Data Based Manufacturing Simulation

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Abstract

The fatigue strength of spring-hard components is significantly influenced by the manufacturing process. According to the FKM [1] guideline for springs, it is possible to evaluate the fatigue strength of such components, whereby manufacturing process parameters such as shot peening, heat treatment and the residual stresses induced by the manufacturing process play a crucial role. Residual stresses that are induced during the manufacturing process have a direct effect on the stress distribution and thus on the fatigue life of the components. However, the exact determination of these residual stresses is associated with considerable challenges, as detailed and time-consuming manufacturing simulations are usually required for this. In order to reduce this effort, an innovative approach was developed that efficiently and precisely determines the process-induced residual stresses. This method is based on performing a large number of non-linear calculations in order to generate a broad database of residual stresses in round wires after the coiling process. Based on this data, a convolutional neural network was trained that can precisely predict the stress profiles in the wire cross-section after coiling. The input parameters used in the computations include the spring geometry and the material class of the spring-hard materials. The output of this surrogate model is the stress state in the wire cross- section and thus provides a reliable basis for taking the residual stresses into account in the fatigue prediction. A significant benefit of this method is the possibility of combining this process step with other manufacturing processes, such as shot peening and heat treatment, and also taking their influence on the residual stress distribution into account. This creates a complete view of the process-induced residual stresses along the entire production chain. The method presented allows a more efficient and comprehensive consideration of residual stresses when determining the fatigue strength of spring-hard components. This not only improves the accuracy of fatigue strength evaluations, but also enables the manufacturing processes to be optimized regarding the fatigue strength and durability of the components. This approach therefore represents a significant advance in the field of fatigue strength analysis and optimization.

1. Importance of residual stresses for fatigue life calculation

Residual stresses play a decisive role in the fatigue strength of components. They influence the local stress distribution and can have either harmful or beneficial effects. Compressive residual stresses have a crack-inhibiting effect and increase the fatigue life, while tensile residual stresses promote crack formation and reduce fatigue strength. The targeted introduction of residual compressive stresses through processes such as shot peening, can significantly extend the fatigue life of mechanical components. Precise analysis and control of residual stresses is therefore essential for optimizing the fatigue resistance of technical components.

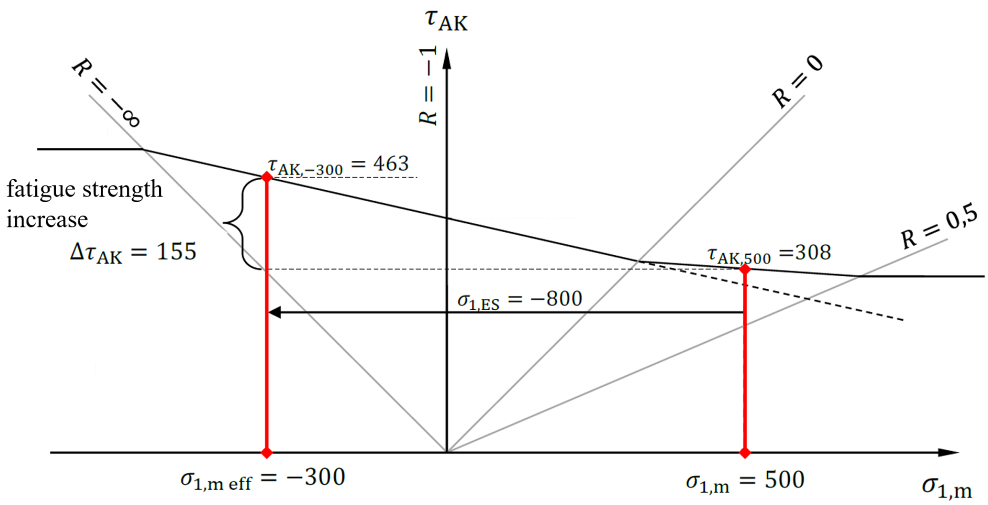

Figure 1: Mean-stress displacement on a spring [2]. Representation in the Haigh diagram in direction of the 1st principal stress. Due to the superposition of load- and residual stresses, the allowed stress amplitude increases from 308 MPa to 463 MPa.

Figure 1 shows the increase in the permissible stress amplitude due to the influence of residual stresses using shot-peening process. However, it is not only this process step that influence the fatigue strength caused by residual stresses, but also the entire manufacturing process, starting with the spring coiling process.

2. Development of a neural network model for the prediction of residual stresses

2.1 Numerical calculations to create a residual stress database

In order to analyse the effects of the coiling process on the resulting residual stresses in spring-hard wires, numerous non-linear (geometry, contact, material) calculations were performed. For this purpose, a parametric model was set up that allows typical spring geometries to be created (cf. Figure 2).

These calculations are based on the finite element method (FEA) and take into account different material grades, strengths and, of course, spring geometries. Various parameters such as wire diameter, coil diameter, pitch angle and material properties were systematically varied in order to generate a comprehensive database.

