Prediction of shot peen forming through direct finite element simulation

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Abstract

Shot peen forming has been widely used in the aerospace industry to shape complex contours of large and relatively thin parts. It is a derivative of the shot peening process that consists of balancing the non-equilibrated induced stresses caused by shot peening. Most of the current studies of peen forming deal with one step of this balancing process which is called conventional peen forming. In this paper, the Finite Element (FE) methodology developed at LM^2, which can account for initial residual stresses (due to the lamination of plates for example), was applied to two specific cases. The first is the stress peen forming where the samples were pre-bent under four different conditions. The simulated results are very consistent with the experimental results and show that with the increase of the pre-bending moment, the resulting deflection increases following the pre-bending direction. The second application is the peen forming simulation of a full-scale wing panel considering several forming processes such as Saturation peening, Chordwise peening and Spanwise peening. The current model runs in less than 10 minutes on a PC. The simulated results reproduce the tendencies experimentally observed on a real full-scale panel.

Keywords: Shot peening, conventional peen forming, stress peen forming, Finite Element Method, induced stress, residual stress

Introduction

Peen forming consists in plastically deforming a relatively thin metallic component through shot impacts or laser pulses in order to upset the mechanical equilibrium and alter its contour [1]. Depending on the requirements, only the surface or the complete cross-section may undergo plastic deformation. The main application of this process is to shape large aerospace panels such as wing or fuselage skins or rocket sections. This technique can be especially attractive for relatively small series of parts with large dimensions since its conventional form does not require costly dies: the shaping effect is achieved through the selection of peening parameters. Stress peen forming, a variation in which the component is elastically pre-stressed during peening, can be used to achieve tighter and more complex curvatures such as the saddle shape, at the expense of tooling costs.

The main challenge is generally to determine the peening parameters required to achieve the desired shape with sufficient accuracy. This task was originally achieved through trial-and-error and the industrial application of the process relied heavily on the operators' skill. The development approach based on physical testing and experience remains common, but numerical-control peening machines now allow more repeatable operations. Some recent works have further considered on-line numerical process control to achieve tight tolerances.

Simulation methodologies have been developed since the mid-1990s [2, 3]. The objective was to predict the response of a given component to given peening treatments. Such a virtual tool would be valuable in the development phase to assess the manufacturability of a new part or try out novel peening treatments to improve current procedures. However, few studies attempted to understand the incremental nature of the process associated with continuous development of curvature during peening. In addition, pre-stressing conditions and representative industrial processes were rarely considered as part of the analyses [4, 5].

The objective of this paper is to present the developed conventional peening forming and stress peen forming FE models at LM^2 [5-9]. Experimental validation on small-scale of samples and the application of the model on real size wing panel shows the predictive capabilities of this model. This article is divided into 5 sections. Following this introduction, section 2 introduces the bases of the simulation methodology. Section 3 presents the validation of this stress peen forming model based on the experimental results by Miao et al. [10]. Section 4 presents an application of this FE model on a real size of wing panel. Section 5 concludes this work and suggests possible improvement and topics for future works.

Principle of the sequence peen forming FE model

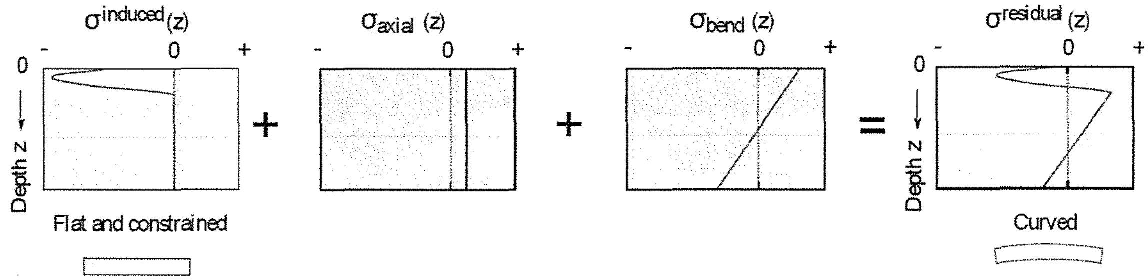


Figure 1. Schematic explanation of the principle of peen forming.

