Parameter Identification for Forming Simulation of High-Strength Steels

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1 Introduction

In the past most of forming-manufacturing processes were mainly based on trials. For cost effective production, simulation is a reliable tool for getting good predictions before starting with manufacturing. The number of plastic deformation steps during one manufacturing process is mostly more than one. However the load direction of all the deformation steps is in the same way. A few applications are dealing with an alternating direction of the forming loads. These cases are affected by hardening and/or softening effects. Additional to this belonging some special effects like Bauschinger-Effect are relevant as well. Knowing of these effects and their range are mandatory for planning and simulating forming processes.

2 Problem and target

Based on a research project the University of Aalen is dealing with massive deformation of prismatic beams made of high-strength steels. The deformation of half-finished products consists of more than one deformation step. In this case the load direction of the sequent deformation steps is alternating; in detail the direction of second deformation is in the opposite to the first deformation step. Due to this, hardening effects occur. In deed first investigation shows that yield stress of the second plastic deformation is lower than yield stress of the first plastic deformation with opposite deformation direction. This effect is called Bauschinger-Effect [1]. Classical tensile-pressure-trials are a common method to analyze the Bauschinger-Effect. Unfortunately based on several reasons the tensile-pressure-trials are not very suitable for high-strength steels. On the one hand the availability of half-finished products is limited related to geometrical dimensions. On the other hand the chipping of this material is very restricted based on the high yield stress. Additional to this, milling influences the residual stress situation inside the specimen.
This report shows a new approach for getting the needed material data via trials compared to classical tensile-pressure trials. The test results will be used for optimization of material cards with LS-Opt. After showing the method itself, conclusion with results and outlook will follow.

3 Investigation methods

3.1 General

Material and geometry of specimen will be described at first. Accordingly the description of trials will follow. Optimization process in LS-Opt will be the third part of present chapter. At least a short introduction of the mathematical-analytical model will be presented.

3.2 Specimen

3.2.1 Material of investigation

The present investigation is based on high-strength spring steel 54SiCr6 (1.7102). This material is mainly used for high-stress and high-dynamic loaded parts like valve springs. Compared to classic spring steel the 54SiCr6 gets a special heat treatment after wire drawing. To get a wire without residual stress inside, oil is used for cooling after heat treatment.
Following table shows the typical material characteristics.

Characteristic	Value
Young's modulus	206,000 MPa
Poissons ratio	0.28
Yield stress	1,749 MPa
Tensile strength	2,050 MPa
Elongation at rupture	~4.5 %

Table 1: material characteristic for 54SiCr6 (1.7102)

Characteristics from table 1 are valid for circular area wire with a diameter of 4 mm - increasing of diameter leads to decreasing of yield stress and tensile strength.

Chemical composition of material 1.7102 is shown in following table.

C [%]	Si [%]	Mn [%]	P max. [%]	S max. [%]	Cr [%]
0.5 - 0.6	1.2 - 1.6	0.5 – 0.8	0.025	0.025	0.5 – 0.8

Table 2: Contents of material for 54SiCr6 (1.7102)

3.2.2 Geometry

For following trials no particular geometry of specimen is needed. The reference diameter is 4 mm. All specimen are used without milling except of cutting them from coil to avoid interactions with residual stress.

3.3 Trial description

3.3.1 Tensile-pressure trials

As described above, due to the high yield stress it is hardly possible to manufacture conventional specimen geometry from raw material without influencing of residual stresses. Alternative testing method is needed.
Due to this, tensile-pressure trials are separated into elementary tensile trials on the one hand and following additional pressure trials on the other hand by using specimen cut out of half-finished product. The testing process starts with specimen fixed by friction in tension testing machine. The length of minimum 300 mm is needed to guarantee the required friction. The brackets for fixing the specimen are manufactured with barbed hooks on clamping side. The geometry itself is based on flat cone. Due to this, the more the axial force increase the more the friction rises. Following picture shows one bracket qualitatively.

