Piotr DANIELCZYK[1], Jacek STADNICKI[2]

FEM SIMULATION OF DP STEEL SHEET STRAIGHTENING IN ROLLER STRAIGHTENING MACHINE

Streszczenie: The article describes the FEM model for simulating sheet metal straightening in a roller straightening machine. The simulation was carried out for DP780 steel with a non-linear material model of kinematic hardening. Optimal straightening machine settings were determined, taking into account curvature and residual stress after straightening.

Słowa kluczowe: sheet metal straightening, elastic-plastic deformation, FEM simulation

SYMULACJA PROCESU PROSTOWANIA STALI DP NA PROSTOWARCE WAŁKOWEJ Z WYKORZYSTANIEM MES

Summary: W artykule omówiono zagadnienie prostowania blach na prostowarce wałkowej. Do symulacji procesu opracowano dyskretny model obliczeniowy z wykorzystaniem metody elementów skończonych. Przeprowadzono szereg testów numerycznych dla blachy ze stali DP780. Wyznaczono optymalne nastawy prostowarki, z uwagi na krzywiznę i naprężenia resztkowe po prostowaniu.

Keywords: prostowanie blach, odkształcenia sprężysto-plastyczne, symulacja MES

1. Introduction

One of the leading technologies in the production of body parts of passenger cars cold-pressed from sheet metal is progressive stamping. In the stamping process, the drawpiece receives its final outline and shape as a result of many successive technological operations of cutting, forming and joining. In a large-lot production of drawpieces ─ parts of car bodies, in progressive stamping technology, the part is usually made of sheet metal which is wound on a coil and during the whole technological production process is connected to a strip which is unrolled and pulled along the die ensuring transport of the part between successive operations of the process. In the final operation of the process ─ trimming, connections between the

[1] dr inż, Akademia Techniczno-Humanistyczna w Bielsku-Białej ,Wydział Budowy Maszyn i Informatyki, pdanielczyk@ath.bielsko.pl
[2] prof. dr hab. inż., Akademia Techniczno-Humanistyczna w Bielsku-Białej ,Wydział Budowy Maszyn i Informatyki, jstadnicki@ath.bielsko.pl

part and the strip are cut. The drawpiece quality (shape-dimensional accuracy) is influenced by both the perfection of the die design as well as the quality and condition of the sheet metal from which the drawpiece is made.
When designing a die, the process currently carried out frequently using dedicated FEM programs to simulate stamping (AutoForm, PamStamp, DynaForm, etc.), designers usually assume that sheet metal before stamping is flat and has no residual stress resulting from previous technological processes of sheet production and the process of being wound on a coil. To achieve such condition of sheet metal, progressive stamping is preceded by an additional operation of sheet metal straightening which is carried out in a roller straightening machine. The scheme of straightening machine is shown in Fig. 1. Depending on the material, the sheet metal thickness h and the radius of curvature R of the sheet strip unrolled from the coil, the positioning of the upper movable rollers relative to the lower fixed rollers is set, changing at the same time the roller pitch z of the upper roller between the lower ones during straightening.

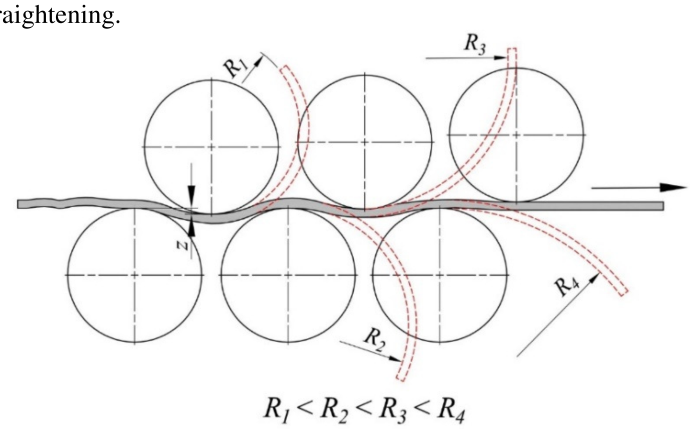

Figure 1. Scheme of sheet metal straightening in a roller straightening machine

The radius of curvature after straightening and the value of internal residual stress depend on the value of the roller pitch. In roller straightening machines most commonly used, the recommended roller pitch value is specified by a nomogram designated by its manufacturer.