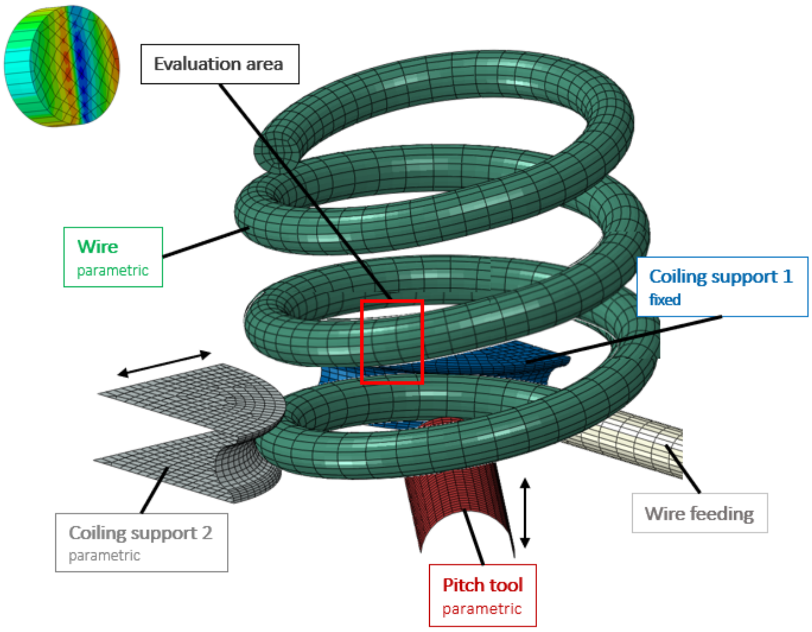

Figure 2: Parametric FEA model used for generating the residual stress database.

The implicit numerical simulations show that the residual stresses are strongly dependent on the geometry and, of course, the nonlinear mechanical properties of the material (including strain hardening). For example, a smaller spring index generally leads to higher residual tensile stresses on the inside of the coils; the stress distribution with a high pitch exhibits a complex superposition of residual stresses from torsion and bending. In addition, hardening effects and springback phenomena also have a significant influence on the resulting stress distributions.

2.2 Training of a Neural Network (NN)

Based on the created database, a Neural Network (NN) was developed, which is able to predict the residual stress distribution in the wire cross-sectional area. These approaches have proven to be powerful in many areas of data analysis, especially when it comes to recognizing complex patterns in multidimensional data.

The following input parameters were used to train the NN:

- **Geometry:** spring index, pitch

- **Material:** material grade, strength

The output values of the model are the residual stresses within the wire cross-section (cf. Figure 3). To maximize model accuracy, the network was trained with an extensive data set generated from several hundred FEA simulations.

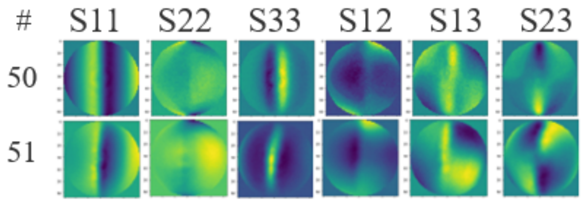

Figure 3: The stress tensor invariants form the output of the neural network.

The NN was validated by comparing the predicted stress distributions with numerical reference values. This showed that the model is capable of predicting the residual stresses with high precision. The mean absolute error between prediction and numerical simulation was in the order of 50 MPa, which is sufficiently accurate for technical applications and therefore suitable for real-time predictions and decision-making.

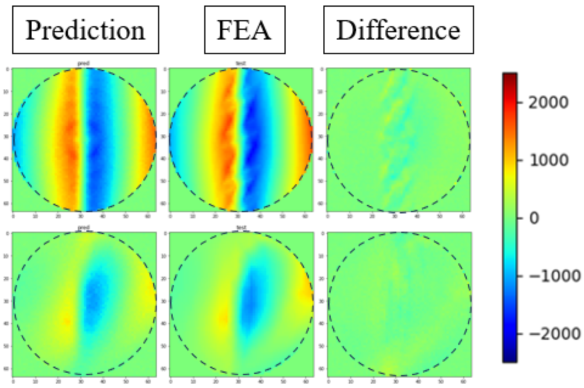

Figure 4: Comparison of the predicted coiling stresses and the ground truth (FEA).

3. Integration of the method into fatigue strength assessment and production optimization

3.1 Combination with other manufacturing steps

A major advantage of the approach presented is that it does not have to be considered in isolation but can be seamlessly integrated into the entire spring manufacturing process chain. In particular, the combination with other manufacturing steps such as shot peening and heat treatment offers great potential for optimizing fatigue strength.

Heat treatment: The resulting stresses from the coiling process can be further influenced by targeted heat treatment processes as seen in Figure 5. A more favourable stress distribution can be achieved through a model-based adjustment of the process parameters, which reduces the risk of stress concentrations.

