Numerical Analysis to Optimize Peen-Forming Process Parameters

Y. Essa[1], M. Laspalas[2], E. García[3], A. Escolán[2], B. Hernández-Gascón[2], and F. Martín de la Escalera[1]

[1] R&T Department, Aernnova Engineering Division,
20 Manoteras Avenue. 4-5 floor, 28050 Madrid, Spain

[2]Materials and Components Div. ITAINNOVA (Instituto Tecnológico de Aragón)
7 María de Luna Street, 50018 Zaragoza, Spain

[3]NMF EUROPA (Aerometallic)
Andalucía Street. Tarazona Industrial Zone. 50500 Tarazona, Zaragoza, Spain

Abstract: *Peen-forming is a practical technique for forming of metallic aeronautical components. The method performance of this cold-working procedure mainly depends on the efficient selection of process parameters. Currently, trial and error procedures, based on operators' experience are used to determine peen-forming intensity patterns. This expensive and time consuming method could be avoided by the accurate estimation of peen-forming process parameters. The absence of a predictive tool to determine these parameters makes difficult to give a quick response to market for the industrialization of new components. A virtual tool is developed to help designers to evaluate the feasibility of applying the peen-forming technique and process parameters to minimize drastically the number of rejected components in the process setup. Peen-forming intensity is usually quantified by means of surface coverage, pre-stress condition, ball size, shot velocity, component thickness, etc. The virtual software is called AERnnova Numerical Optimization of Peen-forming Process (AERNOP). The scope of the present study is to determine the process parameters optimization of peen-forming process using a 3D finite element method (FEM) methodology.*

Keywords: *Virtual tool, flat pattern, residual stresses, optimization, AERNOP.*

1. Introduction

Peen-forming process is characterized by striking the working surface of the panel with small spherical steel shots at a high impact velocity, see Figure 1. Shot impact produces plastic indentation surrounded by elastic region. After ceasing the shot impact, the plastic zone has become permanently deformed and elastic stressed zone is likely to recover unloaded initial conditions. Consequently, compressive residual stress distribution in the near-surface layer is developed as a result of elasto-plastic deformation behavior. Residual stress distribution is produced to maintain equilibrium in the peened layers. Compressive residual stress distribution can extensively reduce the crack growth rate of surface-short-cracks thus increasing the fatigue life of shot peened components.

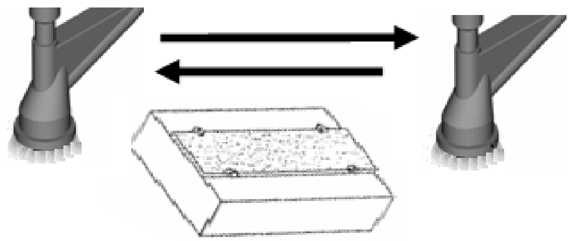


Figure 1. Peen-forming process.

The efficiency of the peen-forming process depends on process intensity, which is the degree of plastic deformation introduced by the impacting shots. The peen-forming intensity is mainly quantified by surface coverage, shot characteristics, pre-stress condition, component characteristics and shot velocity. Surface coverage is defined as the ratio of peened area to the total exposed surface area.

Virtual numerical modeling of peen-forming has received increasing attention from research community to analyse the compressive residual stress mechanism. This is due to the high experimental measurements cost of direct residual stresses, which require the application of semi-destructive tests, moreover time consuming. Multiple impact collisions during peening process have been simulated using quasi-static analysis, Meguid et al. (1985), Li et al. (1991) and Frija et al. (2006). However, dynamic analysis realized by Kobayashi et al. (1998) has demonstrated that static residual stress profile is different from dynamic analysis.

Modeling of peen-forming is performed at increased level of complexity, starting by single shot or by multiple shot impact events. Dynamic simulation of single shot was carried out by Al-Hassani et al. (1999), Hong et al. (2008) and Meguid et al. (1999). Multiple shot impacts have been conducted by Meguid et al. (2007) and, Miao et al. (2009) using finite element models. It is worth mentioning that few references have addressed the final deformation process at component level (Gardinier et al. (1999), Levers (1998), Miao et al. (2011) and Wang et al. (2006)).

