FE 3D Burnishing model
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INTRODUCTION

Finishing processes have always been important in manufacturing of all kinds of parts. A special attention is paid to surface quality, from the viewpoint of both smoothness, and physical and mechanical characteristics. Due to low roughness obtained, methods such as grinding, lapping, honing and polishing are commonly utilized for improving surface finish. Besides these methods there are other methods which improve surface characteristics through plastic deformation; these methods are referred to as burnishing.

Burnishing is a chipless cold-work process, which consists of plastic deformation the surface layer of the workpiece through the indentation of a tool, accompanied by other simple motions that ensure machining along the desired area (figure 1). The pressure generated by the indenter must exceed the yield point of the workpiece’s material and flattens asperities from previous machining process. This causes also strain hardening of the surface layer and induces compressive stresses into it. Finally, the result is a smooth hardened surface, with some improved mechanical properties.

In the past, burnishing was utilized only for smoothing of shafts and bores. After 1950, this method was applied in Germany and the former Soviet Union for work hardening of railway wagon axles and automotive crankshafts. Then, the usage range became more extensive: inner and outer surfaces of hydraulic components, bearings, sealing surfaces, fillets, etc. New materials, new tools’ new attachments’ design made possible the usage of burnishing on CNC machines. In the U.S., this process was first introduced in 1950. After a period of trials, it is now accepted in a narrow area of applications.

Research regarding effective burnishing started in the first half of the 20th century. In 1950, burnishing became the object of a systematic study, including theoretical approach. In present days, development of computer techniques and finite element approach made possible creation of models regarding the intimate phenomena in the surface layer. Nevertheless, there are not many modeling research in this field. A very good approach belongs to Skalski [1, 2, 3], who calculated stress distribution in terms of the applied load. He created a 2D model with his own codes in FORTRAN, simulating the rolling of a cylinder on a flat surface (figure 2).

This paper will present a 3D model of burnishing, using a finite model approach in MARC. It simulates the burnishing process with a profiled roll (torus plus cone) on a cylindrical surface. The results show the 3D stress distribution and plastic strains in the surface layer.

Fig. 1. Principle scheme of roller burnishing Fig. 2. 2D model of burnishing process [1]
PROCESS MODEL

This paper will present a 3D simulation of burnishing, using an elastic-plastic contact specialized software. MARC is considered one of the best commercial software in contact analysis, and this is the reason it has been chosen to perform this simulation. It simulates the burnishing process with a profiled roll (thorus plus cone) on a cylindrical surface. The results show the 3D stress distribution and plastic strains in the surface layer. Far of being exhaustively analyzed, the results try to prove that the model really works and the simulation can be used in many different cases for analyzing and optimizing the parameters of all types of burnishing processes.

The burnishing tool characteristics are shown in Figure 3. Cast iron with nodular graphite, quenched and tempered to 100000 psi is the burnished material. In order to have a practical number of elements for calculations, only the cylinder was meshed; the

Figure 3. Burnishing tool characteristics

Figure 4 2D and 3D images and profiles of the indentation made with 96 lb by the roll
Figure 5 Adapted geometry of roll

Figure 6 Displacement in X direction for indentation with the modified roll

burnishing tool is modeled as a rigid surface. Despite a relatively big difference between the elasticity modulus of tool and workpiece (40 $\times$ 10$^6$ psi for tool and 22 $\times$ 10$^6$ psi for the workpiece), an elastic deformation of tool occurred and this must be taken into account. An indentation was performed with a force of 96 lb and the indented hole dimensions were measured (Figure 4). The tool’s modeled characteristics are changed accordingly (Figure 5), such as the resulted shape of indented hole obtained after simulation with the rigid tool, using the same pressing force, 96 lb, is close to the shape obtained after burnishing with the real, deformable tool (Figure 7). The displacements on pressing direction, X, displayed as contour bands, provide the simulated hole shape (Figure 6). The percentages of the model deviation are: -1.6% for the depth of indentation, +5.8% for the width of indentation on Z direction (Figure 6), and -15.8% for the width of indentation on Y direction (Figure 6).

