Int J Mater Form (2008) Suppl 1:567–570
DOI 10.1007/s12289-008-0319-2

Modelling of the residual stresses induced by belt finishing on a AISI52100 hardened steel

J. Rech[1], G.Kermouche[1], C. Claudin[1], A.Khellouki[1], W.Grzesik[2]

[1]*Ecole Nationale d'Ingénieurs de Saint-Etienne, LTDS, 58 Rue Jean Parot – 42000 Saint-Etienne - France*
e-mail: joel.rech@enise.fr

[2] *Opole University of Technology, Department of Manufacturing Engineering and Production Automation, Poland*
e-mail: w.grzesik@po.opole.pl

ABSTRACT: New technological process consisting of hard turning followed by belt finishing, in place of the widely used method in industry, e.g., grinding, has lately been launched in the automotive industry. This is because, many transmissions parts, such as synchronizing gears, crankshafts and camshafts require superior surface integrity along with appropriate fatigue performance. This paper provides a modelling of part residual stresses produced after belt finishing in order to provide some explanations about the experimental results previously obtained. Indeed, it has been shown that the belt finishing process improves very significantly the surface integrity by the induction of strong compressive residual stresses in the external layer. The model has confirmed this trend. It has also revealed that, among the process parameters of the belt finishing technique, the lubrication appears as a key parameter to get compressive stresses, whereas the elementary force on each abrasive grains influence the depth of the affected layer.

Key words: Hard turning, Belt finishing, Superfinishing, Residual stresses, Finite Element Model.

1 INTRODUCTION

Hard turning of hardened steel with c-BN cutting tools can be essentially performed as precision operation when the surface roughness *Ra* parameter is less than 0.3 µm [1]. Precision finishing of hardened steel components offers manufacturers an attractive alternative to traditional grinding. In particular, it can often cut manufacturing costs, decrease production time, and improve overall product quality [1]. Despite many advantages of hard turning technology, the following limitations can be distinguished, namely [1-4]: high sensitivity to tool wear leading to unacceptable surface roughness, white layers and tensile residual stresses. Additionally this technique necessitates using limited values of cutting speeds if tensile stresses have to be avoided in the external layer, which limits its productivity.
Superfinishing processes, such as belt finishing or honing or roller burnishing, are proposed in addition to hard turning to improve the surface texture [2,4-6], allowing very good surface roughness with Ra << 0.1 µm and much more suitable flat BAC shape. Moreover the surface finish becomes much more stable and independent from the deviation induced by the wear of the c-BN inserts in HT, which is a strategic improvement for large scale productions in fully automatic production systems.
However, few works have been made to investigate the effect of these superfinishing processes on the residual stresses obtained. As far as belt finishing is concerned, this process induces strong compressive residual stresses in a narrow layer ~ 5-10 µm of a AISI52100 hardened steel in any direction tangential to the surface since [6]. So, the aim of this paper deals with the modelling of the modifications due to the belt finishing operation on the residual stress state previously obtained by hard turning.

2 DESCRIPTION OF BELT FINISHING

It is necessary to provide some details about the kinematic of this superfinishing technique in order to understand the principle of the model. As shown in Fig. 1, the belt finishing technique consists in

applying an abrasive belt between the surface and a soft roller. Abrasive belts have a single layer of Al_2O_3 abrasive grains stocked on an elastic paper strip reinforced with fibres. A force is applied by a pneumatic jack on the polymeric roller in order to obtain a sufficient pressure in the contact between abrasive grains and the surface. At the microscopic scale, the contact is localized within the peaks of abrasive grains (Fig. 1). The pressures developed in the local contact zones are high enough to perform material removal and to induce local plastic deformations. The rotation of the workpiece is necessary to obtain a homogeneous surface but the material removal process is mainly due to the axial oscillation of the belt+roller system. The belt finishing process necessitates a plain oil lubrication.
The belt finishing duration is very limited: few seconds. Two steps have to be considered. As described by [6], during the first step, the belt eliminates very quickly the peaks of the surface texture until abrasive grains reach the lower part of the surface texture. After this period, the shape of the surface texture remains constant and is no more improved. The second step consists in a rubbing phase of abrasive grains. The workmaterial is ploughed on each side of grains.

