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Inverse modelling approach in 3-point bending for elasto-plastic material parameter identification of thin spring steel

C Mertin, K Huse and G Hirt

Institute of Metal Forming, RWTH Aachen University, Intzestr. 10, 52056 Aachen, Germany

mertin@ibf.rwth-aachen.de

Abstract. Under process conditions such as bending of flat wire made from high strength spring steel, the occurring strains are many times higher than the maximum strains determined from uniaxial tensile tests. To determine the elasto-plastic material behaviour of high strength spring steel (X10CrNi18-8), an inverse modelling approach using a simple testing method is presented. A 3-point bending test with the resulting force-displacement measurements is used for the inverse analysis. The inverse approach is used for determining the Young's modulus and hardening parameters of the Ludwik-Hollomon's law for bending of high strength spring steel. FE simulations with the optimised material data meet the experimentally measured punch forces during bending. The optimised material data considerably enhances the springback prediction.

1. Introduction

For the electrical industry, springs made from high strength flat wire with distinct elastic properties are formed by multi-stage bending processes. The used materials, i.e. spring steel, are characterised by a brittle material behaviour in terms of high yield stress combined with low ultimate elongation. The occurring strains in bending processes of those materials are many times higher than the maximum strains determined in commonly used standard tests, e.g. tensile tests. Furthermore, the stress profile during bending differs from that in tensile tests. In order to determine the material properties for the required level of strain in the Finite Element Method (FEM) of bending processes, an inverse modelling approach by means of a 3-point bending test is presented.

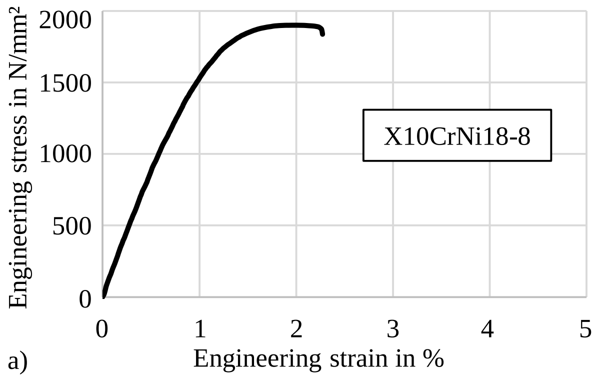
The basic principle of inverse modelling is to optimise input parameters iteratively by minimising a cost function, e.g. least squares method, which evaluates the difference between the experimental and the simulated response of a physical system. One advantage of this inverse approach is that the material parameters are determined under similar load conditions as in the manufacturing of the components. Yoshida et al. and Eggertsen et al. determined the Bauschinger effect in cyclic bending tests using an inverse approach [1,2]. Antonelli et al. used air-bending tests to determine elasto-plastic material parameters of various steel grades without depicting details of the inverse algorithm [3]. Mendiguren et al. determined material data in v-bending of two sheet materials with thicknesses of 1 mm and 1.5 mm and compared it to material data from tensile test. The results show that material data from tensile test are not adequate to predict the punch force in v-bending [4].

This research discusses an inverse modelling approach for the material parameter identification of high strength spring steel. The inverse algorithm is used to optimise elasto-plastic material parameters by minimising iteratively the deviation of the measured and simulated punch forces. The determined material behaviour is evaluated by comparing the simulated springback angles to experimental results and simulations using extrapolated tensile test data.

2. Material and methods

2.1. Materials

The analysed material is a flat wire made from high strength spring steel (X10CrNi18-8) with a thickness of 0.5 mm and a width of 4.8 mm. Figure 1 a) shows a stress-strain diagram from spring steel determined in tensile test. The ultimate elongation is 2.4 % with an elastic amount of approximately 1 %. The tensile strength is about 1900 N/mm². Due to the steep rise of the engineering stress, the initial yield strength is hard to determine from tensile test data, while $R_{p0.2}$ overestimates the initial yield strength.



