Numerical Studies of Shot Peening of High Strength Steels and the related Experimental Investigations by means of Hole Drilling, X-ray and Synchrotron Diffraction Analysis

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Abstract

Numerous experimental works have been done since decades on studying the influence of different shot peening parameters on the surface material conditions in different metals. Most of the research work has been focused on experimentally determining the residual stress and its depth profile by means of x-ray diffraction and corresponding electro-polishing the surface layers or by the hole drilling method. This valuable body of knowledge has led to the development of phenomenological-models to describe the surface material conditions qualitatively. Since there are quite a number of parameters which could influence the residual stress field after shot peening, covering the whole possible process parameters combinations with the purpose of experimentally determining the residual stress profiles could be difficult. A deeper insight into the residual stress states after shot peening could be possible on the basis of sound physical principles by means of numerical approaches.

In this study shot peening of high strength steel S690QL has been modelled and simulated. The results have been compared with the residual stress depth profiles determined by x-ray and synchrotron diffraction and the hole drilling method.

Keywords Shot peening, Residual Stresses, x-ray diffraction, Synchrotron diffraction

Introduction

The diversity of the parameters which could influence the surface conditions i.e. residual stress state, degree of work hardening and topography makes shot peening a strong tool in order to obtain a defined material state for specific applications. Numerous research works have been done since decades on studying the influence of different shot peening parameters on the compressive residual stress states in different base metals. Two mechanisms have been mentioned by Wohlfahrt [1] to be responsible for the development of surface compressive residual stresses as a consequence of shot peening, namely; plastic elongation and hertzian pressure (figure 1).

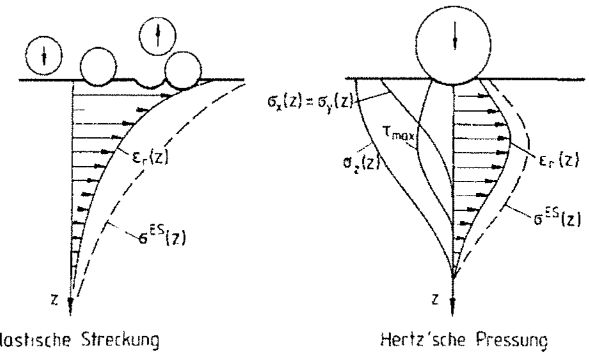

Figure 1: Mechanisms of the development of residual stresses in shot peening [1]: plastic elongation (left), Hertzian pressure (right).

The plastic elongation of the surface layer is pushed back by the elastic stresses in the bulk of the material leading to compressive residual stresses at the very top layer which is reduced in value and turns tensile in deeper layers because of equilibrium reasons. The other mechanism of generating compressive residual stresses is based on the Hertzian theory. With the collision of the shots on the surface, Hertzian pressure as a result of the impact forces arises. This theory describes the stress state below a surface on which a ball is pressed statically. At a certain distance from the surface which is a function of the width of the contact zone the resulting shear stress has its maximum. If the shear stress in this region exceeds a critical value, the consequent plastic deformation leads to a maximum in the compressive residual stress depth profile. In reality both of the aforementioned mechanisms contribute to the residual stress field after shot peening. Wohlfahrt describes in a concept [2] with some practical examples from some studies in the fifties, which of the two mechanisms are dominant in soft, medium hard and hard metals and thus decisive for the compressive residual stress distribution. As a conclusion it is mentioned that in soft materials the plastic elongation mechanism is dominant leading to the maximum compressive residual stress on the top surface whilst in harder materials the Hertzian pressure is more dominant and the maximum compressive residual stress is located below the surface.

