, we will just consider now axisymmetric elements. The two-dimensional model, meshed with linear pressure hybrid 8-node biquadratic axisymmetric element using reduced integration (CAX8RH), is given in figure 7.

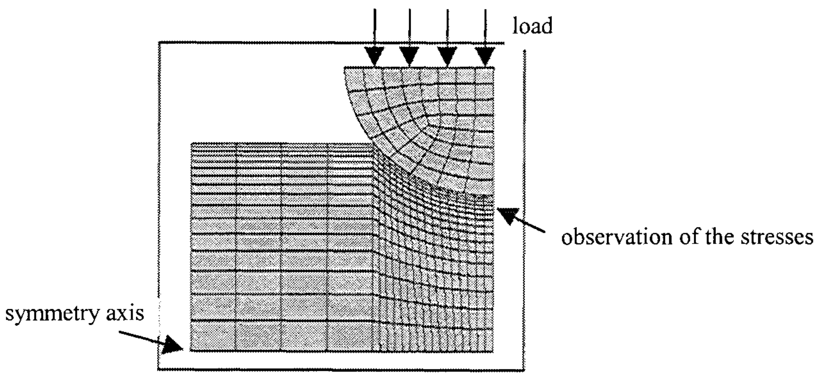

Fig. 7 : two-dimensional model

First, a load equal to 7800 N has been applied on the tool, like in the 3-D model. The corresponding residual stress distributions are plotted in figure 8.

Contrary to the three-dimensional model, a large zone of tensile residual stresses appears in the core of the shaft. This phenomenon is normal since our model is now axisymmetric and so does not exactly simulate the real process of roller burnishing. One has to imagine that, now, the tool entirely surrounds the workpiece and presses it, like a ring with a decreasing diameter.

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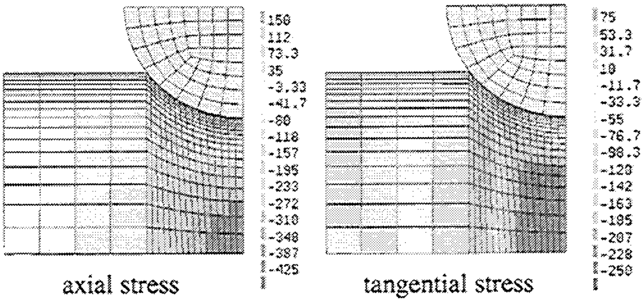

Fig. 8 : residual stress field for the three-dimensional load

However, the aim of this work is to obtain residual stress field generated by roller burnishing in the vicinity of the specimen surface and it may be not necessary to exactly simulate the process. Unfortunately, in our case, surface residual stresses are too weak in comparison with three-dimensional results. Now, by increasing the level of the load applied on the tool, it is possible to approach the axial residual stresses of the three-dimensional model (see Fig. 9).

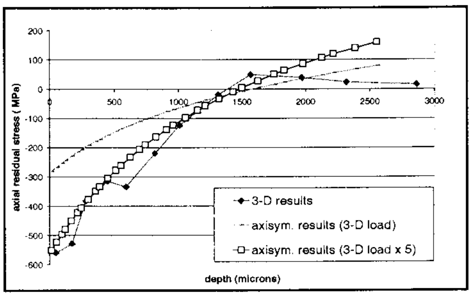

Fig. 9 : comparison between axisymmetric and three-dimensional models : axial residual stresses vs. depth

Thus, an axisymmetric analysis is able to be in good agreement with the three-dimensional results in the vicinity of the contact with the tool (for depth below 2000 microns). Besides, calculations are here quicker (about ten minutes against several hours).

However, this method is not suitable to predict residual stress field. Indeed, first, a tensile zone appears in the core of the shaft and second, the load that one has to apply is not the real one. This method is just satisfactory to recover results obtained by other numerical models or experiments.

As a conclusion for this part, the three-dimensional model remains necessary if one wants to predict residual stresses. But the user will just have stresses versus depth on the vicinity of the contact and not the whole numerical three-dimensional field really generated by roller burnishing.

Then, this is precisely this three-dimensional field that we want to obtain to be able to study crack propagation in the future. Therefore, let us try to be in good

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agreement with experiments using a two-dimensional analysis and then, to generate a three-dimensional model with these results.

4 Obtaining the experimental field from a 2-D analysis

An axisymmetric analysis may approach three-dimensional results and the latter shows a good agreement with experiments. So, if we succeed in obtaining, by slight modifications, the experimental field using axisymmetric calculations, the software ABAQUS will then allow to revolve the model, to transfer the results and so to obtain the three-dimensional field which will permit to study crack propagation.