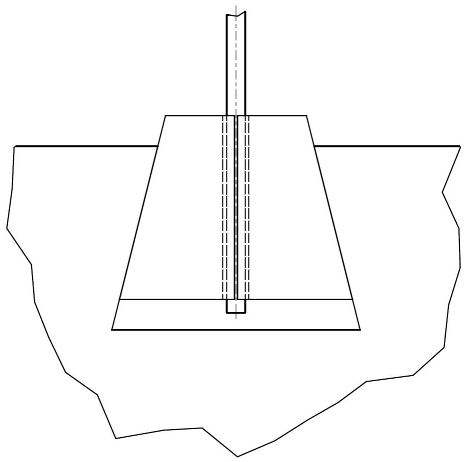

Fig.1: Tensile testing device

For getting information about Bauschinger-Effect it is needed to get plastic deformation during tensile test. To avoid collapse of material the stress has to be limited to maximum strain of 4.5%. Therefore tensile range is possible between approx. 0.85 % and ~4.5%. The border area of this range should be avoided because there will be no useful results (to close to minimum) or the risk of influencing the results by (micro-) damages of specimen is too high (to close to maximum).

After finishing the tensile test, specimen will be cut to a smaller pressure specimen. In deed the new specimen has to be cut totally out of the deformed section of tensile trial. The length of the new specimen is overall 110 mm. The fixture for doing the pressure trials is working on the principle of guided pressing. Main problem of free pressure load on this specimen buckling will occur very fast. Following picture shows the principle of guided pressure fixture.

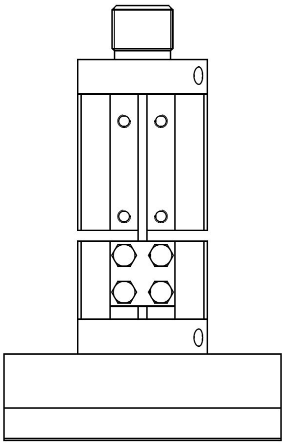

Fig.2: Pressure testing device

Due to narrow tolerances of spring steel wire, the gap between specimen and fixture hole is tight as well. To ensure a minimum of friction between specimen and fixture oil is used at all the contact surfaces.
After finishing the pressure test the resulting diagrams have to be put together. Unfortunately related to the size of specimen no additional hysteresis can be tested.

3.3.2 Bending trials

Additional to conventional tensile-pressure tests bending tests will be used for optimizing parameters as well. The *Europäische Forschungsgesellschaft für Blechverarbeitung e.V.* published a draft including a new test method to analyze hardening and softening effects at steel plates [2]. Following described test method is based on this paper.
The results of bending tests will be a force-displacement diagram contrary to tensile-pressure tests which delivers stress-strain curves. The bending testing device is shown on following picture.

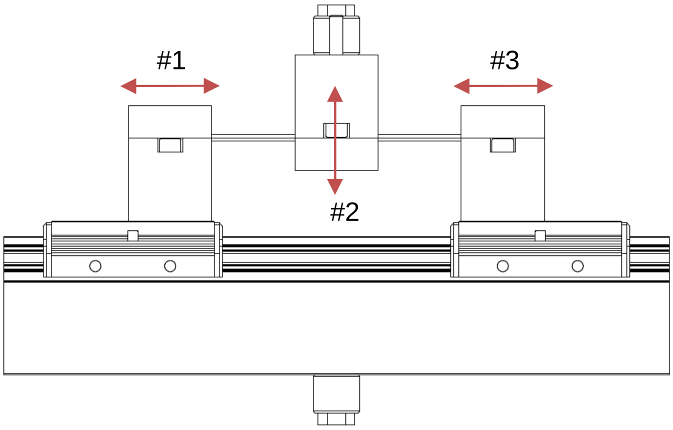

Fig.3: Bending testing device

Die specimen has to be fixed in each of the three bearing points (#1-3). The center bearing (#2), so called the oscillating bearing, will move up and down. The outer bearings (#1, #3) have no degree of freedom in vertical direction but movement in horizontal direction is possible. The movement of the oscillating bearing causes an axial force in the specimen. Therefore the outer bearings will move more closer to the center bearing the more oscillating way is used. The resulting data (force-displacement curve) are not suitable for getting classical material parameters. The results are basis for parameter identification in LS-Opt.