Shot peening: This process generates additional residual compressive stresses on the component surface, which inhibits crack propagation and increases fatigue life. The neural network predicts the production history and enables the specific consideration of the shot peening effects on the residual stresses.

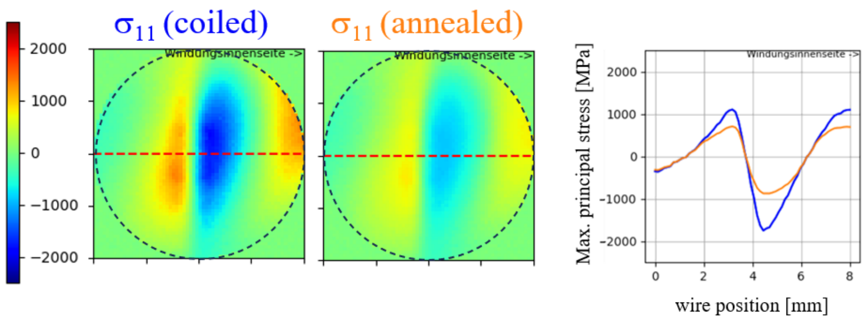

Figure 5: Predicted residual stresses of the wire cross-section (left). Stress distribution with subsequent heat treatment (middle). Stress profile with and without heat treatment (right).

3.2 Improving fatigue life predictions

The ability to precisely determine the process-induced residual stresses has far-reaching effects on the accuracy of fatigue life calculations. The FKM guideline for springs already takes into account the effect of residual stresses, but this is often done on the basis of simplified assumptions [1]. The method presented here allows realistic stress conditions to be incorporated into the calculation, which significantly improves and accelerates the predictions.

In addition to improved strength assessment, the method opens up new possibilities for the targeted optimization of manufacturing processes. For example, the neural network can be used to identify the process parameters that lead to the most favourable residual stresses for a given spring geometry and material grade. This enables data-based process optimization, which increases both component quality and production efficiency.

4. Extended modelling of the residual stress distribution: Stress mapping

Up to now, the individual prediction of residual stress has been presented by specifying geometry and material. This method works efficiently and precisely but is limited to individual cross-sections.

For springs with a complex geometry, such as variable coiling pitch and spring index, it is necessary to obtain a complete description of the residual stress state over the entire spring geometry. This allows load simulations to be carried out considering the residual manufacturing stresses.

An effective mapping strategy is essential for this in order to transfer the predicted individual cross-sectional stresses to the entire component with a complex coiling pitch.

For this purpose, a mapping tool was developed that allows sweep-capable components - as is the case with wire components such as springs - to be assigned the calculated residual stresses depending on the prevailing pitch structure and output as an Abaqus input file (see Figure 6). This allows further calculations to be performed, considering the complete manufacturing history.

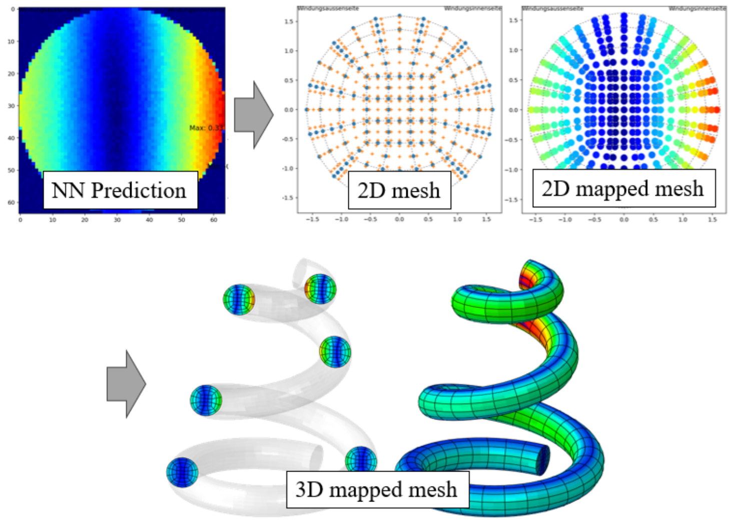

Figure 6: Workflow to map the complete predicted residual stress state by the neural network on a complex sweepable 3D body to perform further FEA calculations considering the manufacturing history.

5. Conclusion and outlook

The method presented for determining the process-induced residual stresses in spring-hard components represents a significant advance in fatigue strength assessment. By combining numerical simulations with machine learning, a powerful tool has been developed that enables rapid and precise prediction of stress distributions, especially in wire parts.

The possibility of integrating these stresses into the fatigue calculation and process optimization opens up new potential for improving component quality and fatigue life.

Experimental validation of the predicted stress states using measurement methods such as the X-ray diffraction method is currently in progress.

Overall, it is clear that data-driven approaches in manufacturing technology have great potential for innovation and can make an important contribution to the further development of fatigue strength analysis and component design.

6. References

[1]
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