Finite Element Simulation of Shot Peening on Spring Steel Wire

U. Kletzin

Technische Universität Ilmenau, Ilmenau, Germany

Abstract

Shot peening is a standard procedure for increasing the durability of dynamically loaded helical springs. The dependences of the residual stress profile from the parameters of the shot peening process are difficult to determine.

The article will describe new developed special program tools for Finite Element simulation of shot peening on spring steel wire to calculate the residual stress profile, e.g. in helical springs, which is highly necessary for fatigue estimations. The interaction between the parameters such as particle dimensions, particle velocity as well as the materials of particles and spring and the expected residual stress profile will be discussed. The article describes a FEA-simulation of the stepwise etching and measuring process of the residual stress profile and a discussion. The program tools are integrated in a Finite-Element-Springprocessor (FE-Springprocessor) developed by the author. A new time saving method of the design process of dynamically loaded helical compression springs based on the results of the residual stress profile calculation will be demonstrated.

Keywords: FEA, helical springs, shot peening, residual stress

Introduction

The user requirements for helical compression springs as well as the complexity and intensity of the verification process are increasing [1]. Hence, the numerical and experimental simulation of the durability of technical springs is gaining wide importance.

Springs have in operation a set of component-specific characteristics that make a numerical lifetime prediction very complex and difficult, such as large deformations, dynamic stress increasing due to vibrations, residual stresses from wire and spring production, complex coupling points from adjacent components, and some complicated spring compression kinematics. In the numerical simulation of springs following issues have so far not found or only insufficient found their way into the state of the art:

- The residual stress behaviour in the spring, resulting from wire manufacturing, spring winding process and following manufacturing processes (heat treatments, shot peening, presetting),
- dynamic stress increasing due to vibrations,
- wear due to tribological loads,
- corrosion.

For the simulation of the residual stress state of helical compression springs made of oil-tempered spring steel wires the manufacturing steps spring winding, spring tempering, shot peening and presetting have to be considered.

Shot peening is a standard process for increasing the durability of dynamically loaded helical compression springs. The resultant compressive stresses close microcracks at the wire surface and produce a more favorable overall stress state in the operation of the spring. The durability-enhancing effect of shot peening can be seen in **Figure 1**. The shot-peening treatment of dynamically loaded helical compression springs can increase the lifetime by much more than the factor 10, wich is often described in the literature and therefore represents the most important manufacturing step in improving the durability.

This paper describes newly developed parameterized program modules for the finite element (FE) analysis of the shot peening process on spring steel wire for calculating the residual stress profile e.g. for helical compression springs. The residual stress profile can be calculated as a function of all relevant influence parameters such as medium size, speed and strength of shot material as well as spring material and the coverage. The simulation results have been validated by X-ray stress measurements. Therefore it was necessary also to simulate the

stepwise removal of the wire surface by chemical etching during the measurement process of the residual stress profile using a further FE model.
Based on the results of the shot peening simulation (residual stresses) and an additional FE simulation of the load stresses, a new time-saving method for the design of dynamically loaded helical compression springs will be presented.
The program tools are integrated in the "FE-Springprocessor" developed by the author.

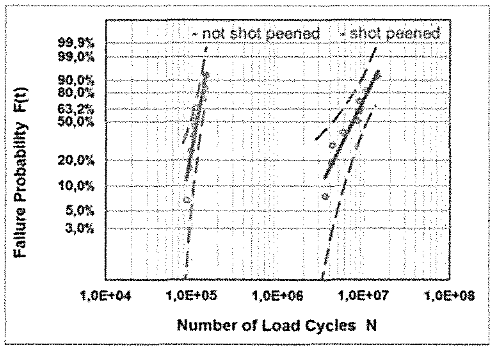


Figure 1: Influence of the compressive stresses due to shot peening e.g. on the durability of a valve spring [2]

Requirements for the Simulation Model of the Shot Peening Process

Dynamically loaded helical compression springs are usually made of oil-tempered spring steel wires according to DIN EN 10270-2. This material can be regarded as residual stress free, because during the wire tempering as the last step of the heat treatment in wire manufactering a homogeneous structure is set. The simulation model has to be constructed fully parameterized, all necessary process parameters, such as wire diameter, shot velocity, shot material, wire material and coverage should be easily changeable.