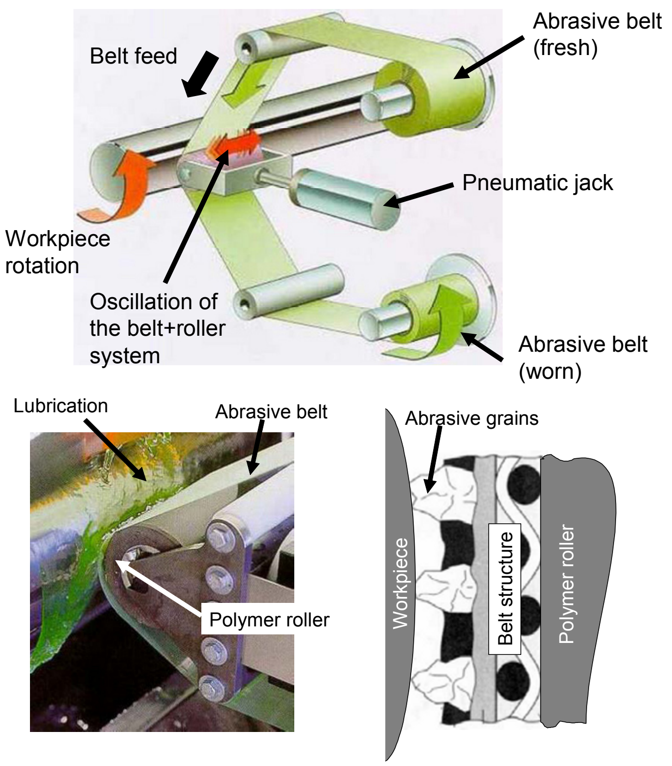

Fig. 1. Principle of belt finishing process.

3 NUMERICAL APPROACH

The objective of this paper is to understand the mechanisms leading to the evolution of the residual stresses towards compression in a very thin external layer.

3.1 Context of the model

The stress state induced by belt finishing originates during the second step of the process consisting in a rubbing phase. In this period, a large amount of the abrasive grains are much rounder. As a consequence, the main work of grains consists in scratching and rubbing the surface. It has been assumed that, from a statistical point of view, all abrasive grains have a similar shape and are indented into the workmaterial with a similar force. So, we have only examined the action of a single grain of the belt on the workpiece during a scratching phase (Fig. 2). Of course, each area of a workpiece is scratched by a large quantity of different grains having different trajectories. So the action of a single grain provides only a trend. However, multiple scratching does modify the trend.

3.2 Assumptions related to the local physics of the belt finishing process

The relative motion between abrasive grains and the workmaterial is small enough to assume that the local temperature reached during this technique should be low and smaller than the critical temperature inducing microstructure transformations. This assumption is in accordance with the experimental observations made during the investigations [6]. Consequently, temperature effects are not considered in the present model.
The modelling of scratching of a single grain on a AISI52100 (Fig. 2) can be performed using a finite element modelling based on previous developments by [7-8]. The indentation force P applied by a single grain on the surface can be determined by the macroscopic force F (~ 340N), the grain size (30µm diam.) and n: number of grains in the contact. Grains are considered as rigid spheres with no space between them (Fig. 2). Then, Hertz theory of contact (rigid sphere over a linear elastic half space [9]) makes it possible to obtain a first approximation of the average penetration depth h of one grain during sliding. In this work, P~0.6 N and h~1 µm.

3.3 Finite element model

The finite element software used is SYSTUS. The developed model is based on the previously published work of [8]. Loading is achieved by monitoring the displacement of the grain, which is first pushed down vertically into the workpiece and then pushed horizontally for the study of scratching. The finite element domain is a right-angled parallelepiped. The x-axis and z-axis are respectively the scratching and indentation axes. The plane y = 0 is a symmetry plane (Fig. 2). The mesh is constituted of 8-node-brick elements with a selective reduced integration scheme to ensure plastic incompressibility. In this study, the material behavior is modelled using large deformation (Updated Lagrangian Formulation) and elastoplastic theory. Because of their high hardness, hardened steels have a high yield stress but cannot ensure high plastic deformation. The AISI52100 hardened steel mechanical properties are chosen in relation to the study of [11]. Due to the low ratio h/R -penetration depth over abrasive grain radius- the element distortion is limited and it does not require the use of remeshing procedure [8,12].