The forming effect associated with peening of thin components can described as shown in Figure 1. Starting from the unbalanced induced stress field $\sigma^{\text{induced}}(z)$, the part stretches and bends to achieve equilibrium at a balanced stress state $\sigma^{\text{residual}}(z)$.
The forming simulation methodology proposed at the LM^2 consists of directly inputting unbalanced induced stress profiles at section points in shell elements and calculating the new equilibrium state with a commercial FE code such as Abaqus/Standard or ANSYS [3]. The input induced stress profiles could be either those predicted by dynamic shot peening modelling or experimentally-determined residual stress data.
In addition, multiple successive equilibrium upsetting and elastic rebalancing steps are simulated to represent more accurately the fact that, as a component deforms throughout forming, the residual stress field varies continuously and affects further forming [6,11]. Impact simulations have shown that the induced stress close to the surface is not very sensitive to the prior residual stress state whereas the induced stress far away from the surface is not affected much by the impacts until rebalancing. These observations were formulated as an interpolation function S_p that relates the induced stress profile $\sigma^{\text{unbalanced}}(z,n)$ at the beginning of calculation step n to the balanced residual stress profile $\sigma^{\text{residual}}(z,n-1)$ at the end of step $n-1$ and the induced stress profile $\sigma^{\text{induced}}(z,n)$ determined for an initially stress-free material subjected to the peening treatment corresponding to step n as:

$$\sigma^{\text{unbalanced}}(z,n) = S_p \times \sigma^{\text{induced}}(z,n) + (1 - S_p(z)) \times \sigma^{\text{residual}}(z,n-1) \qquad (1)$$

The function S_p was defined based on the induced stress profile data and Eq. (1) was applied in each element for the two direct stress components. Geometrical non-linearities as well as contact between samples and their supports were considered in the simulations.
When simulating successive forming treatments involving different shot types and intensities, an additional assumption was imposed. It was decided not to allow the unbalanced stress near the peened surface $\sigma^{\text{unbalanced}}(z,n)$ to become algebraically larger (less compressive) than the prior residual stress $\sigma^{\text{residual}}(z,n-1)$. This hypothesis was only adopted for simplification and still requires validation.
The use of multiple calculation steps to represent a given peen forming treatment means that calibration between the experimental exposure time and the number of simulated steps is required for each treatment [12]. As current FE impact models could not accurately predict the development of optical coverage, the progress of shot peening was measured with the mass of shots impacting a unit area of the target surface. This mass density was derived from known process parameters such as the mass flow rate, the peening trajectory and the nozzle movement velocity.

This methodology was validated using small-scale 1.6 mm thick AA2024-T3 coupons subjected to low intensity peen forming and led to fairly accurate predictions. In addition, this approach was expanded to account for sheet material elastic orthotropy and initial residual stresses [7] as well as the influence of the peening trajectory [8].

Validation of the stress peen forming model

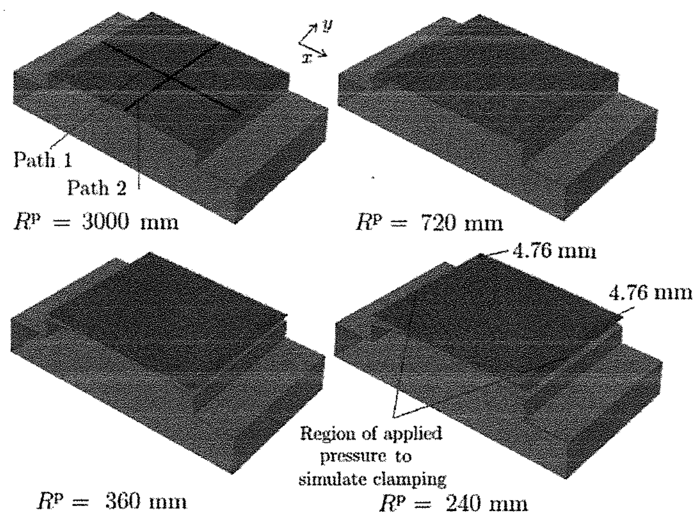


Figure 1. Finite element models with pre-loading device for four radii of curvature R_p =3000mm, 720mm, 360mm and 240mm used in the stress peen forming simulation.

The FE simulation of the stress peen forming model was firstly validated with the stress peen forming experiments performed by Miao et al. [10]. Four square AA 2024-T3 samples with dimensions 76mmX76mmX1.6mm were bent at four different radii of curvatures (∞, 720mm, 360mm and 240mm), which correspond to different level of pre-stressing. Baiker portable air blast machine with Motoman Robot were used to perform shot peening process. Ceramic Zirshot Z425 shots were used with air pressure 1550KPa, mass flow 0.4kg/min and shot velocity 66.2m/s measured by Shot Meter®.