Shot Peening Simulation

The metal forming process of shot peening is based on the elastic-plastic material models of spring steel wire and the shot. The corresponding material curves do not only depend on the type of raw material of the spring, but also on the heat treatments to the spring steel wire up to the finished spring [4]. Hence, stress / strain curves were determined by tensile tests and converted accordingly (tensile stress/ strain cp. **Figure 2** and Youngs modulus) and are available in a web data base of the research group [4]. The module uses the multilinear, isotropic hardening material model of Ansys. Temperature can be included by using test curves of heated wire material. Strain rate effects can be considered by using Pierce Option (better convergence behaviour then Perzina Option).

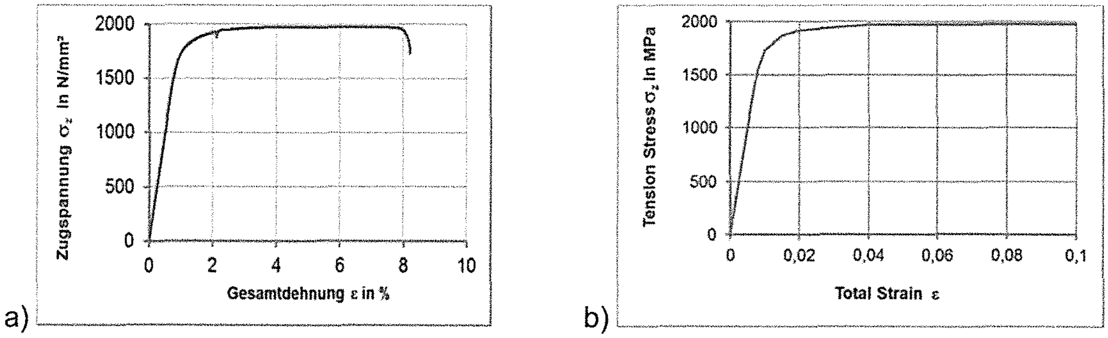


Figure 2: material model for spring steel wire 65SiCr6 SC, d=3mm: a) tensile test curve, fig. downloaded from web data base (http://ramserver2.maschinenbau.tu-ilmenau.de/federdraht) of Research Group "Wire and Springs" TU Ilmenau; b) corresponding FE material model

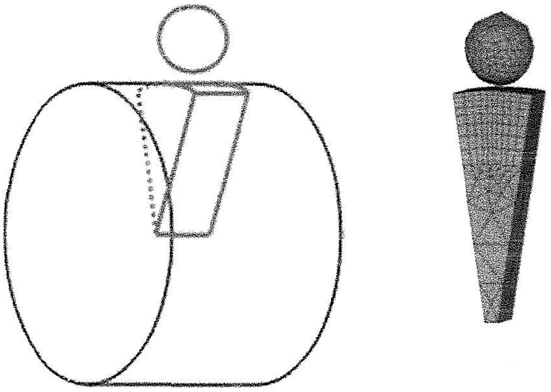


Figure 3: Simulation model

The wire is modeled with Solid 186 elements. It is as shown in **Figure 3** a symmetrical part of the wire cross-section. A sufficient mesh density is important at the wire surface. The constant layer thicknesses is necessary for the subsequent simulation of residual stress measurement process (stepwise etching). The shot (sphere) is modeled with Solid 187 elements (see Figure 3). A symmetrical contact between wire and shot surfacees is used. The wire part is supported by the necessary symmetry boundary conditions and is fixed at wire center. The shot is guided perpendicular to the wire surface.