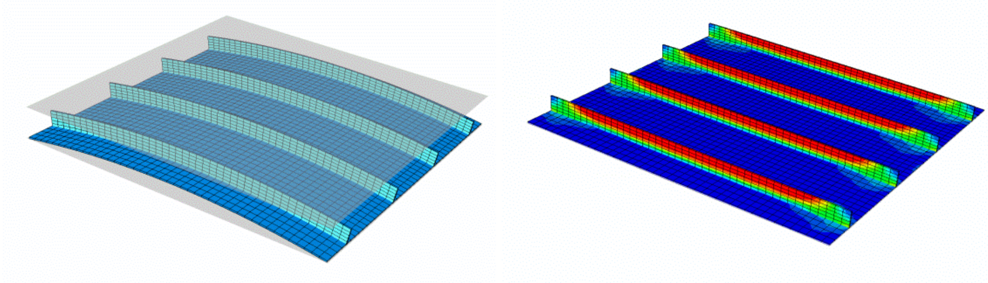
In this study, a methodology that combines different scales to define peen-forming strategy and to estimate the process parameters is presented, and applied for an aeronautical component.

As an antecedent of this work, it is worth to mention a previous contribution to Simulia Community Conference, Laspalas et al. (2011), where a direct FEM methodology for the simulation of peenforming process was presented. In this work the focus is to develop an inverse methodology to optimize process parameters.

2. AERNOP simulation procedure

The numerical tool, namely AERNOP, is developed with the purpose of estimate the optimal peen-forming process parameters. The tool is designed to help the industry to provide a quick feasibility study of any kind of client peen-forming purchase order. The tool can evaluate the viability to obtain the objective geometry by determining the required parameters, applying inverse engineering. To do so, the objective geometry is taken as the starting configuration. Also, the tool can check if obtained parameters are adequate using direct engineering, starting from the flat pattern and predicting the deformation after peen-forming process. Finally, the reached deformed shape can be correlated with the desired deformed shape.

Both approaches are based on the FEM. The inverse method consists on preparing a mesh model of the objective geometry. Two parallel rigid analytical surfaces are modelized and frictionless contacts are defined with the part geometry. The simulation is a static calculation where the component is compressed between both rigid surfaces till it becomes flat ("sandwich method"). The obtained stress distribution is afterwards used, first, for estimating the maximum pre-stress that can be applied to the component, keeping the material in its elastic regime (see Figure 2).



(a) (b)

Figure 2: Sandwich method. (a) Objective geometry inside two rigid surfaces. (b) Plane geometry showing the stress distribution.

Second, the stress distribution is used as a reference for the process parameter estimation. The areas with compressive stresses are the areas that must be stretched by peenforming in the direct process. This technique allows fixing the strategies to be applied in each zone of the component (see **Error! Reference source not found.**).

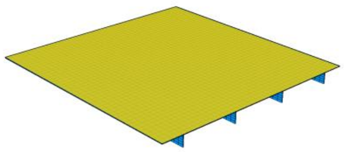
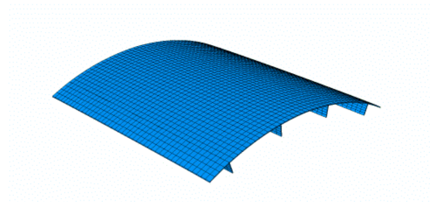
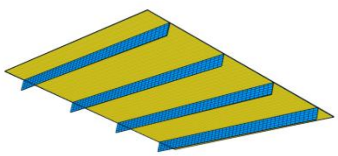
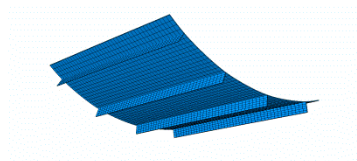
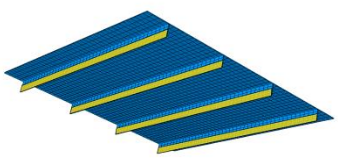
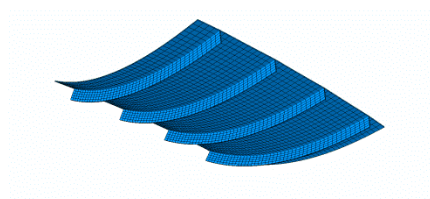
Strategy	**Final shape**
 Peening on top surface	
 Peening on bottom surface	
 Peening on stiffening ribs	

Table 1 – Peenforming strategies

The compressive stress value is related with the peenforming intensity required, but the solution is not unique, different combination of peenforming parameters can result in the same overall deformation.

Using a detailed FE simulation model, the peenforming process is analyzed at the material level. A region of interest of the material is represented and a stream of randomly placed shots impacting the surface is modelled using the discrete element modelling technique (DEM), and a proper contact definition. The calculation is a transient dynamic simulation solved using Abaqus/Explicit where the elasto-plastic response of the material under the surface is analysed as a function of the different process parameters: shot size, velocity and coverage. The ranges of each variable are selected to cover the full processing window. Figure 3 represents an in-plane stress distribution together with the stress profiles through the thickness at different coverage ranges.