2. A material model for stimulating straightening process of a strip in a roller straightening machine

It can be assumed with sufficient accuracy that giving the sheet metal a curvature with radius R as a result of being wound on a coil leads to the so-called cylindrical bending of a rectangular plate with a $b \times h$ section, for which the constitutive equation Eq. (1) expresses the relationship between stress at the surfaces in the sheet metal section and the radius of curvature:

$$\sigma_{max}(R) = E\frac{h}{2R(1-\nu^2)} \quad (1)$$

where E – Young's modulus, ν - Poisson ratio.

In order to straighten a strip of sheet metal with a radius of curvature *R,* the first set of three rollers of the straightening machine should be given a radius of curvature R_1 (roller pitch z_1) that causes stress $\sigma_{max}(R)$greater than the yield stress R_e. In the next sets of three rollers, the roller pitch should be getting smaller so that after leaving the straightener, the strip is straight and the residual stress removed. The change of stress in the sheet metal in the following sets should be carried out in accordance with figure 2. Since deformations of sheet metal during straightening are of elastic-plastic nature whereas during bending of the strip in subsequent sets of three rollers, the stress changes the sign, the sheet metal material model should take into account the hardening of the material after yielding, curve hysteresis $\sigma(\varepsilon)$ as well as the shift of the curve loop $\sigma(\varepsilon)$ caused by the Bauschinger effect.

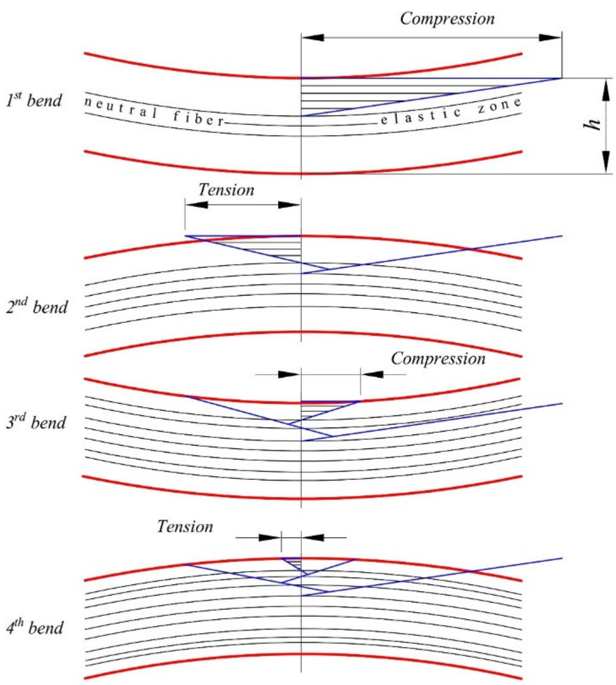

Figure 2. Change of stress in sheet metal during straightening in the following three straightening rollers

AHSS (Advanced High Strength Steel) steel sheets with a dual phase structure (martensite/bainite in the ferrite matrix) are often used for the production of drawpieces that constitute a part of self-supporting bodies of modern passenger cars.