The user can choose between default (ordered) or random positions for the collision points of the shot on the wire surface. For both variants he can also determine the number of collisions (coverage). The load steps are summarized in **table 1**.

Table 1: Load Steps

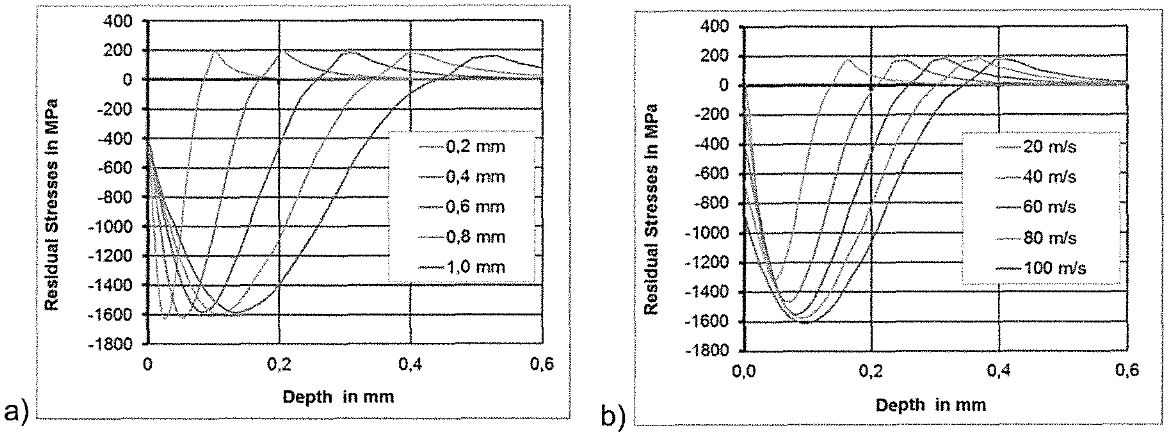
1. Load step	(shot positioning) The shot is positioned relative to the wire surface. The height above the wire surface is fixed.
2. Load step	(Move shot to just above the wire surface) The shot gets a selectable speed.
3. Load step	(collision) By turning transient effects on "timeint, on" the shot gets its initial speed and the shock process is calculated.
4. Load step	(Positioning of the shot in the starting position) The ball is brought into initial position after turn of the transient effects and is made stress and deformation-free by "ekill" and "ealive".

Modell parameters:

- Material properties (Young´s-Modulus, stress-strain curve)
- wire- and shot diameter
- Mesh size of wire and shot
- Shot speed
- Selection ordered or random shot initial positions

Simulation Results

First, the influence of all parameters on the residual stress profile are calculated on the basis of a single impact [5,8]. The results are summarized in **Figure 4**. The calculations were partially repeated with the 3-d model with several shot hits and showed similar dependencies from the parameters settings. After analysis of the literature by Helling [6] maximum achievable residual stresses are 60 … 80% of the yield stress, FEA-simulations calculate up to 200% of the yield stress of the workpiece material.


a) b)

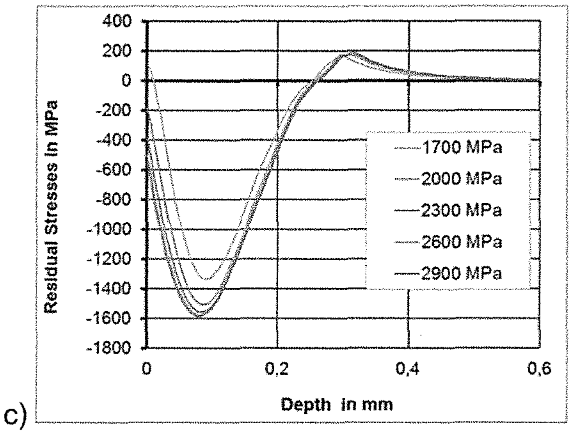

c)

