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# Možnosti stabilizacije preoblikovalnih lastnosti žice z ravnanjem med valji

## Stabilizing the Forming Properties of Wire by Using a Roller-Straightening Process

**Miha Nastran - Karl Kuzman**

*Nestabilne preoblikovalne lastnosti vhodnih materialov predstavljajo v današnjem stanju avtomatizacije proizvodnje še vedno precejšen problem. Zlasti v velikoserijski proizvodnji, pri kateri vse več uporabljamo avtomatizirane montažne linije, je potreba po enakih polizdelkih praktično neizogibna. Dejstvo je, da so raztrosi geometrijskih značilnosti polizdelkov velikokrat posledica neenakomernih mehanskih lastnosti vhodnega materiala, na katerega proizvodni inženirji podjetij, ki se ukvarjajo s kovinsko predelavo, nimajo vpliva. Prispevek prikazuje možnosti stabilizacije preoblikovalnih lastnosti žice z uporabo ravnalnih naprav, ki so sestavni del vsakega proizvodnega procesa predelave žice. V začetku je najprej na kratko prikazana reologija jekel pri izmeničnih obremenitvah. Sledi modeliranje ravnalnega procesa in stabilizacijski algoritem. Na koncu preverimo model na konkretnem industrijskem primeru izdelave reber za mehanizme registratorjev.*

**(Ključne besede: preoblikovanje žice, ravnanje žice, lastnosti preoblikovalne, stabilizacija lastnosti)**

*The unstable forming properties of input material cause many problems in automated production processes. This is particularly so in mass production, where automated assembly lines are increasingly common, and product uniformity is a priority. It is a fact that the main reasons for the fluctuations in part geometries are the inconsistent mechanical properties of the input material, and production engineers are often unable to influence this. Here we investigate the possibility of stabilizing the mechanical properties of wire by using a roller straightener, which is used in every wire-processing production process. At the beginning a short outline of the steel's response during cyclic straining is given. This is followed by the modeling of the wire-straightening process and by the stabilization algorithm. Finally, the model is tested on a real industrial process – the production of leverarch mechanisms for ringbinder files.*

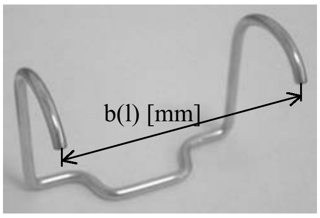
**(Keywords: wire forming, wire straightening, forming properties, stability properties)**

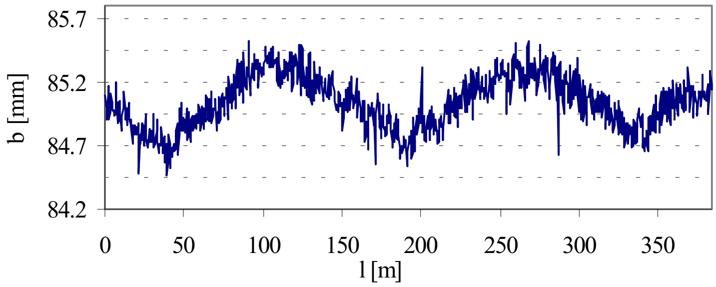
## 0 UVOD

Potreba po enakomernih mehansko preoblikovalnih lastnostih vhodnega materiala se zlasti kaže pri velikoserijski proizvodnji, pri kateri je potrebno zagotoviti ozka tolerančna polja geometrijskih značilnosti polizdelkov[1]. Dejstvo je, da dejansko jekla z absolutno enakomernimi mehanskimi lastnostmi ni. Vselej so v njem zaradi krajevno različne mikrostrukture, ki je posledica predhodnih tehnoloških postopkov obdelave jekla, opazne neenakomernosti, ki se preslikajo v geometrijska odstopanja izdelkov. Industrijski primer neenakomerne geometrijske oblike izdelka je prikazan na sliki 1. Širina izdelanega rebra se s časom spreminja, kljub temu, da parametri procesa ostajajo ves čas nespremenjeni.

## 0 INTRODUCTION

The need for wire with stable mechanical properties is especially important during mass production, where it is necessary to keep the geometrical features of products within narrow tolerance fields [1]. The problem is, however, that it is not possible to obtain steel that has absolutely homogenous mechanical properties. Due to local differences in the microstructure, which is a consequence of previous technological operations, there are always some inhomogenities in mechanical properties, which affect the final geometry. An industrial example of part-geometry fluctuation is presented in Figure 1. The width of the product is time dependent even though the process parameters remain constant.