The influence of shot peening parameters on the material state of the treated surface has been reviewed in several works [1-5]. The results could be summarized in figure 2 in which the effect of the shot peening parameters on the value and depth of maximum compressive residual stress profile is graphed schematically [3]. The arrows show the shifts in the depth profile by increasing the corresponding parameters. It is observed that increasing of all the parameters i.e. velocity, diameter and hardness of the shot, pressure, peening time and hardness of the work piece leads to an increase of the maximum compressive residual stresses. An increase in parameters except the work piece hardness results in an increase of the depth of the compressive residual stress profile. Since there are quite a number of parameters which could influence the residual stress field after shot peening, covering the whole possible process parameters combinations with the purpose of experimentally determining the residual stress profiles could be difficult. A deeper insight into the residual stress states after shot peening could be possible on the basis of sound physical principles by means of numerical approaches. Therefore, the goal of the present study was to develop a computationally efficient approach for predicting the residual stresses induced by the shot peening process.

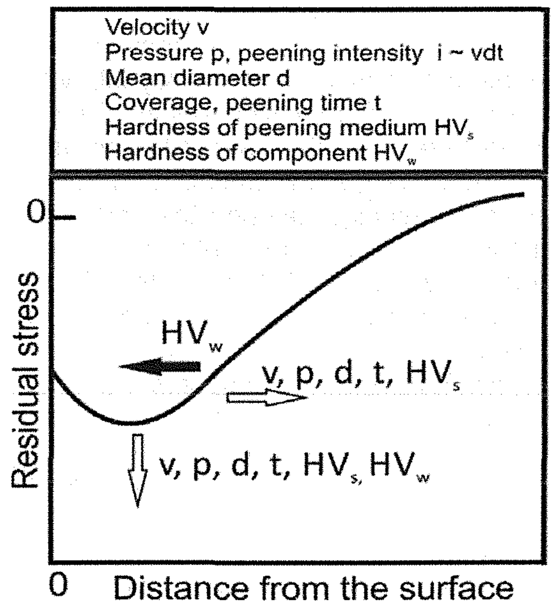

Figure 2: A qualitative model showing the influence of the shot peening parameters on the residual stresses [3].

Numerical Simulation of shot peening

The simulation model for the numerical studies consists of a metal plate (specimen) with the dimension of 10*mm* x 10*mm* x 2*mm* and several thousand of shots with a given diameter D (typically 0.5*mm* – 1.0*mm*). The specimen is modelled as elastic-plastic, while the shots are modelled as rigid spheres. Contact pairs are defined between the shots (master surfaces) and the specimen (slave surface), using the penalty contact algorithm for the normal to surface direction and for the tangential direction (friction coefficient typically μ=0.05 - 0.15).

The shots are distributed randomly over the specimen surface. The shots are assumed to have no rotation and no interaction with each other and have a given initial velocity v in the (negative) y-direction (typically 25*m/s* – 100*m/s*). Each shot has a mass corresponding to its volume and relative density (ρ=7850kg/m^3 for steel).

The mesh spacing must be relatively fine at the impact zone and can coarsen towards the outer region. In the impact area, the mesh features an element length of 100μm in the *x*-direction, 100μm in the *z*-direction and 50-100μm (biased, starting from specimen surface, ending at 0.50*mm* depth) in the *y*-direction. The element type is *ABAQUS* C3D8R (8-node brick, trilinear shape function, reduced integration).
The bottom side of the specimen is fixed by adequate displacement boundary conditions (u_x=u_y=u_z=0) as it is shown in figure 3 (a).
For all simulations a fully dynamic model is used (*ABAQUS EXPLICIT* solver). An explicit dynamic analysis is computationally efficient for the analysis of large models and allows for the definition of very general contact conditions.
The explicit dynamics analysis procedure is based upon the implementation of the explicit central-difference integration rule together with the use of diagonal element mass matrices (its inverse is simple to compute and the vector multiplication of the mass inverse by the inertial force requires only *n* operations, where *n* is the number of degrees of freedom in the model). The explicit procedure integrates through time by using many small time increments. The central-difference operator is conditionally stable. An approximation for the stability limit is given by the smallest transit time of a dilatational wave across any of the elements in the mesh ($\Delta t \approx L_{min}/c_d$, where L_{min} is the smallest element length in the mesh and c_d is the dilatational wave speed). The use of small increments (dictated by the stability limit) is advantageous because it allows the solution to proceed without iterations and without requiring tangent stiffness matrices to be formed. It also simplifies the treatment of contact. In a three-dimensional analysis refining the mesh by a factor of two in each direction will increase the run time in the explicit procedure by a factor of sixteen (eight times as many elements and half the time increment size).
The described model used for the calculations in this work is shown in figure 3 (a). The residual stresses $\sigma_{xx} \approx \sigma_{zz}$ after shot peening are evaluated at paths in the middle of the specimen (*x*=5*mm* ± 2.5*mm*, *z*=5*mm* ± 2.5*mm*, figure 3(b).

