Surface Nanostructuring through a Technique Derived from Shot-Peening: Recent Advances

Constance MOREL (WINOA)

co-author: Pr. Mario GUAGLIANO (Department Mechanical Engineering, Politecnico di Milano)

INTRODUCTION

Over the past decades, ultrafine-grained materials have attracted considerable scientific interests, especially nanocrystalline materials, whose grain size inferior to 100 nm conveys superior mechanical, physical, and chemical properties compared to conventional coarse-grained materials. It is well known that most of failures of engineering materials (such as fatigue fracture, fretting fatigue, wear, corrosion, etc) are very sensitive to the structure and properties of material surface, and in most cases material failures occur on the surface. As a consequence, a material exhibiting a nanostructured surface is expected to be much less likely to undergo such damages without changing the chemical compositions.

Many techniques have been developed to achieve surface nanocrystallization. Referred to as Severe Plastic Deformation (SPD) techniques, they all rely on the plasticity of metals and lead to a mechanically induced nanostructuration of the surface. Some of them can be referred to as “bulk treatments” as they aim at transforming the whole volume of a part They include ECAP (Equal Channel Angular Pressing), HPT (High Pressure Torsion) or drilling. On the other hand, some techniques focus on the surface: SMAT (Surface Mechanical Attrition Treatment) or USSP (Ultrasonic Shot Peenng), ball milling, sliding wear,

While those processes were developed at laboratory scale and are hardly compatible with up-scaling for application to mass-production, Severe Plastic Deformation and the resulting surface nanostructuring can also be achieved through a technique derived from Shot-Peening called NanoPeening®. In most cases, Shot-Peening carried out longer or stronger than usually leads to “over-peening”, which is detrimental to the material, inducing cracks and surface degradation without any change in the microstructure. In the last few years it was discovered that it is possible, under specific conditions, to pass over these effects and reach a nanocrystallised state of the surface. NanoPeening®-type treatments thus allow for the fast generation of a thick layer (several tens of micrometers) characterized by a gradient in grain size from a nanocrystalline microstructure at the surface to the conventional core structure. Like all SPD techniques, the nanostructured layer is produced “in-situ”, i.e. without any external addition like a coating, but this new treatment differs from the processes mentioned earlier in that it offers a real potential in industrial applications with high productivity, reliability and reproducibility. It is also very flexible, as a large range of shapes, sizes and steel grades can be treated.

This article aims at giving a description of NanoPeening® process, including the modeling works carried out with Pr. Guagliano’s team from Politecnico di Milano: using a Finite Elements method, they developed a program that allows for an estimation of the nanostructured layer created by the treatment, for a given set of process parameters.

NANOPEENING® PROCESS: DESCRIPTION AND SIMULATION APPROACH

1. Process description

It is a surface treatment solution derived from blasting. Blasting solutions are widely used to:

- Clean surfaces
- Prepare surfaces (e.g. before coating operations),
- Reinforce surfaces (so-called ShotPeening)

In the case of NanoPeening®, the objective is to transform the surface of the material through a drastic refinement of the metallic grains. The combined effects of hardening and nanostructuration convey an increased resistance to wear (in particular abrasion wear). Indeed, while other processes aiming at nanostructuring surfaces by impacts rely on conditions such as ultrasonic activation of big beads (UltraSonic ShotPeening USSP or Surface Mechanical Attrition Treatment SMAT) or on the contrary very small beads, still motioned by US but at much higher speed (High Energy ShotPeening, HESP), NanoPeening® does not involve UltraSons and use media and speeds that are quite common in the field of ShotPeening. For reasons of confidentiality not all the details can be disclosed but the process is patented. Concretely the equipment to process NP looks very much like any ShotPeening machine, from outside. The difference lies in the way the treatment is carried out, implying a precise combination of parameters, all of them accurately controlled and adjusted to both material and shape treated.

2. Numerical simulation

Finite Element simulations of NanoPeening® were developed to assess the process conditions required for a grain refinement down to a nanometer scale. The FE results are at the basis of a MatLab routine that allows for the prediction of the nanostructured layer thickness as a function of the process parameters. The development was conducted in 3 steps: the first one considered the case of a single impact, then a multiple impacts situation was simulated, and those results were used for the final software.