Sl. 1. *Neenakomernost geometrijske oblike izdelka*
Fig. 1. *Fluctuation of the product geometry*

Vzrok časovnemu spreminjanju geometrijske oblike je potrebno iskati tudi v neenakomernih mehanskih in geometrijskih lastnostih surove žice. Zagotavljanje enakomernih lastnosti jekla že sega na metalurško področje in se z njim v prispevku ne bomo ukvarjali. Bolj kot definiranje vzroka nastanka prikazane neenakomernosti geometrijske oblike izdelka je pomembna rešitev, s katero bi kljub opaznim neenakomernim lastnostim žice stabilizirali krivilni postopek. Reševanje tega problema in smernice za stabilizacijo so tema nadaljnje razprave v prispevku.

## 1 PREOBLIKOVALNE LASTNOSTI ŽICE

Pri raziskavi je bil najprej narejen preskus, s katerim smo potrdili prevladujoč vpliv preoblikovalnih značilnosti žice na končno geometrijsko obliko izdelka. Prav tako smo iskali odvisnost med spreminjanjem geometrijskih parametrov žice ter končno geometrijsko obliko izdelka.

V ta namen je bila izdelana simulacija ravnalnega postopka z uporabo spremenjenega Pragerjevega modela utrjevanja materiala, ki je bila namenjena inverznemu načinu razpoznavanja meje plastičnosti žice. Hkrati s tem je bilo treba konstruirati tudi preskusno ravnalno napravo, ki omogoča meritve prečnih sil, ki delujejo na ravnalno kolo, ter preprosto nastavljanje položajev ravnalnih valjev. Prav tako je preskusna ravnalna priprava rabila sprotnemu merjenju ovalnosti žice, za katero smo prav tako sumili, da lahko vpliva na geometrijske značilnosti izdelka. Izkazalo se je, da ovalnost žice nima bistvenega vpliva na geometrijsko obliko. Na sliki 2 so prikazane povečane vrednosti meritve premera žice v ravnini $x$ in $y$ ter povečana vrednost širine izdelanega rebra.

Korelacijski koeficient med meritvijo premera v ravnini $x$ ter širino rebra je 0,65, med meritvijo širine v ravnini $y$ ter meritvijo geometrijske oblike pa 0,57. Glede na to, da je korelacijski koeficient med geometrijsko obliko in mejo plastičnosti 0,75 (sl. 3), lahko sklepamo na glavni vpliv meje plastičnosti žice na končno geometrijsko obliko izdelka.

Prav tako pokaže teoretičen izračun, da ima spreminjanje prečnega prereza žice v primerjavi s

It is inevitable that the reason for the unstable geometry is to be found in the non-stable mechanical properties of the incoming wire. Keeping the microstructure of the steel homogeneous is the domain of the metallurgist and will not be considered in this paper. The solution of how to stabilize the forming process, in spite of the fluctuation of in the material’s properties, is much more important than finding the reason for the fluctuation of the mechanical properties. This paper discusses the solution to the problem and gives directives for stabilising the process.