Hardening of AHSS steel after yielding, can be described by a non-linear model of Chaboche kinematic hardening [1, 2], where the yield criterion is described by Eq. (2)

$$F = \sqrt{\frac{3}{2}(\boldsymbol{s}-\boldsymbol{\alpha}):(\boldsymbol{s}-\boldsymbol{\alpha})} - R = 0 \tag{2}$$

where $\boldsymbol{s}$ is the stress tensor, $\boldsymbol{\alpha}$ is the back stress denoting the translation of yield surface *F* caused by kinematic hardening and *R* is the size of yield surface in stress space which expands uniformly by isotropic hardening (Fig. 3). If, as in the case of straightening sheet metal in a roller straightener, the plate is bent *n*-fold in the following sets of straightening rollers, the back stress $\boldsymbol{\alpha}$ in formula (2) is the sum of components, whose increment rate may be expressed by Eq. (3).

$$\dot{\boldsymbol{\alpha}} = \sum_{i=1}^{n} \dot{\boldsymbol{\alpha}}_i = \frac{2}{3}\sum_{i=1}^{n}\left(C_i\dot{\varepsilon}_{pl} - \gamma_i\boldsymbol{\alpha}_i\dot{p}\right) \tag{3}$$

where C_i, γ_i are kinematic hardening constants, $\dot{\varepsilon}_{pl}$ is a plastic strain rate, $\dot{p}$ is accumulated equivalent plastic strain rate.

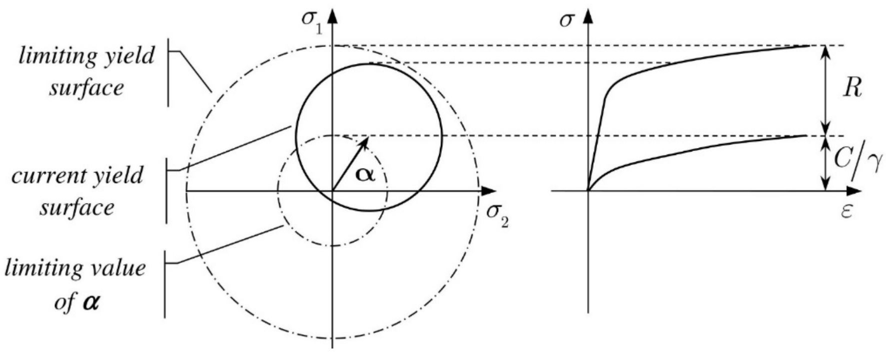

Figure 3. Scheme of the kinematic hardening material model

The evolution of back stress component α_i can be expressed by the Eq. (4)

$$\alpha_i = \nu\frac{C_i}{\gamma_i} + \left(\alpha_{i0} + \nu\frac{C_i}{\gamma_i}\right)e^{-\nu\gamma_i(\varepsilon_{pl}-\varepsilon_{pl0})} \tag{4}$$

where α_i is the magnitude of back stress component, $\nu = \pm 1$ means tension or compression, α_{i0} and ε_{pl0} are the values α_i and ε_{pl} at the beginning of the loading process and ε_{pl} is the equivalent plastic strain. The evolution of isotropic hardening curve (*limiting value of* $\boldsymbol{\alpha}$ in Fig. 3) can be expressed by Eq. (5)

$$\boldsymbol{\sigma}_{ISO} = \sigma_{SAT}(1 - e^{-bp}) \tag{5}$$

where σ_{SAT} is the saturation stress at large strain, *b* is the saturation rate of isotropic hardening stress, *p* is accumulated plastic strain.
In order to characterize the Bauschinger effect in the material model, the Bauschinger ratio r_{BE} defined in the way proposed in [3] may be employed by Eq.(6)

$$r_{BE} = \frac{|\sigma_l| + \sigma_r}{2|\sigma_l|} \tag{6}$$

where σ_l is the initial yield strength during the loading process, and σ_r is the initial yield stress in the subsequent reloading.
Values of material constants C_i and γ_i from Eq. (3) and r_{BE} from formula Eq. (6) were determined experimentally by the authors of work [4] on the basis of uniaxial tensile test and subsequent cycles in the tension/compression test. For a sheet made of DP780

dual phase steel, the straightening simulation of which is described in the next section of the article, the values of these constants are presented in Table 1.