Single impact

The effect of impact angle was studied through single impact simulations (with different impact angle), considering a 3D model with a single shot. The target or substrate is modelled as a parallelepiped body (3*3*1.5 mm^3), large enough to avoid the effects of boundary conditions on the residual stress state in the impact zone. The impact area (1*1 mm^2) is located at the centre of the rectangular face. Target mesh is set up by C3D8R 8-node linear brick elements with reduced integration and hourglass control [1]. All the lateral faces (including the base) are surrounded by the so-called half infinite elements that provide quiet boundaries by minimizing the reflection of dilatational and shear waves back to the region of interest [2]. As for the substrate material (low alloy stainless steel AISI 304 L), it was modelled using nonlinear kinematic Chaboche hardening model [3], taking into account the monotonic and cyclic mechanical characteristics known for this grade.

On the other hand, steel shots were modelled as spherical bodies consisting of tetrahedral C3D4 elements with an isotropic elastic behaviour. Pictures of the target's and shot's models are presented on Figure 1

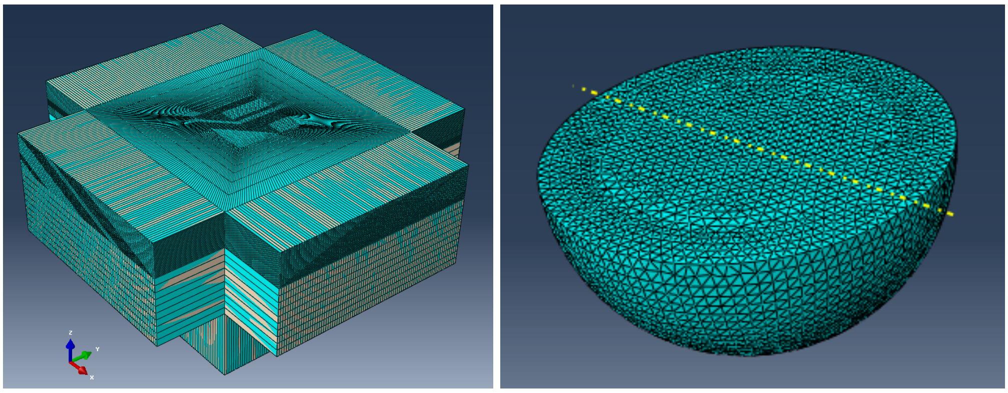

Figure 1: View of the models in Abaqus: substrate (left) and 0.6mm shot (right)

The velocity of the particle (shot) in any directions, is a vector considering the impact angle and absolute velocity.

General contact was used as the criteria of contact with an isotropic Coulomb friction coefficient equal to μ= 0.2 [4]. A single impact simulation was performed to measure the dimensions of the plastic indentation induced by the oblique impact. The chosen element sizes (1/20 and 1/10 of indentation diameter for impact area and for shots, respectively) resulted in acceptable convergence in terms of stress and equivalent plastic strain in the impact zone.

First simulations were done with vertical impact to validate the model on the basis of dimple (impact) size, i.e. diameter d and depth h. The results were compared to the empirical equations presented by Kirk [5]. The Kirk models for d and h are presented in Equations (1) and (2), respectively, where D stands for shot diameter, v for shot velocity, ρ for shot density, B for shot hardness, and e for damping energy. The three latter parameters were set at 7860 kg/m^3 for ρ, 201 HB for B and 0.71 for e.

$$d = \frac{0{,}02931 \cdot D \cdot (1 - e^2)^{0.25} \cdot \rho^{0.25} \cdot v^{0.5}}{B^{0.25}} \tag{1}$$

$$h = \frac{\left[D - \left(D^2 - d^2\right)^{0.5}\right]}{2} \tag{2}$$

The software outputs maps plotting d and h. The displacements obtained in the case of a vertical impact are presented on top of Figure 2, while the bottom of the same figure shows a comparison of the FE simulation with Kirk model: as can be seen, the results match well both in terms of diameter and depth of the impact.