Two important features in a manufacturing process simulation are temperature and friction. Burnishing is a superficial plastic deformation process. The depth of deformed layer is small, varying, if the process improves only the surface quality, between 0.001 and 0.01 in. Usually, a water-based coolant having a moderate pressure is applied on the tool-workpiece contact area, thus the temperature, having significant increase only in superficial layers of workpiece, is rapidly dissipated. Almost no author is concerned with the study of temperature influence on the burnishing process.

MARC has implemented a modified Coulomb friction relation in order to avoid numerical difficulties [5]. The well-known relation written for stresses is:

$$|\sigma_{fr}| \leq \mu|\sigma_n|$$

(1)

where $\sigma_n$ is the normal stress, $\sigma_t$ is the tangential stress and $\mu$ is the friction coefficient. The modified relation is [98]:

$$|\sigma_{fr}| \leq \mu|\sigma_n| \frac{2}{\pi} \arctan \left( \frac{v_r}{C} \right)$$

(2)
where \( v_r \) is the relative velocity between the bodies in contact and \( C \) is a constant that adjust the function’s shape. In this mode, the variable \( v_r \) is explicitly introduced in equation and this fact eludes the non-determination of friction force when there is no relative motion between the contacted bodies. The smaller the value of constant \( C \), the conformer with the original Coulomb relation is Equation 2. In the same time, a too small value of \( C \) creates convergence problems. The value of \( C \) was chosen 0.01. The new generation of coolants insures a very good lubrication by fine oil particles in suspension. A friction coefficient of 0.05 looks appropriate for this simulation.

Two stages of simulation were performed: indentation and rolling three paths with a certain length, the distance between them being equal to feed rate, that is 0.012 in/rev. The force for indentation was applied gradually, by displacing uniformly the roll on the X direction, during 9 increments. A tenth increment is used for bodies release. The kinematics and geometry are symmetrically about a longitudinal plane, therefore a half of model is used (Figure 8). Rolling had a number of stages, which are presented, for rolling a path, in Figure 9. They are repeated three times for the entire cycle. The kinematics is not symmetric, therefore the entire model has to be used (Figure 8). During the entire simulation, the adaptive mesh feature was used for increasing the accuracy of contact and stress gradient on the contact surface.

![Figure 8 Models for indentation and rolling](image)

**RESULTS**

The evolution of four parameters was studied: plastic deformation on the pressing direction (X), normal stress on the pressing direction and tangential stresses in two perpendicular planes that contain pressing direction (XY and XZ), during both indentation and rolling.

**Indentation**

The aspect of displacements on pressing direction, X, is presented in Figure 7. The graph representing the evolution of component \( \varepsilon_{plxx} \) of plastic deformation tensor’s extreme values is presented in Figure 10 and residual \( \varepsilon_{plxx} \) distribution map, displayed for section given by axis Z-Z (Figure 7) after releasing, in Figure 11. A rapidly increasing of plastic compression up to a value around 1.7 \( \times \) 10^{-2} can be noted, and then a
Fluctuations in the evolution of plastic elongation can be observed, that is common in FEM calculations because of the discretization involved. The area mostly elongated after releasing is the sublayer located near the margin of the zone compressed by the thoroidal part of tool (Figure 11).

The evolution of component $\sigma_{xx}$ of stress tensor, important for determining the thickness of work hardened layer, is presented in Figure 12. The distribution map at increment 9, when maximum pressure is applied, is displayed in Figure 13 for the same section B-B. Compressive stress increases and reaches fast the cracking limit in the superficial layer, when the large number of
dislocations created block each other and induce the work hardening. The thickness of hardened layer is approximately 0.0075 in (Figure 13).