The test rig is installed in a Zwick tension-testing-machine. Recording of displacement is based on machine traverse position; force is measured by the load cell in the traverse.

3.4 Optimization

3.4.1 General

For simulating the forming process in LS-Dyna the knowledge of the correct material card parameters is mandatory. While using simple material cards like MAT003 parameter identification by hand is possible and a common way. For complex material cards it is hardly possible to do it in the same way. For this case a curve fitting tool is needed. LS-Opt provide a useful curve fitting algorithm.

3.4.2 Material model

Related to several investigations in the past [3] simple material models are not suitable for the recent simulation. Therefore MAT003 and MAT024 do not represent the right material characteristics. Material model MAT125 provides nearly every degree of freedom to generate the correct material behavior in LS-Dyna [4]. The material model is based on Yoshida/Uemori theorem [5].

3.4.3 Finite element model for tensile/pressure

The used finite element model is a simple cube. The deformation is based on movement of the upper four nodes. The lower nodes are fixed in force direction. The one-element-model is defined as a solid model. Used material is MAT125; additional integration points are not needed. The load is defined as follows: At starting point the cube is in default position. Afterwards tensile load by stretching the cube to maximum tension will be done. After reaching the maximum deformation the direction of load changes to pressure and the cube will be compressed. After reaching the pressure maximum (which comes up to same percentile amount as the tensile maximum based on default length) the cube will relax to the default position.
Following pictures show the finite element model and the load diagram.

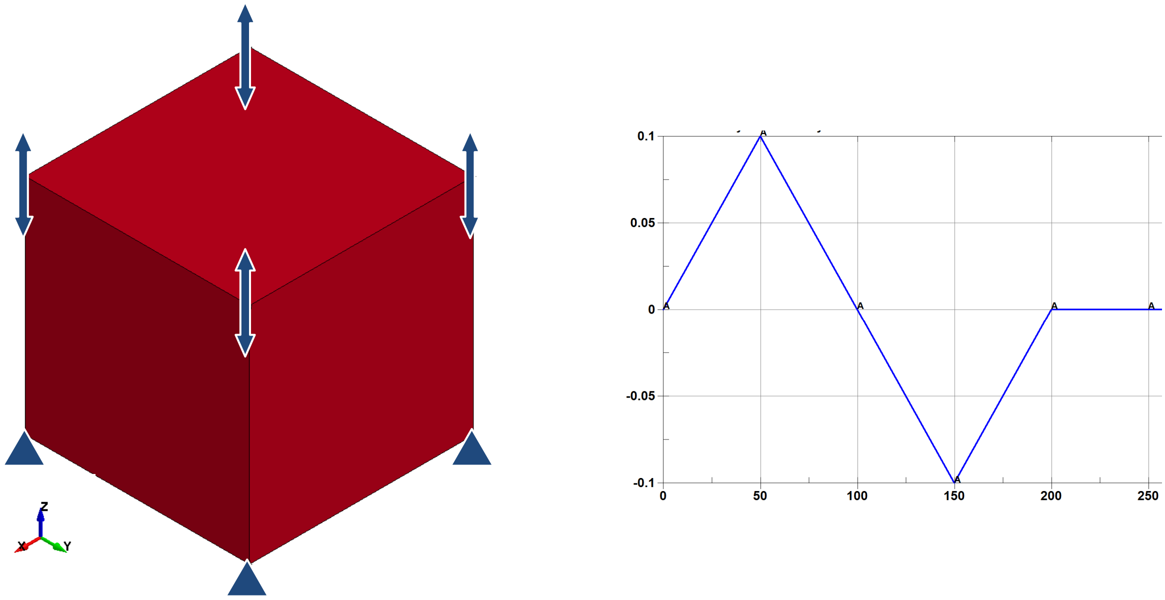

Fig.4: Optimization tensile/pressure-test model and load curve

Preprocessing will be done by analyzing the stress in force direction and deformation as well to get the stress-strain-curve.