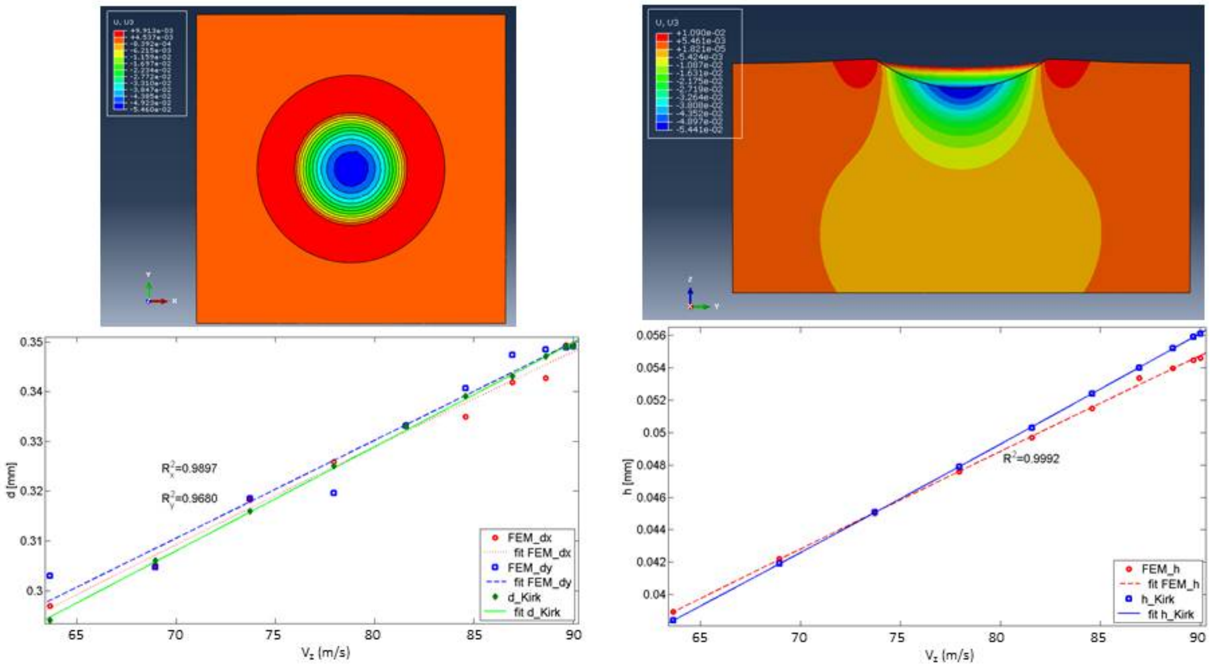

Figure 2: Simulation of a dimple resulting from a vertical single impact (top) and comparison with Kirk model (bottom) in terms of diameter (left) and depth (right)

The procedure was then applied in the case of an inclined impact (shot direction tilted from the normal to the vertical, as illustrated on Figure 3). As shown by the simulations presented on Figure 4, it resulted in an ellipse-like indentation.