Table 1. Constants of the DP780 kinematic hardening model

i	1	2	2
r_{BE}		0.774	
C_i, MPa	551.7	36069.5	59 794.6
γ_i,	1.0	101.5	454.1
Q, MPa		105	
b		8.9	

Fig. 4 illustratively shows the course of changes in stress and strain during bending of the strip from sheet metal in the following sets of three straightening rollers using non-linear models of kinematic hardening of the material.

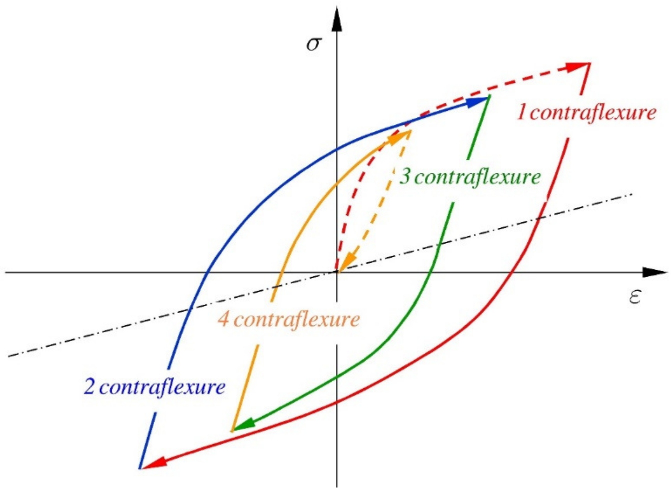

Figure 4. Illustrative course of changes in stress and strain during straightening

3. FEM model for simulating straightening

The object of analyses is a straightening machine with four sets of three straightening rollers, which is schematically shown in Fig. 5. The sheet metal strip unrolled from a coil is fed to the set of straightening rollers by a pair of driven input rollers and then goes through the next set of three rollers where it is bent ─ straightened. With this machine, the operator can adjust the roller pitch z_1 in the first set and the roller pitch z_4 in the last set of three rollers. The roller pitches in the other sets result from these settings. In order to perform a straightening simulation, a parametric three-dimensional geometric model of a straightening roller set and a strip of sheet metal with initial curvature were built and later used to build the FEM model. Due to the efficiency of numerical calculations, the width of the model was set at ten thicknesses of straightened sheet metal (for thickness h = 1.5 mm, the width of the model was 15 mm), which ensured that the conditions of cylindrical bending of a rectangular plate were met.

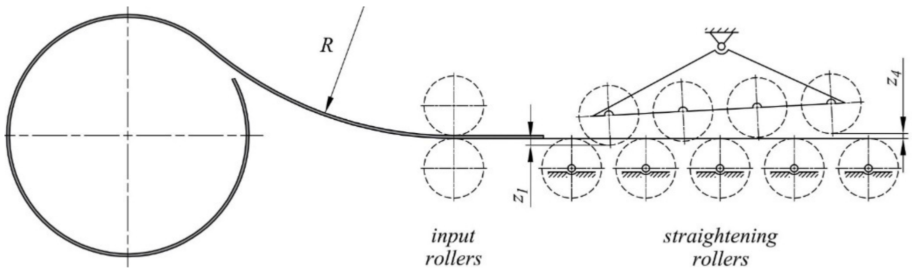

Figure 5. Scheme of the straightening machine analyzed

The FEM model shown in Fig. 6 was prepared in the Ansys Workbench package [5] taking into account the following assumptions:

- sheet metal strip at the entrance to the straightening machine has a preliminary curvature with a radius of R = 3.2 m, the value of which was measured by the drawpiece manufacturer,
- SOLID185 eight-node hexagonal elements with assigned material constants corresponding to the kinematic hardening model for DP780 steel (Table 2) were used to model the strip,
- all rollers are perfectly rigid and can rotate around their own axis,
- TARGE17 / CONTA174 contact elements with friction with the coefficient of friction μ = 0.15 were used between the straightening rollers and the sheet metal,
- the model was supplemented with additional four pairs of rollers, whose task is to maintain the given initial curvature during straightening simulation; Rigidity of contact elements between these rollers and the strip was chosen so that the stress in the strip section before straightening was close to zero.