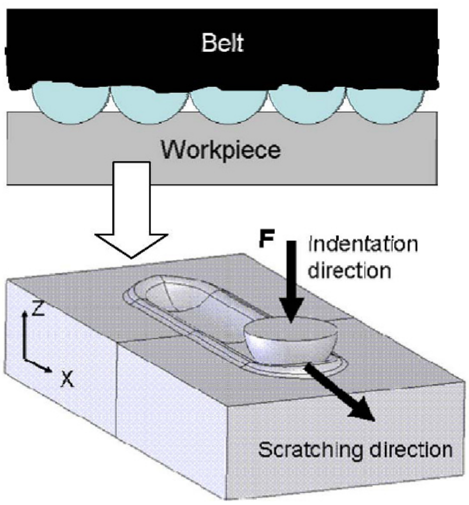

Fig. 2. Modelling of the action of a single abrasive grain on the workpiece.

The nature of the contact grain / workpiece being unknown (frictionless or adhesive contact), the two following cases are investigated:

- frictionless contact: The macroscopic friction depends only on the plastic shearing in the bulk of the material.
- local friction modelled using a Coulomb coefficient : μ = 0.2.

3.4 Numerical results

The extraction of the residual stress profiles induced by the scratching is illustrated in Fig. 3 and the profiles obtained are plotted in Fig. 3 and 4.

In the first case without any local friction (lubricated contact), scratching induces plastic yielding and as a consequence high compressive stresses (around 2000 MPa) in the external layer (around 10 μm). As a consequence, tensile residual stresses appear in the sublayer in order to respect the mechanical equilibrium.

In presence of local friction, a much more important plastic yielding occurs leading to a peak of tensile stresses (around 500 MPa) in the very thin external layer (around 200 nm). The peak of compressive stresses is lower (around 1500 MPa) in presence of local friction but the trend is similar for both curves. Moreover the use of plein oil as lubricant during the belt finishing operation makes it possible to assume that the friction can be neglected. As a consequence, the avoidance of friction phenomena between abrasive grains and the workmaterial seems to be more relevant.

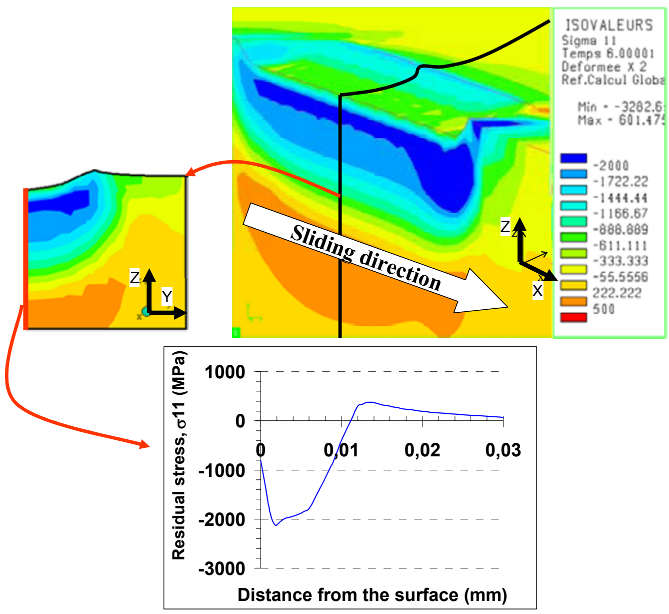

Fig. 3. Extraction of the σ11 residual stress profile after sliding in the steady state of the scratch.

In both cases, the residual stress field is affected over a depth of 10 μm which is in agreement with experimental observations showing an affected zone around 6 μm since [6]. Even if the absolute difference is not so much important, the problem is related to the inaccuracy of the penetration depth computation due to the different assumptions we used previously. Fig. 9 shows residual stress profiles obtained numerically without any local friction and with different penetration depth: 0.25 µm to 2 µm. It is shown that the size of the affected zone highly depends on the penetration depth of abrasive grains (e.g. on the local force applied on the grain). The higher the penetration is, the deeper the affected layer is. Nevertheless the shape of the curves remains similar. In practice, penetration depth depends on the macroscopic force applied by the system (the pneumatic jack), on the rigidity of the polymeric roller, on the grain size and on the density of grains.