Four-node reduced integration shell elements in ABAQUS were used to model the aluminium alloy strips with Young's modulus 71.7GPa and Poisson's ratio 0.33. Rigid body with radii of curvatures 240mm, 60mm, 720mm and 3000mm were modeled as the support blocks as in Figure 1. The initial stress state due to the plate manufacturing process was imported into the plate. The plate was pressed against the rigid body by applying uniform pressure on the clamped edges as in the experimental setup to simulate the pre-loading process. The shot peening induced stress from XRD measurement were progressively imported into the shell model using the method introduced in Section 2. Finally a free springback analysis was carried out to achieve the final deformed shape after peen forming. Figure 2 presents the simulated deflections and the comparison with the experimental results. Uz represents the deflection between the center and a point on the edge in x direction (38, 0) and in y direction (0, 38). It can be seen that FE simulation results are consistent with the experimental results which show the validation of the developed FE model.

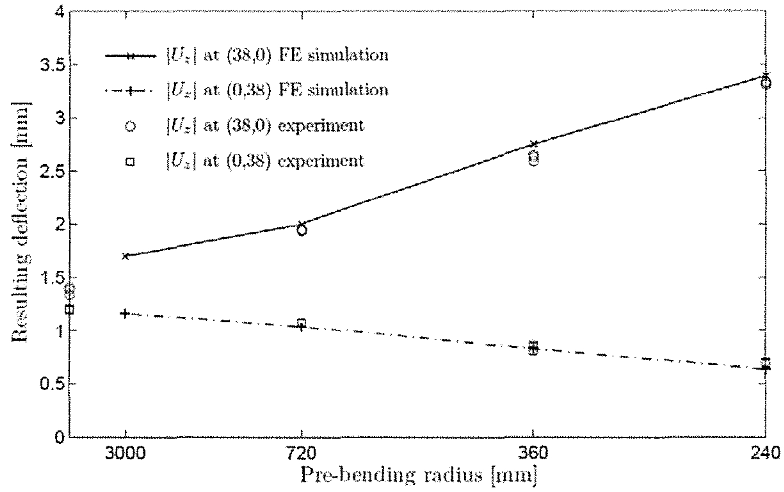


Figure 2. Comparison between simulation and experimental results for pre-loading conditions and resulting defections in x and y directions of the square plate.

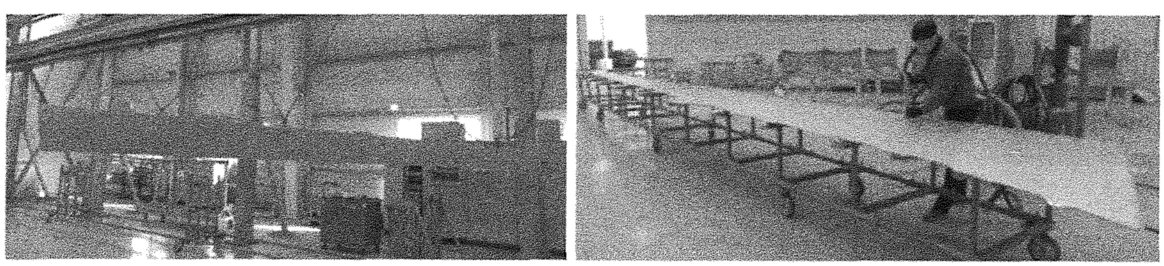
Application of the FE peen forming model on real wing panel

Industrial peen forming processes are generally intricate multi-stage treatments. As part of development work conducted in collaboration with Airbus Industries, the finite element modeling methodology was applied to simulate an actual A320 wing panel forming process using the ANSYS commercial code [13]. Three peen forming stages have been considered in the simulation: saturation peening, chordwise forming and spanwise forming. The former two operations are illustrated in Figure 3.

For each stage of the process, the predicted or measured induced stress was imported into the part in one step, which means the incremental aspect of the process and the peening trajectory were not considered [8]. After each stage, the calculated balanced residual stress field was considered as the initial stress for the next simulation step. It should be noted that, in this analysis, the contact between the panel and supports were not simulated. Only simple displacements supports have been added to avoid the reverse deflection of the panel due to gravity.

Figure 5 shows the final predicted total deflection after all of the three peen forming steps. In order to compare with the experimental results, a contour near the checking fixture rib #2 (see Figure 4) was selected to assess the forming tendency. From Figure 6, it can be seen that from the simulation, the sum of the deflection at the front and rear edges is 43.98+31.34 = 75.32mm.