Straightening simulation was carried out in the module for *Transient* type analyses, assuming the maximum strip speed achievable in the straightener, i.e. v = 40 m/min. It is worth noting that due to the physical nonlinearities of the FEM model, the time of simulation carried out on a computer with an i7 processor and16 GB of RAM was over 8 hours.

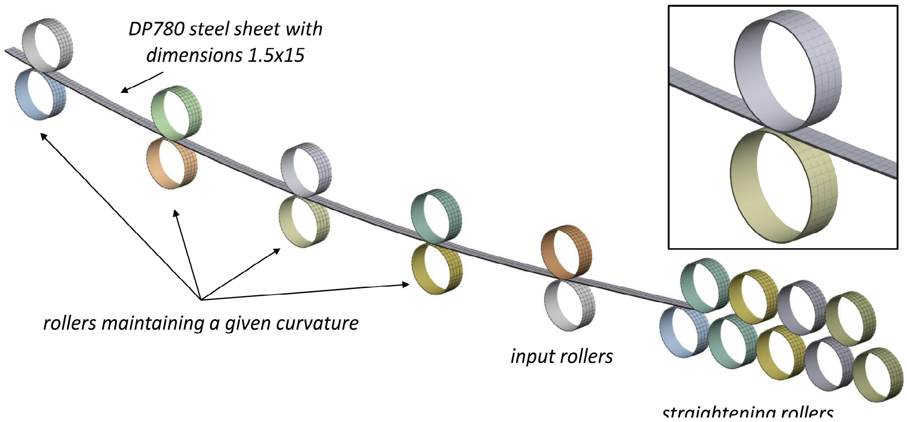

Figure 6. FEM model for simulation of straightening

4. Simulation results

Numerical simulations were carried out for various sizes of roller pitch from $z_1 = 0$ (bend by sheet thickness in the first set of three rollers) to $z_1 = 1.0$ mm, with the set value $z_4 = h = 1.5$ mm (lack of bending in the last set). The straightening quality criteria were:

– chord height h_r (Fig. 7),
– residual stress value in the strip or more precisely what is important for straightening quality, the difference between residual stresses in the outer layers of the strip cross-section after straightening σ_r.

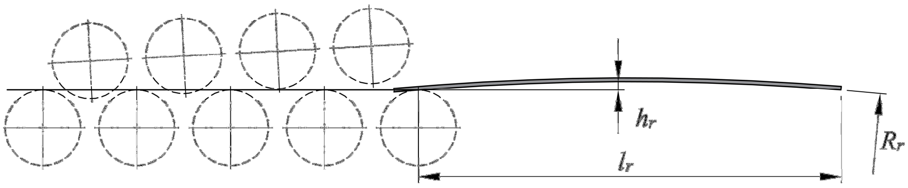

Figure 7. Chord height of sheet metal strip after straightening

Fig. 8 shows the distribution of stresses in the strip during straightening for exemplary values of roller pitches $z_1 = 0$, $z_4 = 1.5$ mm. For a more accurate assessment of the residual stress after straightening, Fig. 9 shows its distribution in the straightened strip section. In the analyzed case, the chord height after straightening was $h_r = 0.46$ mm which corresponds to the radius value $R_r = 6.25$ m, and the difference between the values of reduced stresses in the outer layers of the strip after straightening was 2.4 MPa.