3.4.4 Finite element model for bending

The finite element model for simulating the bending test in LS-Dyna is based on the real situation which is described in 3.3.2. Due to the double symmetric situation only a quarter-model is needed. Following graphic shows the model.

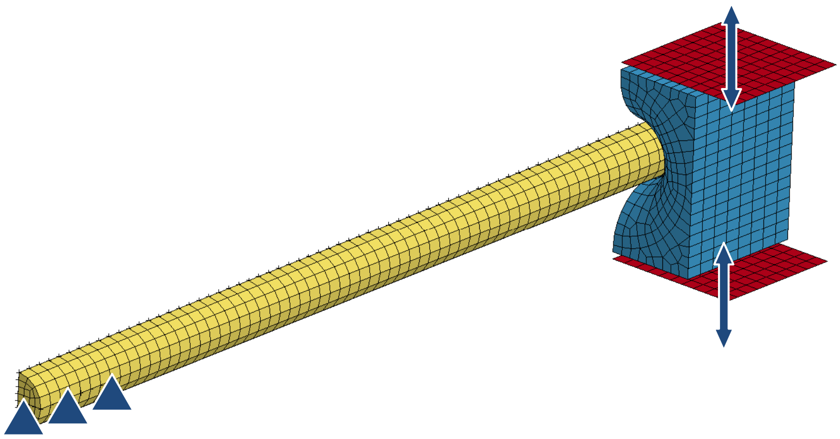

Fig.5: Optimization bending test model - LS-Opt

Following table shows relevant details for used options.

Characteristics	Wire	Bearings	Plates
Element type	Solid	Solid	Shell
Element form	-2	-2	2
Material	MAT125	MAT020	MAT020
Part of optimization	Yes	No	No

Table 3: Details of LS-Opt model

For better post-processing the oscillating bearing is fixed by two imaginary plates. The displacement in vertical direction is controlled by these plates. Due to reality the other bearing is able to move in axial direction of the specimen without friction-based forces.
Between imaginary plates and oscillating bearing a surface to surface contact area is configured. This contact delivers the force information which is needed for the force-displacement curve. The displacement in the simulation model is starting at zero position. The oscillation bearing moves to the lower extreme change direction and moves to the upper extreme with the same amount. After reaching the upper extreme the oscillating bearing moves back to zero position. The curve in figure 4 are qualitatively the same than the used curve for bending simulation.

3.4.5 LS-Opt algorithm

LS-Opt is doing a curve fitting by comparing the given curves based on trials and the calculated curves by LS-Dyna. Present investigation includes two optimizations: the tensile/pressure trials and the bending trials. Due to quarter-modeling for bending test simulation the force values in force-displacement curves have to be quartered as well. Related to material description of MAT125 following table shows the needed parameters, the chosen range and the starting point for optimization.

Parameter	Starting point	Minimum	Maximum
R	0.5	0	2
HCLID		0	
OPT		0	
CB	1	0	5
Y	1.75	1	2
SC	10	0	50
K	100	100	300
RSAT	1	0	5
SB	1	0	5
H	1	0	5
EA	150	100	200
COE	3.5	2	5
IOPT		1	
C1	2	0	5
C2	1	0	5

Table 4: Parameters for MAT125 and configuration

Ending criteria for optimization are a maximum of ten iterations or a curve matching of lower 0.01 %.

3.5 Analytical-mathematical verification model

Following introduction describes the used analytical-mathematical model for first (comparing) verification of residual stress and spring back.
For describing the stress curve of bending situation the common known material model of idealistic material behavior will be modified to a hardening material model with two lines in the plastic strain area. Following chart shows the comparison between real material behavior (based on stress-strain-curve) and mathematical modeling as described.