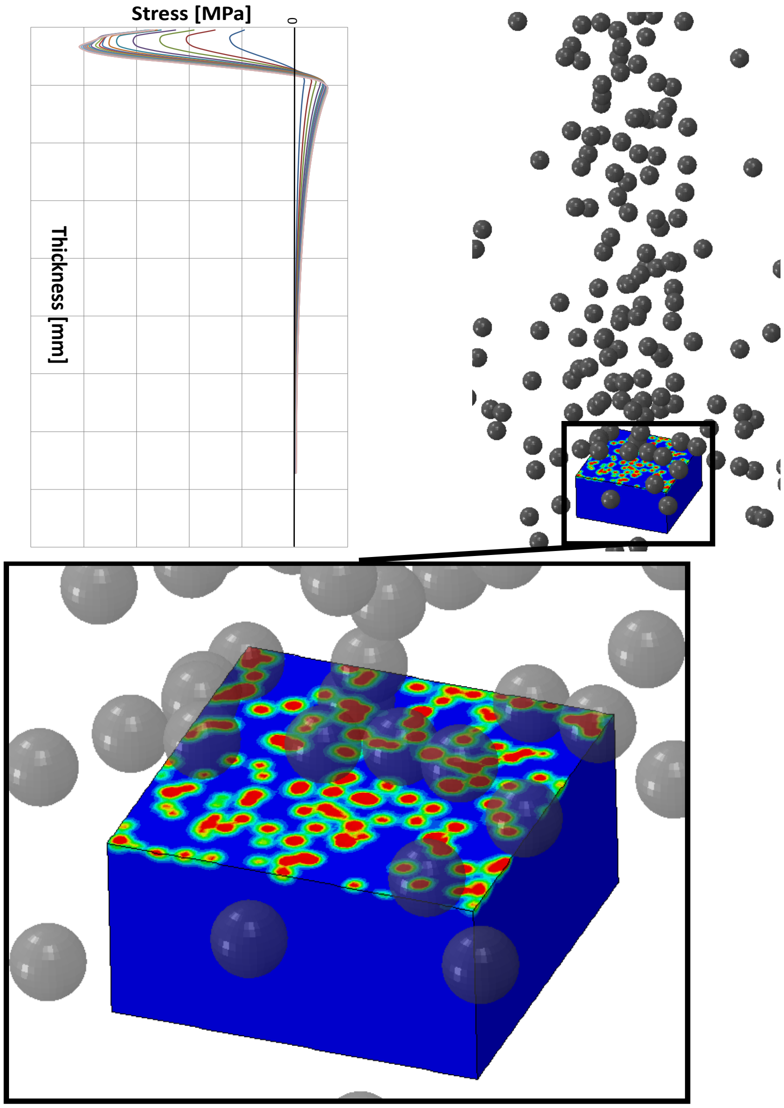


Figure 3: Multiple impact stress distribution profile evolution

This family of residual stress profiles is post-processed and a peenforming intensity function is defined, which represent the deformation capability for each combination of peening parameters (see Figure 4). Based on this intensity function and in the stress distribution obtained in the component using the “sandwich method” a process estimator tool determines the optimal process parameters, under predefined criteria. This is required because different combinations of parameters (ball size, velocity, coverage, etc) might result in the same intensity, i.e. deformation capability. These optimization criteria are based on the know-how of the manufacturing company and additional requisites imposed by the client.

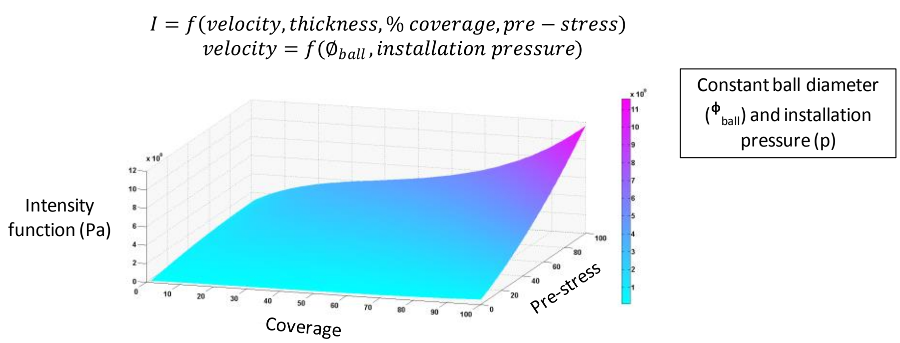


Figure 4: Intensity function (I).