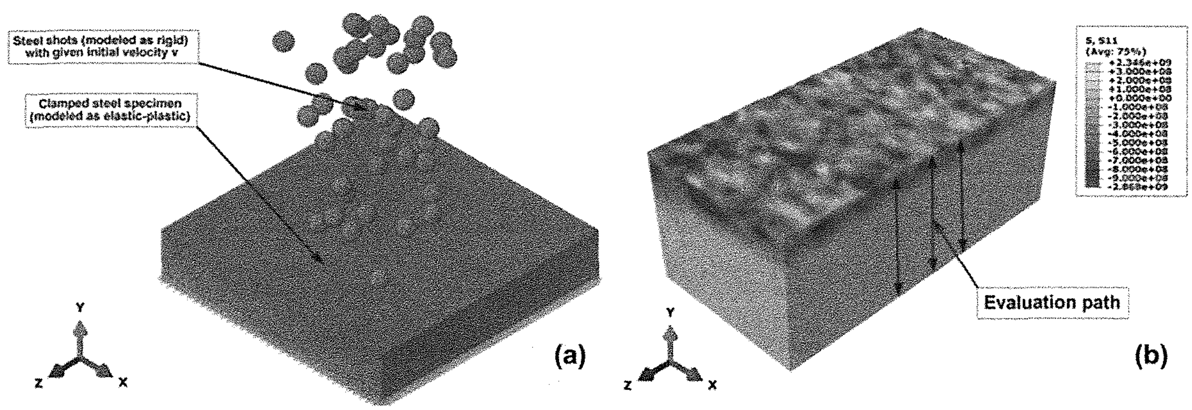

Figure 3: (a) FE-Model of specimen and shots (b) Stress distribution after shot peening (cut view), exemplary evaluation paths

The considered material is the high strength construction steel *S690QL*, with an initial yield strength of $\sigma_y \approx 800 MPa$ and an elastic modulus *E*=210*GPa*. The resulting residual stress depth profiles (shot diameter *D*=0.60*mm*, initial shot velocity *v*=80*m/s*, friction coefficient μ=0.15) are shown in Figure 4a.
In general, the plastic deformation from shot peening induces compressive residual stresses in the peened surface balanced by some tensile stress in the interior. Maximum compressive stresses of 72.5% of the initial yield strength (approximately 580*MPa* for the considered material) were determined. According to the Hertzian contact between the spherical shots and the plane plate, the maximum compressive stress was evaluated in a depth of approximately *0.125mm*. Figure 4b shows the evolution of the residual stress depth profile. At a number of approximately 100 *shots/mm*^{2} a saturated state was reached with a surface coverage of more

than 100%. After the shot peening process the residual stress depth profile changes slightly due to the decay of the dynamic effects.