Figure 4: Summary of the effects of influencing parameters (default parameter:

d_W=4mm; d_S=0,6mm; v_S=60m/s; Mat_S = 2,5 MPa;
Mat_W = 1800 MPa)
a) variation of wire diameter d_W (0,2 ...1,5 mm)
b) variation of shot velocity v_S (20 ...150 m/s)
c) variation of sthot strength Mat_S (1700...3000 MPa)

The calculated results are indeed in the range of the values reported in the literature (cp. [6]), they are too high compared to measured residual stress profiles by X-ray about a factor of approximately 2 (cp. **Figure 5**). The zero crossing of the calculated residual stresses (change of pressure to tensile stress in relation to the wire surface) agreed quite well with the measured residual stress profiles.

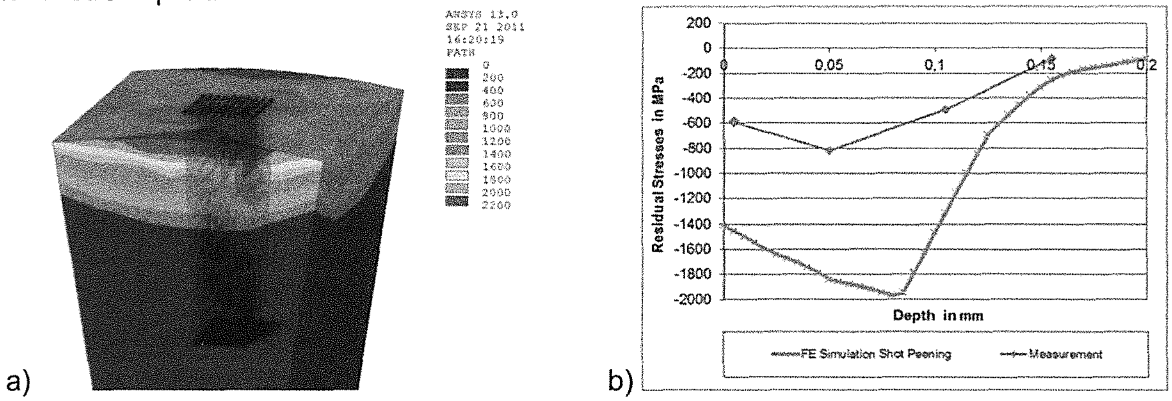

a) b)

Figure 5: Simulation results of the three-dimensional model for wire diameter 3mm; shot diameter 0,4mm; impact speed 80m/s; 13 shots on an area of about 0,3*0,3mm²: a) Stress plot with 100 postprocessing pathes; b) Comparision to measurement

Evaluation of Results of the Residual Stress Calculations

A residual stress state is characterized by a mechanical balance of the residual stresses. To measure the depth profile of residual stresses by X-ray the wire surface must be gradually removed by an etching process. The equilibrium of the residual stresses is disturbed by the removal of the wire surface by electrochemical polishing. Due to stress redistribution results a new balance state with changed residual stresses. A publication confirms this process [6]. Thereafter, the maximum residual stress reduced by the stepwise removal of the wire surface by etching by about 60% compared to the state before etching.

Simulation of Residual Stress Measuring (Stepwise Etching)

For simulation of the residual stress measurement process, it is necessary to remove the wire surface gradually. The model then provides each of the residual stress states at the wire surface in the measurement spot. Therefore, the respective wire elements were set residual stress free via Ansys command "Ekill". The resulting residual stress state in the remaining wire elements is calculated. By gradually "switching off" of the surface elements, the residual stresses are moved in the direction of the wire axis. **Figure 6** shows the resultant residual stress profile, wich is now directly comparable with the results of residual stress measurement by X-Ray. This results are in a very good conformity between simulation and measurement. The measurements were carried out at TU Ilmenau.