3. Demonstration example

The developed methodology was applied on a complex aeronautical component having several sizes of windows, different thicknesses along the panel, stringers and curvature representing an example of objective demonstrator for a specific client order. Details of the objective work-piece can be observed in Figure 5.

Figure 5. Details of the objective aeronautical demonstrator.

An appropriate finite element 3D quality mesh must be prepared and it has to take into considerations the very small holes and the different thicknesses, moreover the stringers. The final FEM mesh can be observed in Figure 6. The total mesh size has about 20000 elements.

Figure 6. Finite element mesh.

In Figure 7 is represented the coverage map derived from the developed tool. In this case, there is no need to apply pre-stress boundary conditions.

The application of the previously described methodology result in a prediction of the peening parameters, which include the shot size and velocity required, the pre-stress level and the coverage distribution (Figure 6). In this case no pre-stress is required and only is necessary to apply shot on the aeronautical side of the panel.

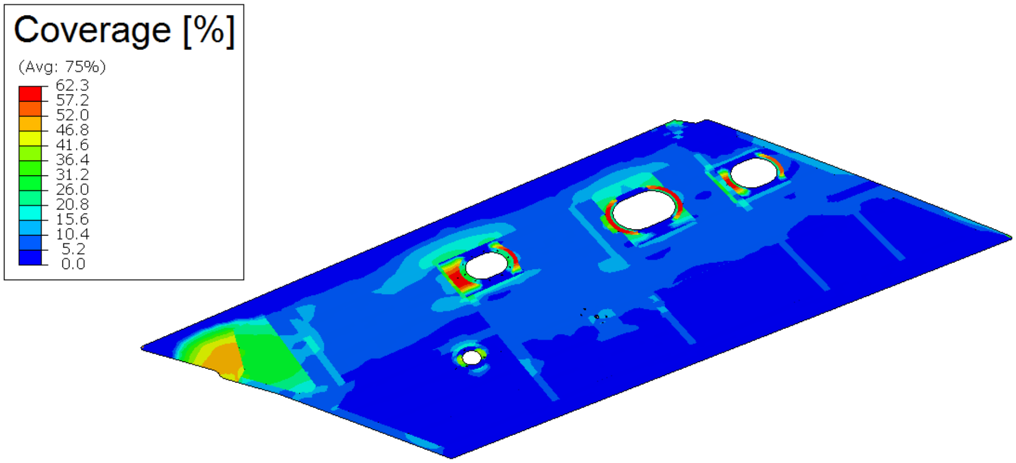


Figure 7: Coverage distribution on the demonstrator.

Finally, considering the obtained results, a study was done applying these acquired parameters on a flat pattern using the calculation tool AERNOP, as a direct FEM method. This is for the sake of comparison of the deformed shape obtained using the estimated parameters and the objective geometry. The comparison between both geometries is performed by applying the methodology known as “best fitting”, which applies a rotation and translation of the geometry to minimizing the distances between the similar points of both geometries. The results can be shown in Figure 8, where the product obtained after the direct method (gray) is superimposed to the target part (green). The maximum error is 12mm, which can be observed in Figure 9. This is an acceptable error over 2000mm demonstrator long.

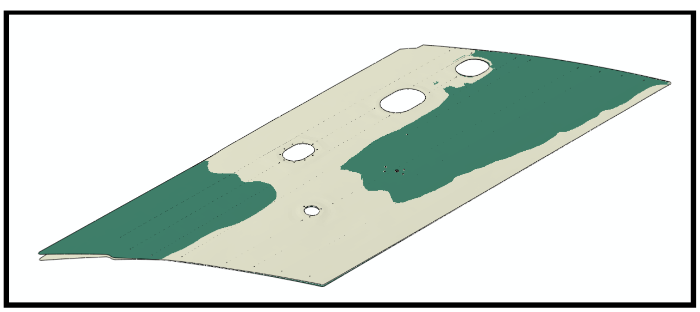


Figure 8: Best fitting strategy between the geometry of the aircraft panel under study (green) and that obtained by the direct method (grey).