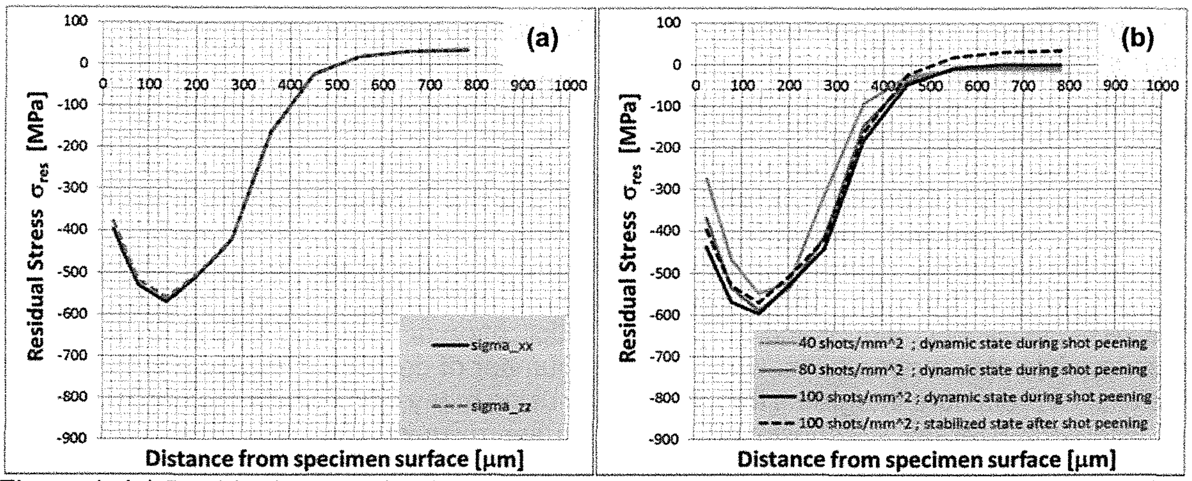

Figure 4: (a) Residual stress depth profiles for longitudinal direction and transverse direction (b) Residual stress depth profiles for different numbers of shots

The most critical issues in simulation and modelling of shot peening are the material hardening behavior and the impact velocity of the shots (both are afflicted with some uncertainty) and the peening time. The resulting residual stress depth profiles (D=0.60mm, v=80m/s, μ=0.15) for different material hardening models and different initial shot velocities are shown in Figure 5.

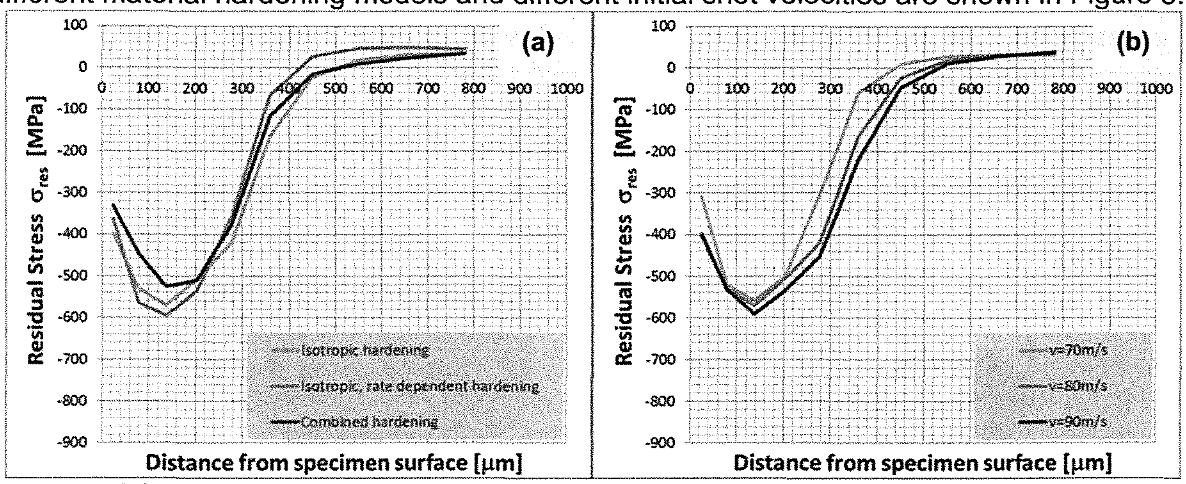

Figure 5: (a) Residual stress depth profiles for different material hardening models (b) Residual stress depth profiles for different initial shot velocities

The material hardening law features an observable quantitative effect on the stress depth profile; it mainly influences the peak value of the compressive residual stress. Figure 5 (a) compares the stress depth profile for an isotropic strain rate independent hardening law with the respective profiles for an isotropic strain rate dependent hardening law (Johnson Cook) and a mixed isotropic-kinematic (combined) strain rate independent hardening model (Chaboche-model). The combined hardening model includes softening of material after a change of the loading direction and provides a lower peak stress. The isotropic rate dependent hardening model respects the increase of the yield strength with increasing strain rate and provides a higher peak stress compared to the results for the isotropic strain rate independent hardening law. Due to the impact of multiple shots the elastic-plastic material undergoes local hardening cycles. Thus, the combined hardening model should provide the most realistic results when it is enhanced by strain rate dependence. Nevertheless, the isotropic hardening model provides reasonable results too, which are sufficiently accurate for a first estimate of the stress depth profile.