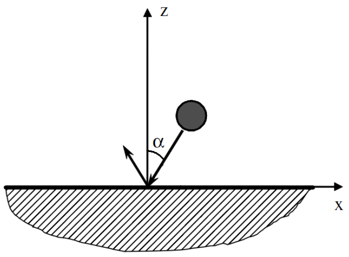

Figure 3: Schematic view of an inclined impact

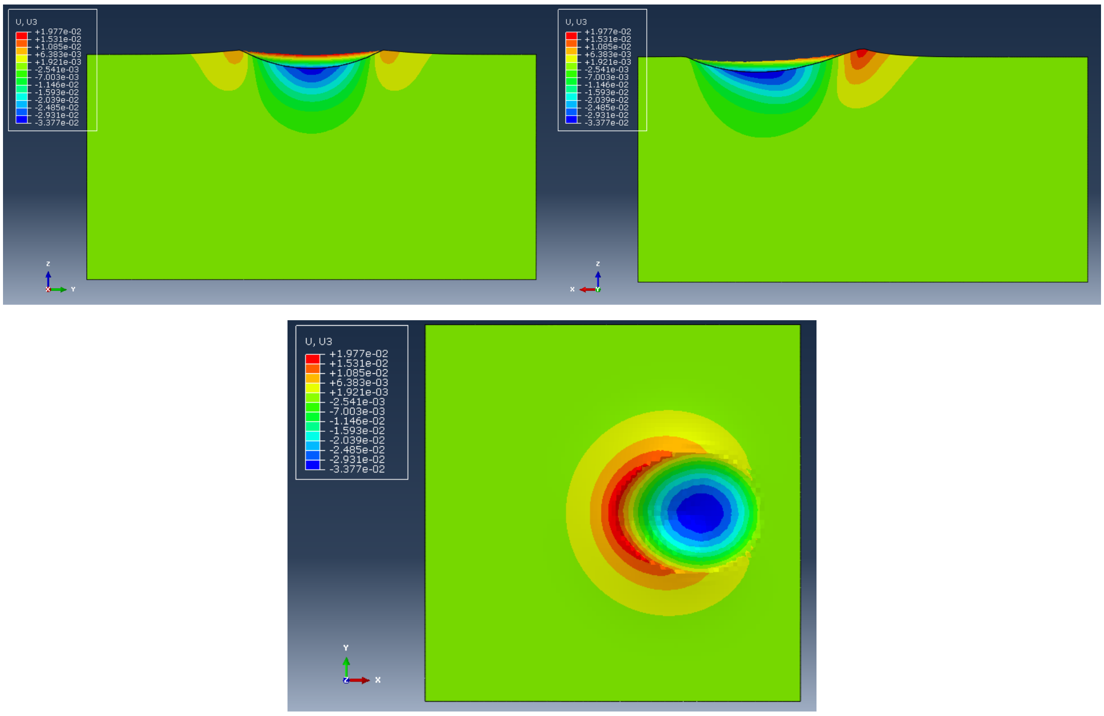

Figure 4: Different views of the substrate deformation under inclined impact (45°)

The ellipsoidal shape of the impact affects the plastic equivalent strain (PEEQ) distribution: as can be seen on Figure 5, it is no more uniform but its maximum is shifted in the direction of the shot.

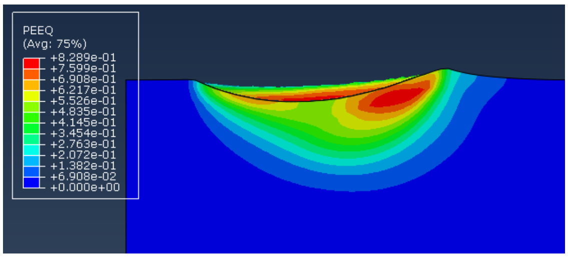

Figure 5: PEEQ distribution after an impact with an angle of 45°

Still in the case of single impact, the angle was then varied (but keeping constant the shot velocity). The maximum value of obtained PEEQ was plotted against the impact angle. The corresponding graph, proposed on Figure 6, highlights the decrease in maximum PEEQ as the angle moves from 0 (vertical impact) to 45°.

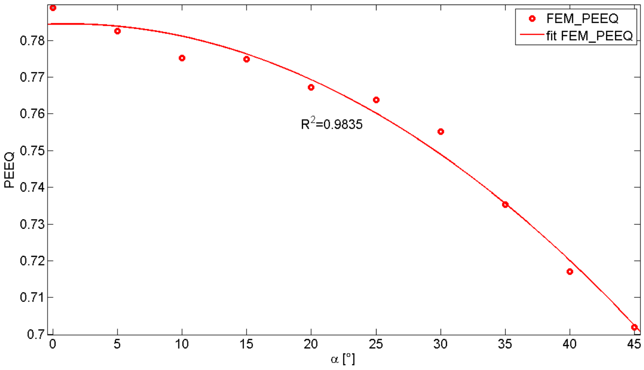

Figure 6: Evolution of maximum PEEQ as a function of impact angle

Multiple impacts

In order to propose a realistic model of the NanoPeening® process, the next step was to develop a FE model taking into account a large number of identical shots hitting the surface with random impact angles at random locations and in random sequences.

A large number of single impact simulations were performed on the basis of a full factorial plan (DOE) with the three main peening parameters that are surface coverage, shot diameter and shot velocity, in order to evaluate the impact size in each case. The values that were used are listed in Table 1.