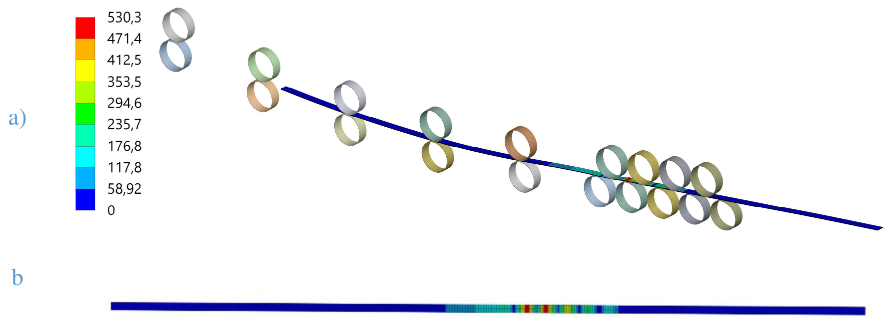

Figure 8. Stress distribution in the strip after straightening in MPa, a) isometric view, b) top view

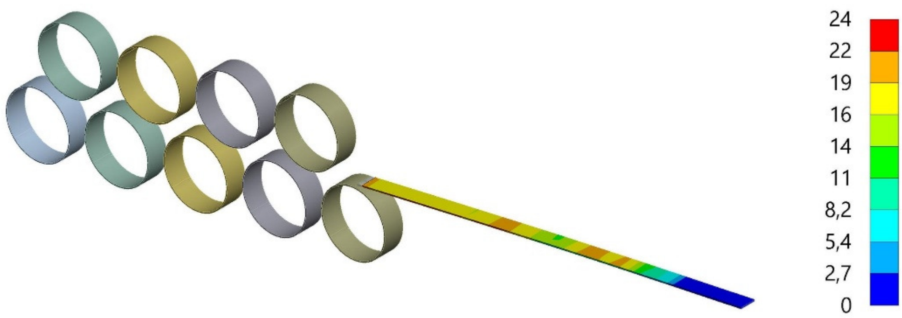

Figure 9. Residual stress distribution in the straightened strip section in MPa

Further simulations were carried out for different values of z_1 roller pitch. Fig. 10 shows the dependence between the chord height of the tape h_r and the radius of curvature R_r after straightening on the value of roller pitch z_1. However, the influence of the z_1 roller pitch on the value of residual stress in the strip after straightening σ_r (z_1) is shown in Fig. 11.

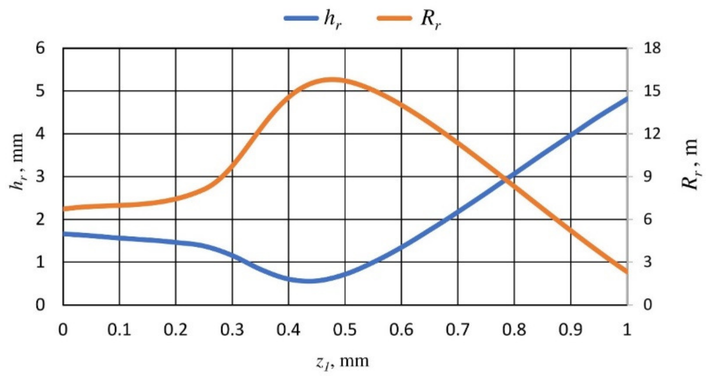

Figure 10. Impact of the roller pitch z_1 on the chord height h_r and the radius of curvature R_r after straightening

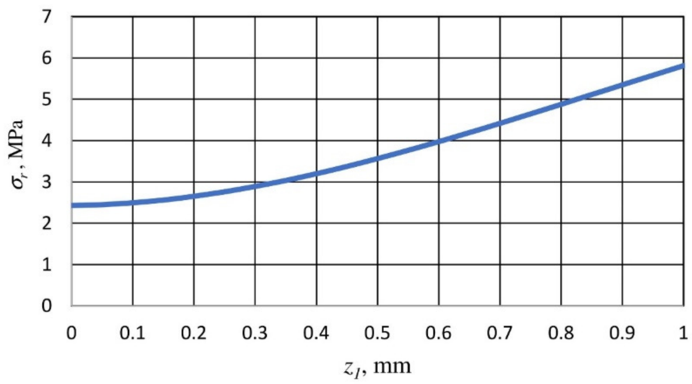

Figure 11. Influence of roller pitch z_1 on residual stress σ_r after straightening