The impact velocity of the shots influences the peak value and the penetration depth of the compressive residual stresses; see Figure 5 (b). These results are in good agreement with well-known experimental observations [3].

Shot Peening of the S690QL Samples

In order to validate the model, small samples (figure 6) with the dimension of $50mm$x$50mm$x$8mm$ from a high strength steel S690QL were shot peened by the company Curtiss wright Surface Technologies. The choice of this steel was also motivated because of its importance in future welded structures [6]. Three different samples with low, medium and high intensities with full coverage of 200% (controlled by peenscan) were shot peened:

- Sample A: CW06/ 0.20 - 0.25mmA LOW
- Sample B: CW06/ 0.35 - 0.40mmA MIDDLE
- Sample C: CW06/ 0.45 - 0.50mmA HIGH

Figure 6: Geometry of the S690QL steel sample in this investigation.

Since in the numerical analysis, the residual stress state was saturated after using the intensity corresponding to 100 shots/mm^2 (figure 4b), in this study the sample C which was also peened experimentally with the maximum intensity of 0.45-0.5 mmA was used for further investigations.

Experimental determination of residual stresses

According to the depth limitations of each of the techniques used to determine the residual stress fields, it is always necessary to apply a combination of several methods. X-ray diffraction was used in this investigation first for the determination of the surface residual stresses. For the sub-surface investigations, the synchrotron beam line (EDDI – BESSY II) at the Helholtz Zentrum for Materials and Energy (HZB) was used. The synchrotron diffraction in reflection mode in this experiment was capable to cover the first 100 µm of the top layer. For deeper layers up to a depth of 400 µm the investigations were carried out by means of the hole drilling method. For comparison reasons the x-ray diffraction technique with electro-polishing the surface layers up to a depth of 200µm was applied too. The residual stress depth profiles in two directions from the synchrotron diffraction up to the depth of 100 µmm, the x-ray results up to the depth of 200µ and the hole drilling results up to the depth of 400µm are all plotted in figure 7.