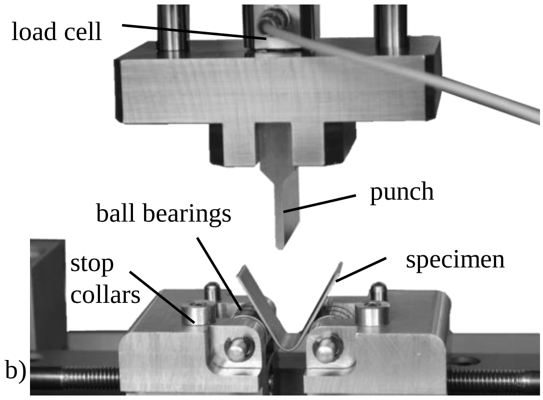


Figure 1. a) Stress-strain diagram from high strength spring steel determined in tensile test; b) experimental set-up of the 3-point bending test used for the inverse approach.

2.2. 3-point bending experiment

The 3-point bending tests were performed on a servo-hydraulic testing machine. Figure 1 b) shows the experimental set-up of the 3-point bending test. The punch radius is 1 mm and moves with a constant velocity of 1 mm/s. The die consists of ball bearings with a radius of 5.5 mm to ensure a minimal friction between die and specimen. For all experiments, a die width of 20 mm and a tool path of 10 mm are used. The force is measured at the centre and vertically to the surface of the specimen. Stop collars ensure a correct positioning of the specimen. The force is measured with an accuracy of ±1 N.

2.3. Finite Element model

The 3-point bending test is simulated with the FE code LS-DYNA. The implicit solver is used for both forming simulation and springback simulation. The tools are considered as rigid bodies. The sheet is discretised using fully-integrated shell elements, which are accurate in springback prediction [5]. The tool displacement is described by the measured displacement-curve from the servo-hydraulic testing machine to minimise the error during the acceleration and deceleration.

3. Inverse modelling approach

3.1. Material model

The Young's modulus basically describes the elastic material behaviour. A sensitivity analysis showed that the Poisson ratio has no considerable effect during bending and therefore, a constant value from literature of 0.3 is used. The plastic material behaviour in terms of the true stress – true strain curve is described by the Ludwik-Hollomon equation (1) and assuming the von Mises yield criterion:

$$\sigma(\varphi) = \sigma_0 + K\varphi^n \tag{1}$$

where σ is the yield stress, φ is the plastic strain, K is a material constant and n is the hardening parameter.

3.2. Inverse algorithm and parameter identification

For the inverse modelling approach, the FE-model was coupled with an optimisation algorithm which is available in the commercial software MATLAB®. The least squares method combined with the Levenberg-Marquardt algorithm is used. Boundary conditions are set to avoid local minima and stabilise the identification algorithm. Force-displacement curves from the 3-point bending experiments are used as reference values. The cost function of the least squares method is defined as:

$$c(\boldsymbol{\rho}) = \sum_{i=1}^{n} \left(F_i^{exp} - F_i^{num}(\boldsymbol{\rho})\right)^2 \tag{2}$$

where F^{exp} and F^{num} are the measured and simulated bending forces, $\boldsymbol{\rho}$ is the target vector of the material parameters and n is the number of reference values.

The proposed identification strategy is used to optimise the elastic material parameter and plastic material parameters separately. The Young's modulus (E) is calculated using the elastic region of the force-displacement curve in the beginning of the experiment. The hardening behaviour in terms of the Ludwig-Hollomon parameters are determined using the complete data set from the force-displacement curves. The target vectors $\boldsymbol{\rho}_{elast}$ and $\boldsymbol{\rho}_{plast}$ for the separated approach are defined as:

$$\boldsymbol{\rho}_{elast} = [E], \quad \boldsymbol{\rho}_{plast} = [\sigma_{yo}, K, n] \tag{3}$$

4. Results and discussion

Table 1 shows the start values used for the optimisation algorithm and the calculated parameters of the target vectors $\boldsymbol{\rho}_{elast}$ and $\boldsymbol{\rho}_{plast}$. For the optimisation of the elastic material behaviour, a total of 7 iterations, which result in 16 FE-simulations, are needed. The plastic material parameters are determined within 20 iterations, which are 84 simulations using the Levenberg-Marquardt algorithm. Using the start values, the cost function $c(\boldsymbol{\rho})$ of the least squares method of the target vector $\boldsymbol{\rho}_{plast}$ shows a sum of 642. The optimised material parameters of $\boldsymbol{\rho}_{plast}$ lower the result of the cost function to 33. The comparatively high end value of the least squares results from noise of sliding contacts between the sheet and the die in the FE-model.