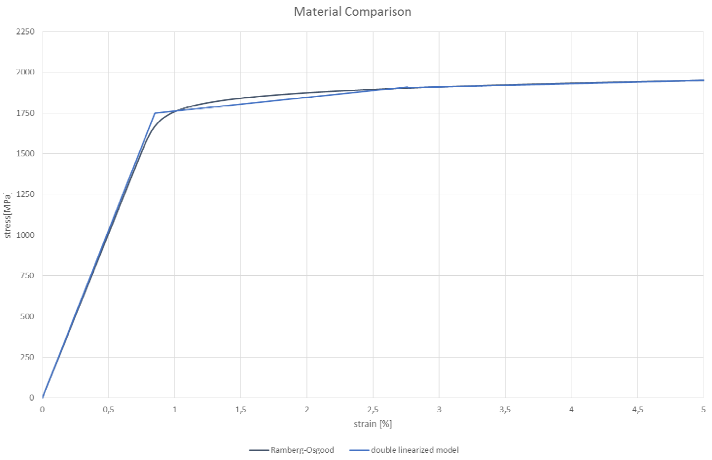

Fig.6: Mathematical material model – stress-strain curve

Following mathematical term describes the Bending moment in general.

$$M_{b,ges} = M_{b,el} + M_{b,pl} = \int_{0}^{a_1} \sigma_{el}(z) z b(z) dz + \int_{a_1}^{a_2} \sigma_{pl,1}(z) z b(z) dz = \int_{a_2}^{a_{\max}} \sigma_{pl,2}(z) z b(z) dz$$

Based on this relationship, needed information will be calculated for first comparison. Detailed description of formula and the resulting terms are not included in this article.

4 Investigation results

4.1 Tensile/pressure trials

Due to the results of tensile/pressure trials [3] several stress-strain curves with different deformation values in tensile and pressure direction are available. Following diagram shows a stress-strain curve example.

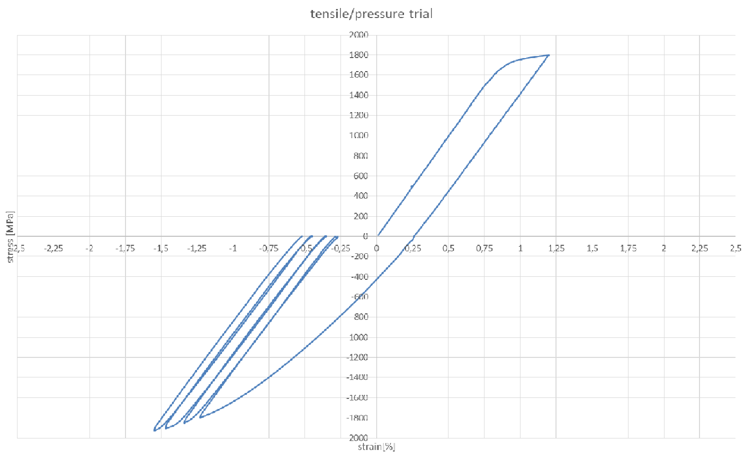

Fig.7: Tensile/pressure stress-strain-curve

Indeed the Bauschinger-Effect is clearly obvious. The yield stress point of pressure load after tension load is, compared to tensile yield stress, much lower. Detailed discussion of test results is documented in [3].

4.2 Bending trials

Compared to tensile/pressure trials there are several advantages. Bending trials are not limited by the amount of oscillation hysteresis. The only limitation is rupture of specimen. Additional the measurement equipment is fully integrated to the tension-testing-machine – no additional measurement equipment is needed. No additional manipulation of specimen is needed during test itself.

The bending trials have been done for several load steps repeating times to increase the quality of results. Following diagram shows an example with oscillation of ± 9 mm.