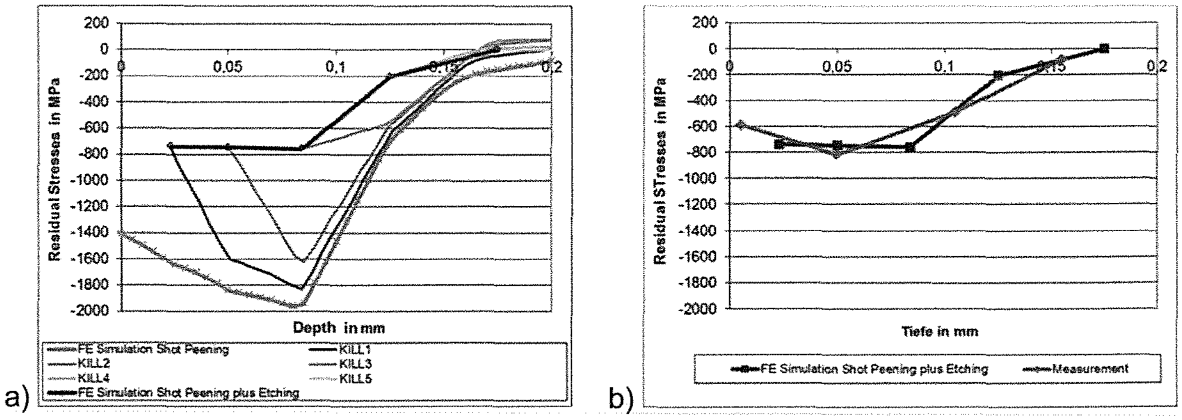


Figure 6: Results of the simulation of the residual stress measurement
a) Comparison of shot peening simulations with and without subsequent simulation of residual stress measurement (stepwise etching). b) Comparision of simulation results and X-Ray measurement results (Parameters of the simulation cp. **Figure 4**)

The presented FE modules are programmed parameterized (Ansys Parametric Design Language) and were integrated into the user interface of the FE-Springprocessor by using the Ansys User Interface Design Language [3][8]. The related input masks permit a user-friendly initialization of the parameters.

Principle of Local Fatigue Strength

The life time of a dynamically loaded component depends on the applied loads (forces, torque) and the resulting stresses in the material, such as mean stress and stress amplitude. The relationship between the tolerable stress amplitude and the mean stress is described by the mean stress sensitivity. In principle, tensile mean stresses have negative and pressure mean stresses have positive effects to the tolerable stress amplitudes. Similar to the mean stresses, the residual stresses have a positive or negative effect on the dynamic strength of the component. The influence of the residual stresses is defined by the residual stress sensitivity m and is theoretically between $0 < m < 1$ and practically between $0 < m < 0.38$ [7].

The superposition of the allowable stress amplitude without residual stresses (σ_a^M) as a function of the mean stress, and the locally available residual stress (σ^{ES}) can be calculated using Equation 1.

$$\sigma_a^{M,ES} = \sigma_a^M - m \cdot \sigma^{ES} \qquad (1)$$

It follows the curve of the local fatigue strength ($\sigma_a^{M,ES}$).
The curve of the local fatigue strength thus results from the residual stress profile and a material strength parameter for dynamic loads. The amount of material strength characteristic value depends on the required number of load cycles (Wöhler curve).
Due to the described relationships, a correlation between the curve of the local fatigue strength and the number of load cycles results is given.

The method permits the estimation of the tolerable number of load cycles of the shot peened spring by examining the tolerable number of load cycles of a sample spring without residual stresses (much lower experimental effort) and additional measurement of residual stresses of a shot peened sample spring [2]. By this approach, the experimental effort (test period) can be reduced down to about 1/10 The results can differ by a factor of 2 [2].