5. Conclusions

On the basis of Fig. 10 and 11, the best settings can be selected separately for each of the adopted criteria. Since it is desirable in the straightening process that both the chord height h_r and the stress value σ_r get close to zero, the task of searching for optimal settings can be treated as a two-criterion task. Transformation of the $h_r(z_1)$ and $\sigma_r(z_1)$ curves into the criterion space (Fig. 12) allows to determine the set of compromises (the Pareto set) where the optimal solution is found. Since the ideal however does not existing solution is point $\tilde{Q} = [0\ 0]^T$ in the criteria space, the optimal solution for the task will be a point being a member of the set of compromises located closest to the ideal solution $\tilde{Q}$, in the sense of the accepted metric.

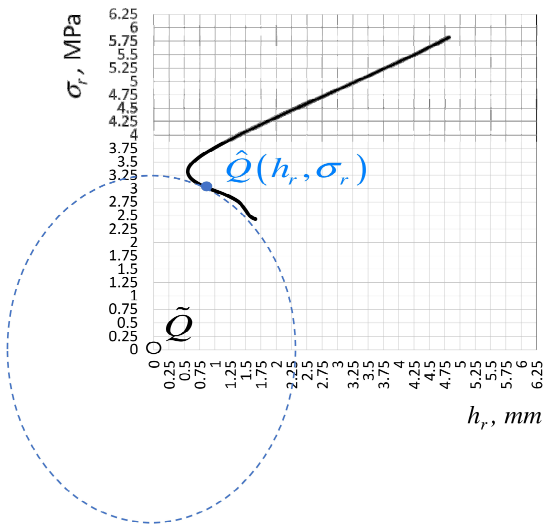

Figure 12. Problem in the criteria space

For practical reasons, straightening quality criterion $h_r \to$ min is more important than the criterion for minimizing the residual stress $\sigma_r \to$ min, especially since, as can be seen in Fig. 11, the differences in stress values σ_r in the analyzed range of roller pitch changes z_1 do not exceed 3 MPa. Therefore, adopting Euclid's metric as a measure of the distance from the solution to the ideal point, the task can be solved as a two-criterion task, where $h_r \to$ min is twice as important as $\sigma_r \to$ min. Then, as shown in Fig.12, the optimal solution is a point with coordinates $\tilde{Q} = [0.5\ 3.05]^T$ that the optimal roller pitch value of $z_1^{opt} = 0.51$ mm corresponds to. Finally, the optimal setting of the straightening machine for a DP780 sheet steel with the thickness of 1.5 mm can be taken as a bend in the first set of three rollers with a sheet thickness of h_r + 0.51 =2.01 mm and the lack of bending in the last three rollers.

REFERENCES

1. CHABOCHE J.L.: A review of some plasticity and viscoplasticity constitutive theories, Int. J. Plast., 24(2008)10, 1642-1693.
2. GUERICKE W.: Material model describing cyclic elastic-plastic deformation on roller levelling and straightening processes, Metal Forming 80(2009)4, 281-287.
3. KIM D., LEE M.G., KIM. C, WENNER M.L., WAGONER R.H., BARLAT F., et al. : Measurements of anisotropic yielding, bauschinger and transient behavior of automotive dual-phase steel sheets. Met. Mater. Int., 9(2003)561, 561-570.
4. YAGUANG L., YONG S., HYUK J.B., DAYONG L.: A numerical study of chain-die forming of the AHSS U-channel and contrast with roll forming, Int. J. of Mech. S., 135 (2018), 279-293.
5. Ansys® Academic Research Mechanical, Release 18.1, Help System.