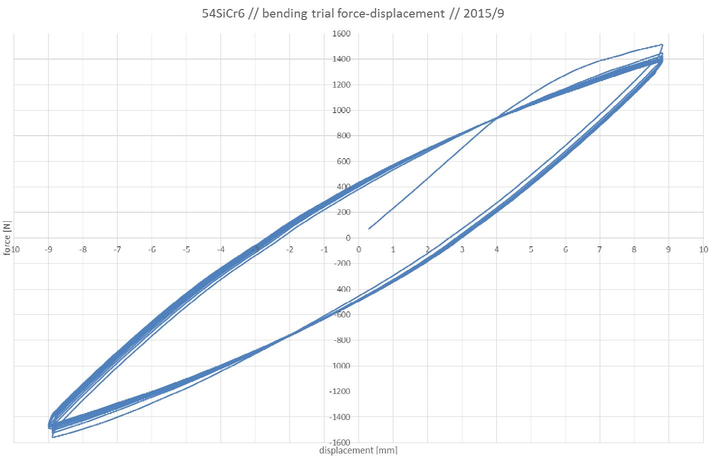

Fig.8: Bending force-displacement-curve

4.3 Curve fitting with LS-Opt

After getting trial results the data are used for curve fitting with LS-Opt. First curve fitting is done with tensile/pressure trials. For the optimization two curves with different magnitudes from test series are used. Following diagrams show the curve fitting results for both cases stopped after ten iterations.

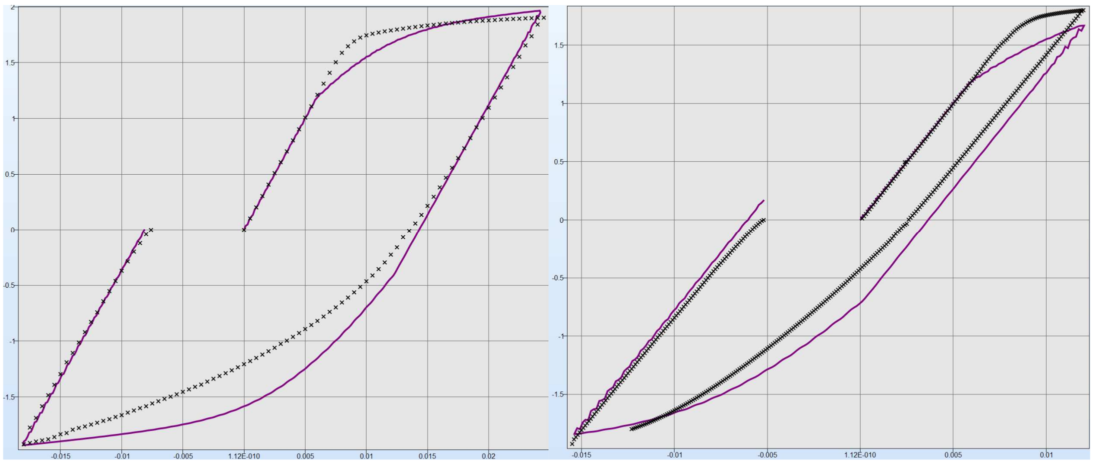

Fig.9: Optimization results – tensile/pressure trials

Additional to the first curve fitting process a second curve fitting run, based on bending test results, will be performed. Due to first optimization boundary conditions are the same. After ten iterations following results are available.

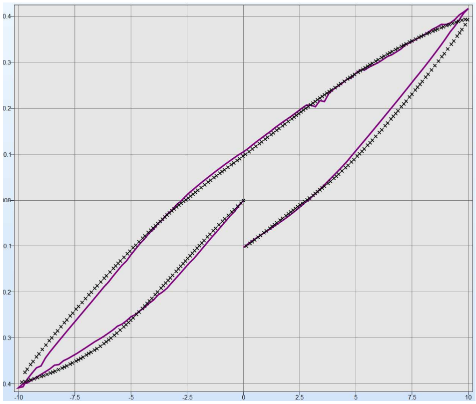

Fig.10: Optimization results – bending trials

Resulting parameters for both curve fitting optimizations are listened in the table below.