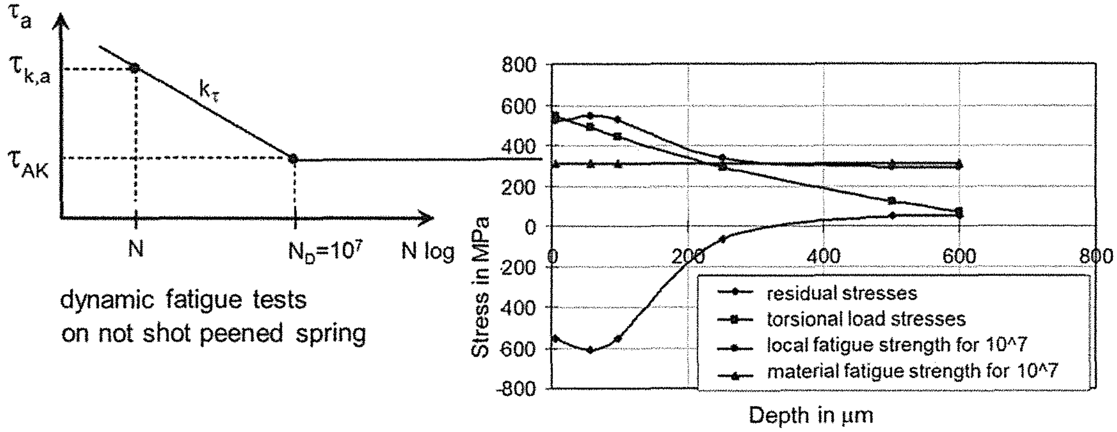


Figure 7: Estimation of tolerable load cycles by using the principle of local fatigue strength

Discussion and Conclusions

The durability of dynamically loaded springs is determined not only by the load stresses but also very much by the existing residual stresses. A life time simulation without consideration of the residual stresses is therefore not possible. This paper describes FE modules which permit the simulation of residual stress profiles caused by the production step shot peening. These were validated on residual stress measurements and show very good results. The modules were developed in Ansys, are built completely parameterized and can be used very easy via input masks. Also for the further manufacturing processes of helical compression springs additional FE modules were developed. To be mentioned here is the simulation model for the tempering process after shot peening, which leads to the smoothing of the residual stresses at the surface. By using these FEA models the development process of dynamically loaded springs can be shortened, one procedure is the described method for calculating the local fatigue strength. Future work is concerned with the study of the influence of the roundness of the shot on the residual stress profile and the surface roughness of wires.

References

[1] Bacher-Höchst, M.; Haydn, W.; Auweder, G.: Federn in der Kraftfahrzeugzulieferindustrie – Anforderung und Auslegung. DVM-Tag 2002. Federn in der Fahrzeugtechnik. Tagungsbd.,S. 99-108

[2] Kletzin, U.; Reich, R.: Lebensdauervorhersage für Schraubendruckfedern. Abschlussbericht AiF-Projekt IGF 15747 BR (2009)

[3] Kletzin, U.: Finite-Elemente-basiertes Entwurfssystem für Federn und Federanordnungen. Dissertation TU Ilmenau, 2000

[4] Weiß, M.; Geinitz, V. u.a.: Ermittlung von funktions- und fertigungsrelevanten Federdrahtkennwerten (E- und G-Modul). Abschlussbericht Forschungsthema: AiF 14306 BR (2007)

[5] Winkler, M.: FEM-Simulation des Kugelstrahlprozesses an Federstahldrähten. Masterarbeit TU Ilmenau (2010)

[6] Droste gen. Helling, C. (2000). Numerische Untersuchungen zum Kugelstrahlen. Dissertation, Universität Siegen.

[7] Macherauch. E.; Wohlfahrt, H.: Ermüdungsverhalten metallischer Werkstoffe, 1985

[8] Kletzin, U.; Winkler, M.: Finite Elemente Simulation des Kugelstrahlens von Federstahldraht, CADFEM Users Meeting Stuttgart, 2011