Our aim is not to predict the residual stress field but to obtain the experimental one by the finite element method. We will now consider the specimens which will be used, in the future, for the investigations about crack propagation. Material of the workpiece is the same as in the precedent part but the groove is smaller. These shafts have been subjected to roller burnishing and residual stress measurements have been performed by CETIM using X-ray diffraction method. No pieces of information about roller burnishing are here necessary because the unique goal of these investigations is to obtain, by some means or others, the experimental field by a finite element model.

The model is meshed with 8-node biquadratic axisymmetric elements and to simplify the numerical process of contact, the tool is no more considered as a malleable body but now as a rigid surface.

The precedent part showed us that the load applied to the axisymmetric model was not the real one. Here, we have chosen to force a displacement of the tool which will come into contact with the piece and press it. Again, it may be noticed that the displacement of the tool that has to be applied to find a good agreement with experimental residual stresses does not correspond to the experimental one.

In the same way, we observed a large tensile zone in the core of the axisymmetric model. Initial conditions (compressive stresses) have been then introduced numerically in this zone to reduce tension and so to approach experimental results. The results are plotted in figure 10.

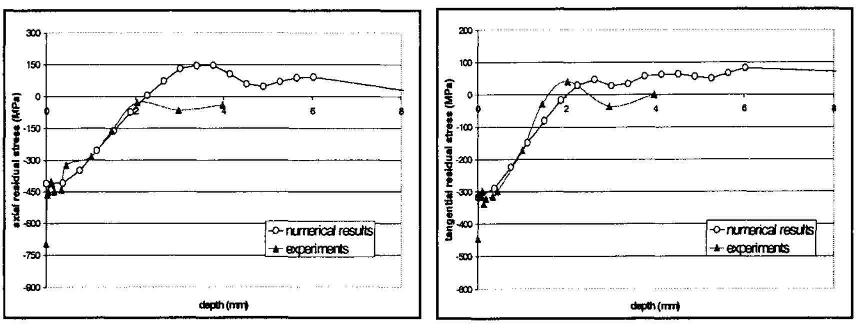

Fig. 10 : comparison between 2-D numerical results and experiments : axial and tangential residual stresses vs. depth

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Numerical results are in good agreement with experiments. Compressive residual stresses are well represented by the model. Moreover, the tensile zone is reduced and shows stresses whose level is not too high.

It can also be pointed out that, in this case, the experimental curve gives residual stresses without correction due to layer removal included in the measuring method. For instance, for axial residual stresses, in reality, a tensile zone should appear in depth to balance the structure. Our numerical results are all the more satisfactory.

Then, the software ABAQUS permits to revolve the axisymmetric model and to transfer the outputs to the three-dimensional model generated. The corresponding results are given in figure 11.

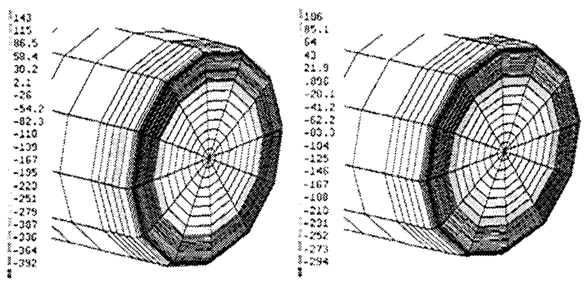

Fig. 11 : numerical axial and tangential residual stress field

We obtain, by the finite element method, a model which represents the experimental shaft. However, in reality, measurements are limited. Only axial or tangential residual stresses can be measured. Now, with the numerical model, all stresses and strains are attainable.

This three-dimensional model will allow us to study, in the near future, by the finite element method, crack propagation in such residual stress fields. The shaft will be subjected numerically to three-point bending and we will be able to observe the effects of residual stresses on crack propagation.

5 Conclusions

A first part of this work presents the results of a three-dimensional model. The analysis is static and the conditions of roller burnishing are simplified : neither the tool nor the piece rotates and the only parameter is the burnishing force.

Provided that one resolves meshing problems to simplify the numerical contact process, the results are in good agreement with experiments. The typical compressive residual stresses of roller burnishing are well obtained. However, the three-dimensional numerical field represents this process just in the vicinity of the contact between the tool and the workpiece and not on the whole circumference of the shaft. Therefore, predicting three-dimensional residual stress field remains a complex problem.

Nevertheless, this work has also shown that axisymmetric analyses permit to find more easily three-dimensional numerical results. Some slight modifications must be done because increased tensile residual stresses appear in the core of the shaft and the numerical load does not correspond to the real one.

Knowing the level of residual stresses thanks to experiments, it is then possible, by an axisymmetric analysis, to obtain a numerical field that approaches very well the experimental one. Then, this two-dimensional field may be transformed into a three-dimensional one.

Thus, a numerical three-dimensional field is generated and it corresponds to the experimental measurements of residual stresses. It is then possible to use all the facilities of the finite element method to study this kind of fields. All stresses and strains are attainable and in the near future, we will be able to look into the effects of compressive residual stresses on crack propagation.

Acknowledgments

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