Shot diameter (mm)	0.42 / 0.6 / 0.85
Shot velocity (m/s)	50 / 60 / 70
Surface coverage (%)	100 / 300 / 500

Table 1: Parameters used for DOE

Then a Python [6] subroutine was developed to optimize the number of random impacts and their repetition on each point based on the desired coverage percentage to be simulated. After several runs of the Python subroutine it was found that the number of impacts normally ranges from 2.1 to 2.2 N_{opt} (N_{opt}=Total impact Area/Dimple area).

For one of the analyses, a mapping of residual stresses was performed on an area equal to what is commonly used for residual stress measurement by X-Ray diffraction. The resulting 3D view of the surface is shown on Figure 7. Distribution of residual stresses and PEEQ as a function of depth for different surface coverages are presented on Figure 8.

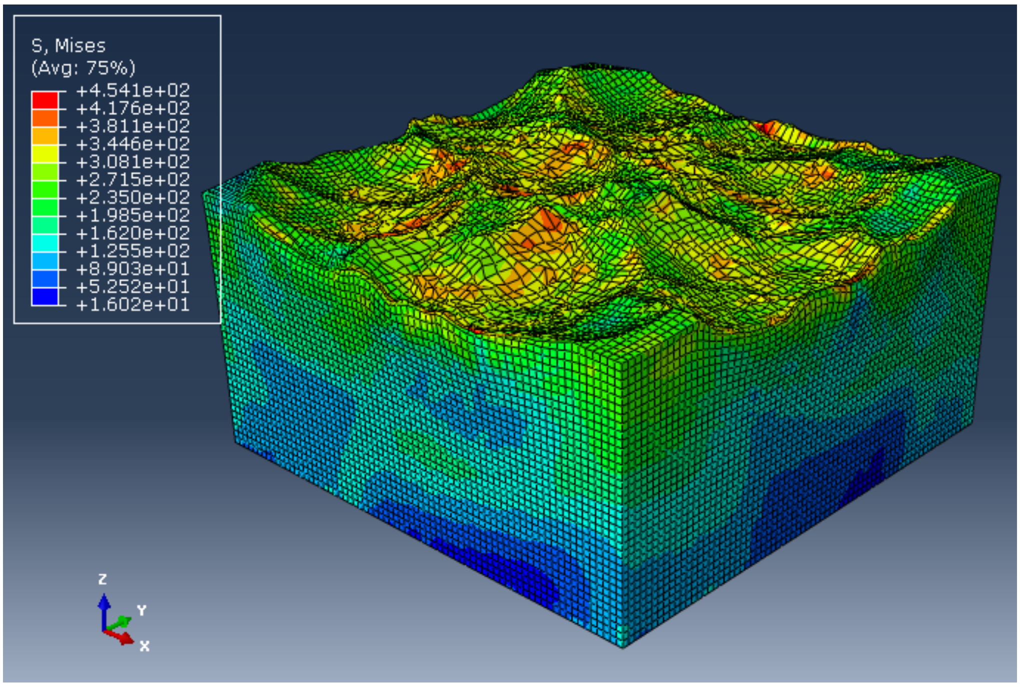

Figure 7: Surface topography simulated by FE

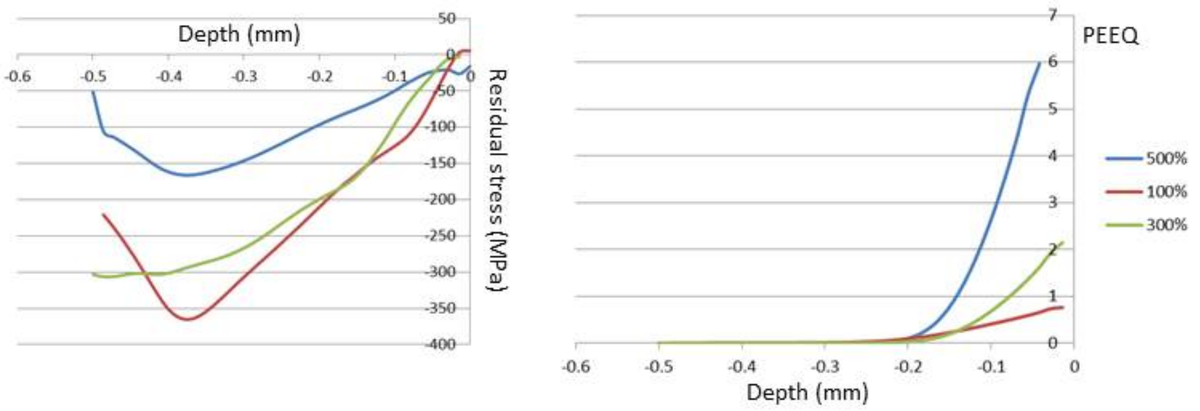

Figure 8: Residual stresses and equivalent plastic strain (PEEQ) obtained by FE simulations (shot diameter and velocity fixed at 0.6 mm and 90 m/s, respectively)

Software

The final step of the work was to develop a software able, given a set of parameters, to assess the residual stress distribution and to check whether the conditions required for grain refinement are fulfilled. For that purpose, the considered parameters (shot size and velocity, coverage as well as the estimated maximum impact angle) were merged into a swap parameter. This new approach relies on the calculation of the energy conveyed by the multiple impacts resulting from the considered peening parameters. As a first step, the dimple size, in the case of a single impact, is calculated from the process parameters converted into impact energy. Then it is used to evaluate the total number of impacts required to reach the desired coverage and the total impact energy of the process.

Based on the energy of the process, and the results of the simulations with different parameters, it is possible to have an estimation of the stress in each depth of the samples after shot peening process. The very same procedure can be applied for PEEQ.

Upon input of peening process parameters, the software returns a simulated profile of residual stresses as a function of depth as well as the maximum PEEQ value and the thickness of material characterized by a particularly high PEEQ; as this factor is known to be determining in grain refinement, the thickness thus found can be considered as the one of the nanostructured layer.