Parameter	Tensile/pressure	Bending
R	0.222	1.97604
HCLID	0	
OPT	0	
CB	2	49.4783
Y	1.18	1.25255
SC	16.92	3.38523
K	361.7	270.845
RSAT	0.7675	0.9286
SB	0.6127	-0.22895
H	0.4745	1.87225
EA	150	150
COE	3.44	3.555
IOPT	1	
C1	3.261	1.97604
C2	0.676	1.55876

Table 5: Curve fitting resulting parameters

4.4 Results of cross checking simulation

Due to different parameter results for same material, cross checking is necessary. Therefore the results from tensile/pressure optimization are used for bending simulation and vice versa. First the output of tensile optimization is used for bending simulation. Following diagram shows the result.

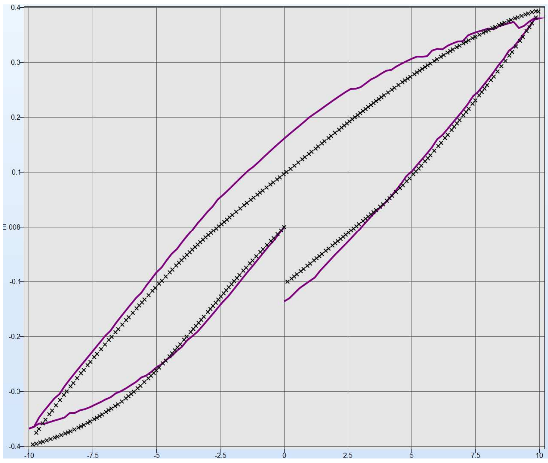

Fig.11: Cross checking – tension parameters for bending simulation

Due to first cross checking, next diagram shows the usage of bending result parameters for tensile/pressure simulation.

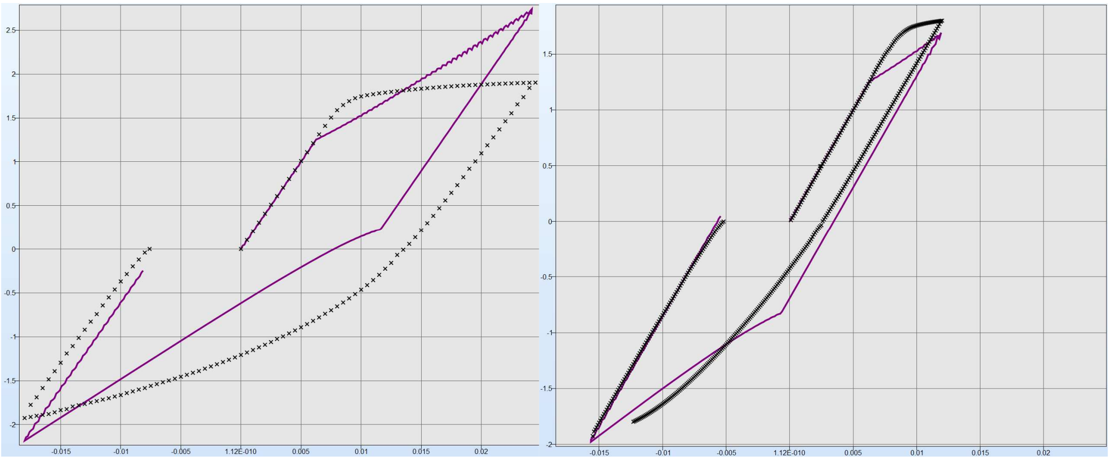

Fig.12: Cross checking – bending parameters for tension simulation

5 Results

Tensile/pressure optimization as well as bending optimization directs to realistic parameters. Numerical curve of both cases seems apparently more or less close to the trial curves to which they have to fit. The results for both trial types will be shown at first in standalone and at last the results of cross checking simulation.

5.1 Tensile/pressure optimization

The calculated parameters lead to curves which do not fit very well to the given curves from trials. Especially the yield stress points for tensile and pressure load are not suitable. Due to following restriction of the Yoshida/Uemori model the material model is not able to fit in a better way.
Following diagram shows the elementary conditions of the model.