For reference, the configuration at rib #2 between the checking fixture and the as-machined panel (before peen forming) is shown in Figure 7. The sum of the gaps at the front and rear was 11.5+58 = 69.5 mm. It is found that the prediction is within 8.5% of physical results. Comparison of these two values suggests that the developed FE model tends to predict forming results in a good scale.



(a) Saturation Peening

(b) Chordwise Forming

Figure 3. Wing panel on supports for saturation peening and chordwise forming.

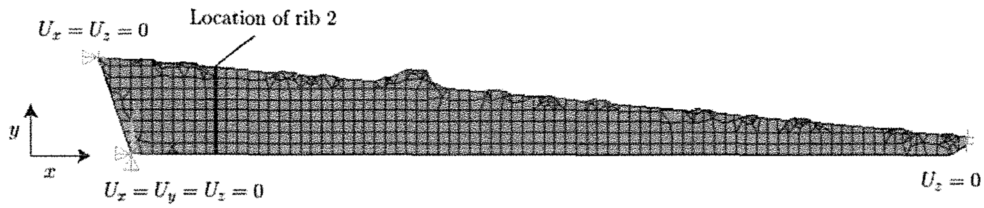


Figure 4. ANSYS FE model of wing panel. Boundary conditions were applied at selected corners to prevent rigid body motion.

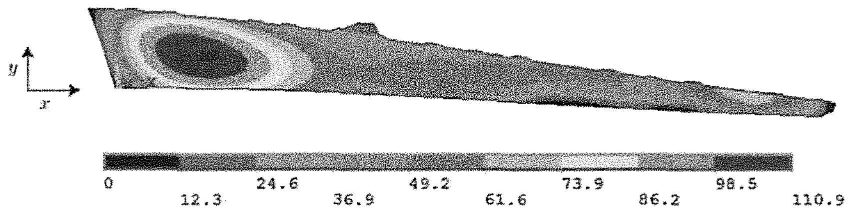


Figure 5. Total deflection Uz after all peen forming processes. (unit: mm)

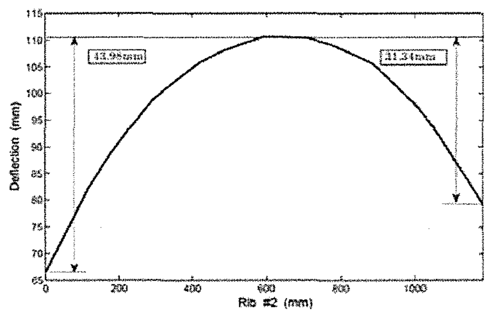


Figure 6. Predicted deflection of the panel near rib #2.

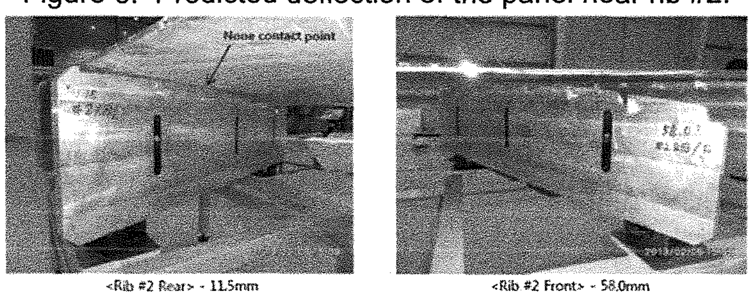


Figure 7 Distance between the rib #2 checking fixture and flat panel before peen forming.

Discussion and Conclusions

The predictive capabilities of the FE model developed at the LM2 to simulate the incremental nature of the peen forming process were illustrated by considering initial stress caused from manufacturing process, stress peen forming with pre-bending loading as well as multi-stage peen forming processes.

The FE model was validated firstly for stress peen forming on small scale plates with dimensions of 76mmX16mmX1.6mm. Four pre-loading conditions were simulated and were consistent well with the experimental results Further studies on stress peen forming will be focused on obtain cylindrical formed shape using one shot peening intensity/coverage and considering different pre-stressing condition in the plate.

A practical application of the FE model has been shown by simulating the multi-stage peen forming of the full scale wing panel. The preliminary predictions results present good agreement with the experimental results although significant simplifications have been applied. Further studies of this real wing panel forming process will include the simulation between the panel and support ribs, the incremental forming process etc., which are included in the ongoing research topic at LM2 with Airbus.

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