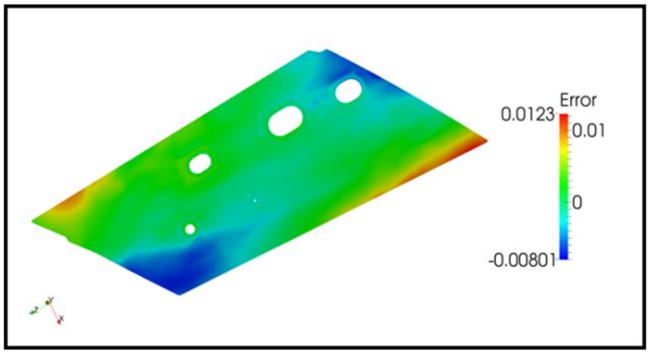


Figure 9: Error distribution applying best fitting strategy.

4. Conclusions

The proved methodology, AERNOP, was conducted to simulate the peen-forming process, estimate the process parameters and provide coverage contours to the operator in the industry. The methodology was applied on a complex aeronautical demonstrator using sandwich method and obtained results were used as a direct method. Best fitting process was applied to compare the geometries. The results are very promising.

The developed simulation tool, AERNOP, allows predicting the peen-forming parameters. This tool can be very helpful for designers to assess the process feasibility in early stages, allowing to anticipate manufacturing problems and to take the necessary actions in advance. It can estimate, a priori, the optimum shot peening parameters to be used by expert workers in the peen-forming process setup, which reduce time and cost consumed during the process set up.

5. Acknowledgement

This project has been partially supported by the Centre for the Development of Industrial Technology (CDTI), Spanish Ministry of Economy and Competitiveness. Their financial support is greatly appreciated.

6. References

1. Al-Hassani, S.T.S., K. Kormi, K and D.C. Webb. “Numerical Simulation of Multiple Shot Impact”, The 7th international conference on shot peening ICSP7, Warsaw 1999.

2. Frija, M., Hassine, T., Fathallah, R., Bouraoui, C., Dogui, A. “Finite Element Modelling of Shotpeening Process: Prediction of the Compressive Residual Stresses, the Plastic Deformations and the Surface Integrity”. Mat Sci Eng A, 426 173–180, 2006.

3. Gardinier, D.S. and Platts, M.J. "Towards Peen Forming Process Optimization", The 7th International Conference on Shotpeening ICSP7 Conference, Warsaw 1999.
4. Hong, T., Ooi, J.Y. and Shaw, B.A. "A Numerical Study of the Residual Stress Pattern from Single Shot Impacting on a Metallic Component", Advances in Engineering Software, vol. 39, pp. 743-756 2008.
5. Kobayashi, M., Matsui, T., Murakami, Y. "Mechanism of creation of compressive residual stress by shot peening". Int J Fatigue, 20 351–7, 1998.
6. Laspalas, M., Gómez, J., Martín de la Escalera, F., Sánchez, R., Jiménez, M.A. "Simulation of Peen Forming Process of Aluminum Aeronautic Panel". Id1242, Barcelona, Spain 2011.
7. Levers, A., and A. Prior, "Finite Element Analysis of Shot Peening". Journal of Materials Processing Technology, vol.80-81, pp. 304-308, 1998.
8. Li, A.K., Yao, M., Wang, D., Wang, R., "Mechanical Approach to the Residual Stress Field Induced by Shotpeening". Mater Sci Eng, A147 167–73, 1991.
9. Meguid, S.A., and Klair, M.S., "An Examination of the Relevance of Co-indentation Ctudies to Incomplete Coverage in Shotpeening Using the Finite-Element Method," J Mech Working Technol, no. 11, 87–104, 1985.
10. Meguid, S.A., Shagal, G., Stranart, J.C. and Daly, J. "Three-Dimensional Dynamic Finite Element Analysis of Shotpeening Induced Residual Stresses", Finite Element in Analysis and Design vol. 31, pp. 179-191, 1999.
11. Meguid, S.A., Shagal, G. and Stranart, J.C. "Development and Validation of Novel FE Models for 3D Analysis of Peening of Strain-Rate Sensitive Materials", Journal of Engineering Materials and Technology, vol. 129, pp. 271-283, 2007.
12. Miao, H.Y., Larose, S., Perron, C. and Lévesque, M. " On the Potential Applications of a 3D Random Finite Element Model for the Simulation of Shot Peening", Advances in Engineering Software, vol. 40, pp. 1023-1038, 2009.
13. Miao H.Y, Larose, S., Perron, C., Lévesque, M. "Numerical Simulation of the Stress Peen Forming Process and Experimental Validation," Advances in Engineering Software 42 963–975, 2011.
14. Wang, T., Platts, M.J. and Levers, A. "A process for Shot Peen Forming", Journal of Materials Processing Technology, vol. 172, pp. 159-162, 2006.