In this part it was dealt with the process itself and the principles of the simulations on which is based the software developed to predict the thickness of the nanostructure layer that can be expected from given process parameters. In the following, it will be shown how this nanostructured layer exhibits particular properties in terms of chemical diffusion.

CONCLUSION

A descriptive numerical simulation that takes into account different aspects of the treatment has been developed with the principal aim to estimate the distribution of residual stresses and assess the favourable condition for grain refinement.

As said at the beginning of the chapter, the first purpose of NanoPeening®, as well as of any surface nanostructuration treatment, is to protect materials against wear by creating a nanostructured surface layer. This is the most obvious application but not the only one and this chapter aimed at highlighting other remarkable characteristics by focusing on diffusion properties. They are involved in many fields and could lead for instance to an optimization of thermochemical Heat treatment or, in the case of tribo-corrosion, to the development of new stainless steel grade.

REFERENCES

[1] S. Bagherifard, R. Ghelichi, M. Guagliano, Surface & Coatings Technology 204 (2010) 4081–4090.

[2] Abaqus Analysis User's Manual (2007), version 6.11.

[3] J. Lemaitre, J.L. Chaboche, Mécanique des matériaux solides, DUNOD, Paris, 1998.

[4] T. Kim, J.H. Lee, H. Lee, S.K. Cheong, Material and Design 31 (2010) 50-59.

[5] D. Kirk, The shot peener, 2010, pp. 25-32.

[6] Python documentation, http://docs.python.org/.

[7] Mao X-Y, Li D-Y, Fang F., Tan R-S., Jiang J-Q, « Can severe plastic deformation alone generate a nanocrystalline structure? », Philosophical Magazine Letters, 90 (2010) 349-360.

[8] Tong W-P., Sui M-L., Lu J., Lu K., Tao N-R., Wang Z-B., « An investigation of surface nanocrystallization mechanism in Fe induced by surface mechanical attrition treatment », Acta Materialia, 50 (2002) 4603-4616.

[9] Semenova I-P., Raab G-I., Saitova L-R., Valiev R-Z., « The effect of equal-channel angular pressing on the structure and mechanical behavior of Ti–6Al–4V alloy », Materials Science and Engineering, A vol. 387-389 (2004) 805-808.