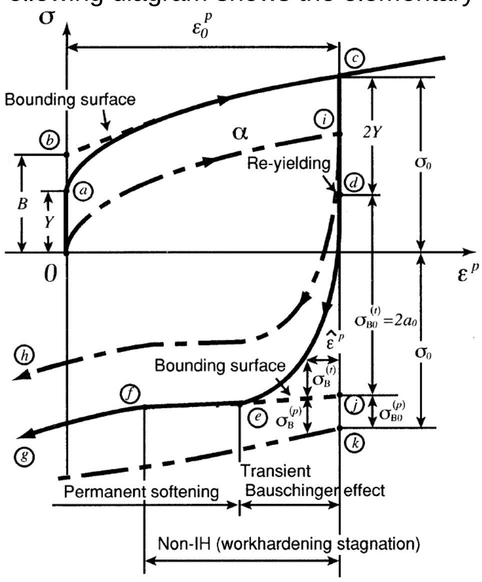

Fig.13: Yoshida/Uemori model [5]

The yield stress for the second load case, here pressure, is located at twice times of yield stress in tensile load case. This material behavior is not convenient to the material behavior from trials.

5.2 Bending optimization

Compared to the optimization of tensile/pressure trials the bending optimization fits in a quite better way to the material behavior from trials. The restriction described in the chapter before is not obvious.

5.3 Cross checking simulation

5.3.1 Tensile/pressure parameters for bending simulation

Figure 11 shows the result of using the parameters got from tensile/pressure optimization for bending simulation. Compared to figure 10 the force at yield stress point in figure 11 is lower. The percentage difference of maximum deviation equals approx. 10 %. In the area of beginning pressure load, the needed force for deformation is simulated higher than tested.

5.3.2 Bending parameters for tensile/pressure simulation

The result for this simulation is shown in figure 12. The curves of numerical simulation describe a complete different plasticity behavior of material than in reality. The gradient in plastic deformation section is several times higher than test results show.

6 Summary

In general the possibility for getting the needed parameters by curve fitting is possible. For every investigated case, especially bending and tensile/pressure load cases, parameters are identified.

Cross checking of the results is mandatory due to the big differences from one load case transferred to another one.

Related to the results, the optimization for this material will not be valid for the whole behavior. In deed the optimization has to be defined for specific boundary conditions. Especially the bending simulation is more generous than tensile/pressure simulation. This behavior is based on the high elastic zone in bending specimen. In tension/pressure cases, the whole area will plasticize after reaching the yield stress. Therefore inaccurate parameters are acts stronger.
Unfortunately LS-Dyno does not provide any material which do not use the restriction for yield stress described above. Due to this, a better parameter optimization will not be possible.

Additional the transferability from the one basic load situation to another is not possible if the parameters do not fit in total. This is based on different weighting of elastic and plastic mechanism during deformation.
Further parameter optimization of present situation will be done with following restrictions:

- Due to the real specific manufacturing process the plastic deformation is mainly located in the high deformation part (>2% deformation) of the stress-strain curve. That means the section directly after yield stress is not as relevant for the results as in other situations.
- The optimization for bending simulation will be only done with bending optimization.

7 Literature

[1] Bauschiner, Johann: "Über die Veränderung der Elastizitätsgrenze und der Festigkeit des Eisens und Stahls durch Strecken und Quetschen, durch Erwärmen und Abhkühlen und durch oftmal wiederholte Beanspruchung", Mitteilung aus dem mechanisch-technischen Laboratorium, München, 1886, 62

[2] „Ermittlung des kinematischen Verfestigungsverhaltens im Wechselbiegeversuch", Europäische Forschungsgemeinschaft für Blechverarbeitung, Hannover, 2013, 3

[3] Thomisch, Marco; Kley, Markus: „Simulation von plastischen Biegeumformprozessen unter dem Schwerpunkt der Spannungsbetrachtung", SIMPEP, Koblenz/Lahnstein, 2014, 9

[4] Livermore Software Technology Corporation: „LS-Dyna Keyword User's Manual Volume II Material Models", Version R7.0, 2013, 1154

[5] Yoshida, Fusahito; Uemori, Takeshi: „A model of large-strain cyclic plasticity describing the Bauschinger effect and workhardening stagnation", International journal of Plasticity, 2002, 26