Component’s $\tau_{xy}$ progress during indentation is presented in Figure 14. The distribution map at increment 9, is displayed in Figure 15 for section A-A, representative for variation of this stress component. A non-uniform evolution of positive values of this shear stress component can be observed during first five increments, when the adaptive meshing feature splits the elements in the contact area. $\sigma_{xy}$ has positive values in this area because of the friction between roll and workpiece, that doesn’t permit the displacement of upper layers. This can be easily remarked in Figure 15. It is interesting to note that the maximum negative value increases almost four times after releasing. The affected area is the superficial layer located near the margin of the zone compressed by the thoroidal part of tool, in the symmetry section.

The evolution of component $\tau_{zx}$ of stress tensor is presented in Figure 16. The distribution map at increment 9 for section B-B is presented in Figure 17. The symmetry as long as the thoroidal part of roll contacts the workpiece can be noted, during first three increments; a slightly asymmetry, obvious after releasing, can be observed after the conical part of roll touches the workpiece.

Rolling
The map of final displacements on pressing direction, $X$, is presented in Figure 18. Non-uniform deformation along the paths can be noted, due to the adaptive mesh feature. The section where deformations close to the experimental ones were obtained is the section A-A.

The graph representing the evolution of the extreme values of tension and compression for component $\varepsilon_{plxx}$ of plastic deformation tensor is presented in Figure 19. Maximum compression value increases fast up to about 0.024, having slight variations after that. Maximum tension value, which occurs in the lateral and frontal wave of material generated by the moving roll, permanently increases during simulated
rolling. It doesn’t look like it reached a steady state during three paths with the chosen length of path; therefore, the simulation has to be extended to more and longer paths. The tensile strain on XX direction reaches almost a half of the compression strain, indicating a big molding rate of the material, which is firstly tensioned ahead of roll and then compressed.

The evolution of normal component $\sigma_{xx}$ of stress tensor is presented in Figure 20. Maximum values of tension stress slightly and continuously increase and are not affected of releases. Neither this parameter looks to reach a steady state. An important parameter, which is the compression normal stress on XX direction, indicates the degree of work hardening of the superficial layer of material and the depth of this layer points out the depth of work hardening. Its values vary around 310,000 psi, more than the ultimate stress, indicating the dislocations movement and reciprocal block, characteristic to work hardening.

Shear components of stress tensor $\tau_{xy}$ and $\tau_{zx}$ are presented in Figure 21.
Maximum and minimum values of $\tau_{xy}$ have a quasi-symmetrical evolution, which is interesting, taking into account that the process is not kinematically symmetric in the plane XY. The process is kinematically symmetric about the other plane, XZ, but it is not geometrically symmetric, the roll having the conical shaped part; a slightly difference between the extreme values of $\tau_{zx}$ can be noted. The positive values are due to the compression of the more inclined thoroidal contact part of roll and this is the reason they have somewhat bigger values in modulus.

CONCLUSIONS

In this study, a completely new 3D model of burnishing process was simulated using the FEM program MARC, considered one of the best commercial software in contact analysis. The simulation has two phases: indentation, used especially for calibrating the model by adjusting the geometry of the rigid roll, and a second one, burnishing of three paths with a certain length each, used especially for analyzing the data from the consistency point of view. The results, plastic strain on the main compression direction and all components of stress tensor that contain the compression direction, are consistent in terms of the obtained values and their distribution. The simulation offers a comprehensive image of the burnishing process. This work will be expanded to:

- Use the methodology for different burnishing methods and optimize the process;
- Optimization of the process from the subsurface damages point of view;
- Use it for the new hard burnishing process;
- Use the simulation for predict the surface strengthening;
- Optimization of the process kinematics;
- Use the methodology in future development of elastic-plastic contact specialized software;
- future use of methodology when certainly improved computing power will produce a lot improved results and will permit to accurately predict the roughness.

REFERENCES


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