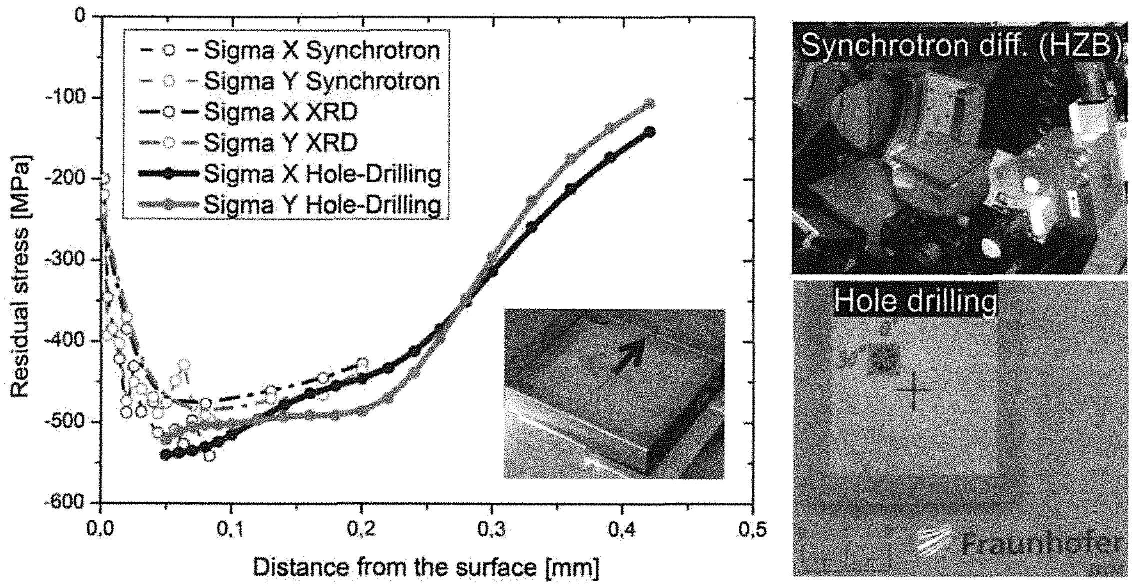

Figure 7: Experimental determination of the residual stress depth profiles in sample C by means of x-ray and synchrotron diffraction and hole drilling method.

Comparison of the numerical and experimental results

Plotting now the results achieved in the numerical analysis with those of the experimental parts, a good qualitative agreement of the respective residual stress depth profiles could be observed (figure 8). The material model with the isotropic hardening estimate the value of the maximum compressive residual stresses quiet well. However the depth of the maximum compressive residual stress and also the steep gradient of the sub-surface residual stress in the first 100µm of the sample could be better estimated by the other two models. Due to the uncertainties with respect to the appropriate material hardening behavior and the assumption of the rigidity of the shots, one can conclude that the current simulation model has an uncertainty concerning the determined residual stress depth profile of approximately ±50*MPa*.

Conclusions

The residual stress depth profiles in a small steel samples (S690QL) after shot peening were calculated by explicit simulations in ABAQUS. The experimental results by means of x-ray and synchrotron diffraction and the hole drilling technique revealed a good agreement with the numerical results. Maximum compressive residual stresses up to 70-75% of the yield strength of the high strength steel S690QL, up to a depth of 400-500µm could be induced by shot peening. This was obtained by both numerical and experimental investigations. By having an appropriate material plasticity model, the influence of different process parameters on the surface conditions regarding residual stresses, work hardening could be described. It was observed that regardless of the material models, the described residual stress fields had a qualitatively and quantitatively good agreement with the experiments. The isotropic hardening model considering the strain rate dependency overestimated a bit the maximum compressive residual stress of about 10%. This model could describe however the steep gradient of the sub-surface residual stress quiet well. For an accurate determination of the residual stress depth profiles a combination of x-ray, synchrotron diffraction and hole drilling showed to be promising.

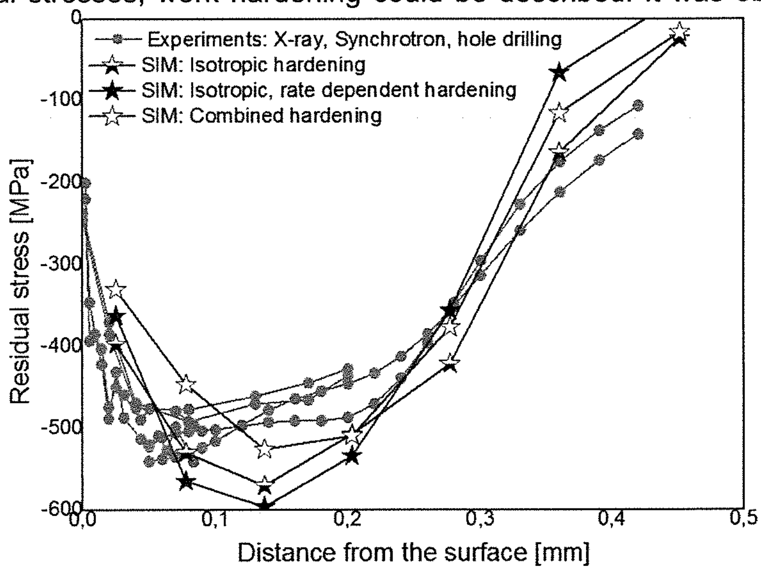

Figure 8: Comparison of the numerical and experimental results.

Aknowledgment

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