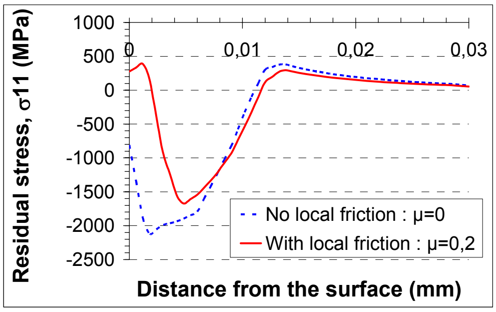

Fig. 4. Distribution of the residual stress σ11 on the sub layer for a penetration depth of 1µm (FE results).

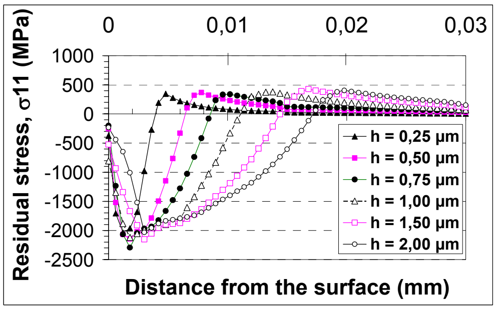

Fig. 5. Distribution of the residual stress σ11 on the sublayer for different penetration depth *h* and without any local friction (FE results)

These analyses show that belt finishing affects an external layer mainly by strain hardening and induces a compressive field along some micrometers; its thickness depending on the average penetration of the abrasive grains in the contact between the belt and the workpiece (i.e. on the macroscopic force applied by the system, on the rigidity of the roller, on the grain size and on the density of grains).

4 CONCLUSIONS

The objective of the paper was to investigate the modifications of the surface integrity induced by a belt finishing operation on hardened bearing steels.
In parallel to the well-known great surface texture, previous work have shown experimentally that belt finishing process generates compressive residual stresses on surfaces. This paper has shown by means of a finite element analysis, that the effects of belt finishing on the residual stress distribution can be explained by the action of abrasive grains rubbing the surface at the end of a belt finishing operation. In standard conditions, compressive stresses are induced in the skin.
The compressive layer affected by belt finishing is strongly related to the lubrication. A lack of lubrication could induce tensile stresses.
The depth of this affected layer depends on the local load applied on the grain

REFERENCES

1. F. Klocke, E. Brinksmeier, K. Weinert, Capability profile of hard cutting and grinding processes, CIRP Annals 54(2) (2005), 557-580.
2. H.K. Tönshoff, C. Arendt, R. Ben Amor, Cutting of hardened steel, CIRP Annals 49(1-2) (2000), 431-434 and 547-566.
3. J. Rech, A. Moisan, Surface integrity in finish hard turning of case-hardened steels, International Journal of Machine Tools and Manufacture, 43 (2003), 543-550.
4. A. Khellouki, J. Rech, H. Zahouani, Influence of the belt finishing process on the surface texture obtained after hard turning, Journal of Engineering Manufacture, (2007), 221, Iss. 7 (2007), 1129-1137..
5. A. Coulon, Effect of the honing drum upon the inducement of compressive residual stresses, Journal of Mechanical Working Technology, 8 (1983), 161-169.
6. J.Rech, G.Kermouche, W.Grzesik, C.Garcia-Rosales, A.Khellouki, V.Garcia-Navas. Characterization and modelling of the residual stresses induced by belt finishing on a AISI52100 hardened steel, Journal for Materials Processing, Accepted for publication, (2008).
7. M. Barge, G. Kermouche, P. Gilles, J.M. Bergheau, Experimental and numerical study of the ploughing part of abrasive wear, Wear, 255 (2003), 30-37.
8. G. Kermouche, J.M. Bergheau, Simulation numérique de la rayure des matériaux, European Journal of Computational Mechanics, 15 (2006), 221-232.
9. K.L. Johnsson, Contact mechanics, Cambridge University Press (1985).
10. J.M. Challen, P.L.B. Oxley, An explanation of the different regimes of friction and wear using asperity deformation models, wear, 53 (1979), 229-243.
11. G.Poulachon, Aspects phénoménologiques, mécaniques et métallurgiques en tournage c-BN des aciers durcis, Ph. D. Thesis, ENSAM Cluny, France, (1999).
12. G. Kermouche, J.L. Loubet, J.M. Bergheau, A 3D finite element pocedure for modelling scratch test, Proceedings of the 10th International Conference Metrology and Properties of Engineering Surfaces, Saint-Etienne, ISBN 2-86272-389-4, (2005), 311-320.