Table 1. Calculated material parameters from high strength spring steel.

Material parameter	Unit	Start value	Determined value
E	N/mm²	140,000	170,660
σ_0	N/mm²	1,250	1,157
K	-	1,000	939
n	-	0.10	0.134

The calculation of the Young's modulus is stable by using a minimum of four reference values during the elastic loading to avoid errors resulting from noise of the force measurement. The optimised value of the Young's modulus is independent from the choice of the start value. The optimised values of the Ludwik-Hollomon parameters are dependent on the start values due to correlation between the parameters. Start values of extrapolated tensile test data support the optimisation with respect to material data that meet the bending experiment. Furthermore, a mutual balancing of the parameters is minimised. However, the result of $c(\boldsymbol{\rho})$ is not necessarily the global optimum. An iterative adjustment of the start values is necessary to avoid local minima and to receive a global minimum in the least squares method. Using underestimated values from extrapolated tensile test data and overestimated ones facilitate the choice of start values.

Figure 2 shows the force-time curve of the 3-point bending experiment compared to simulations with material data from tensile tests and those from the inverse modelling approach. Material data from tensile tests overestimate the bending force in 3-point bending of spring steel by up to 10 %. During bending, a characteristic stress distribution occurs in the cross section of the bending zone – compression to tension. Material data from the inverse modelling approach meet the experimental data. To model the load conditions during bending of high strength flat wire, enhanced material data for numerical investigations should be used.

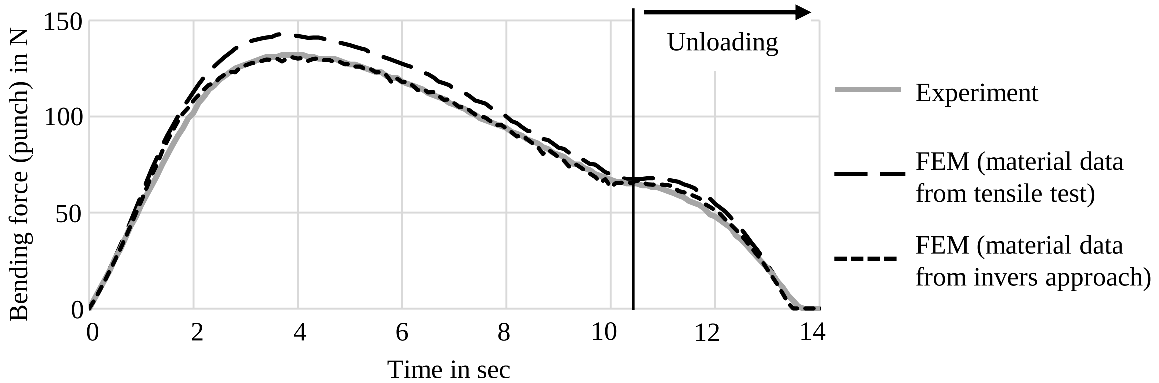


Figure 2. Force-time curves of the bending experiment compared to those from FE-simulations with material data from tensile test and material data from the inverse modelling approach.

To evaluate the quality of the optimised material data, springback angles from the bending experiment are compared to those from FE-simulations using material data from tensile tests and material data from the inverse modelling approach. The experimental and simulated springback angle of the bending tests are summarised in table 2. The bending angle of 128° results from a tool path of 10 mm. Using material data from the inverse modelling approach improves the accuracy of the springback prediction in the FEM of bending by approximately 2°.

Table 2. Experimental and simulated springback angles of high strength spring steel.

	Bending angle	Angle after springback	Deviation to the experiment
Experiment	128°	93.7°	-
FEM (material data from tensile test)	128°	90.0°	3.7°
FEM (material data from inverse approach)	128°	92.2°	1.5°

5. Conclusion
The inverse modelling approach in 3-point bending is suitable to determine the elasto-plastic material behaviour in terms of the Young's modulus and Ludwik-Hollomon law of high strength flat wire made from spring steel. The introduced inverse modelling approach is sensitive to the choice of start values. Start values of extrapolated data from tensile tests improve the quality of the calculation. Simulations using the optimised material data meet the measured punch forces of the 3-point bending experiments. Furthermore, the optimised material data enhance considerably the accuracy of the springback prediction in the FEM during bending of spring steel.

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