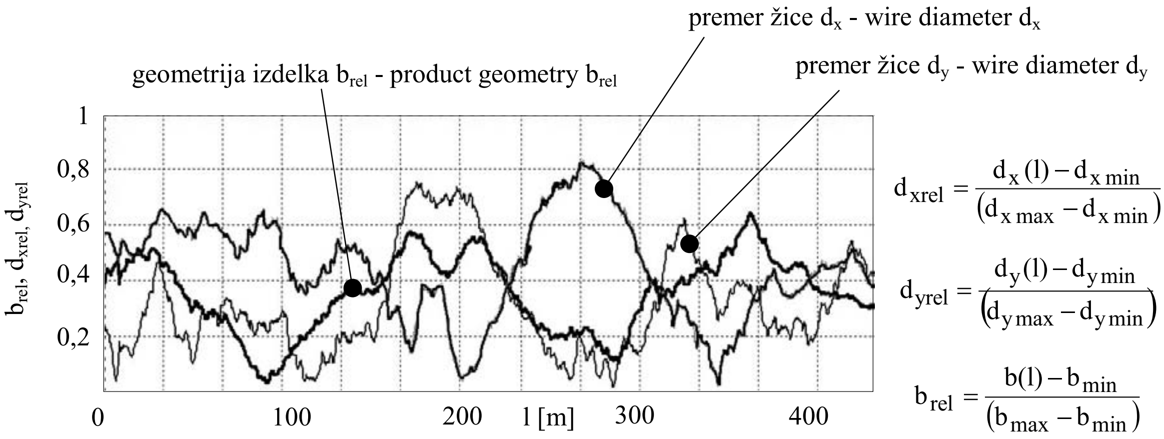
## 1 FORMING PROPERTIES OF WIRE

First, a test was made to confirm the major influence of the mechanical properties on the geometry of the product. The correlation between the fluctuation in the wire’s geometry and the geometry of the finished part were checked as well.

A simulation of the straightening process was made, and a modification of Prager’s flow rule was used. It serves for the inverse approach to the identification of the wire’s flow stress. Parallel to this an experimental wire straightener was designed in such a way that it was possible to measure the transverse roller forces and to preset the rollers simple way. The experimental straightener also serves for measuring the wire diameter. We also suspected that the wire diameter has an influence on the final product geometry. It was shown that the fluctuation in the wire’s diameter has no influence on the final geometry of the part. The scaled value of the measurements of wire’s diameter in the xz and yz planes are shown in Figure 2, together with the scaled values of the part’s width.

The correlation between the part geometry and the wire diameter in the x direction is 0.65, while between the diameter in the y direction and the part’s geometry it is only 0.57. The correlation between the flow stress and the part’s geometry is 0.75, which implies a major influence of the flow stress.

A theoretical calculation shows that the influence of the wire’s diameter on the transverse roller forces can be neglected. From which it can be




Sl. 2. *Odvisnost med geometrijsko obliko izdelka in premerom žice*
Fig. 2. *Correlation between the product geometry and the wire's diameter*

spremembo meje plastičnosti zanemarljiv vpliv na velikost prečnih sil na ravnalne valje. S tem lahko sklepamo, da je sprememba prečne sile povezana izključno s spremembo meje plastičnosti žice.

Na sliki 3 je prikazana meja plastičnosti žice v odvisnosti od lege žice v kolutu [2], kjer je lepo razvidna soodvisnost med geometrijsko obliko izdelka ter mejo plastičnosti žice. Sklepamo lahko, da imajo preoblikovalne lastnosti žice bistven vpliv na nadaljnji krivilni postopek, vplivajo pa tudi na premer žice. Spreminjanje premera žice nima bistvenega vpliva na krivilni postopek, saj so odstopanja premajhna.

concluded that the variation in the transverse roller forces is only a consequence of the fluctuation in the flow stress.

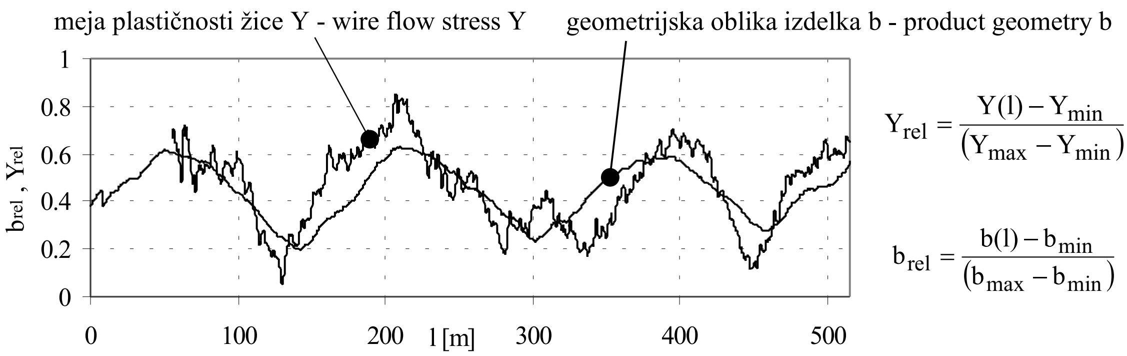
The time dependence of the wire's flow stress [2] is presented in figure 3. The correlation between the wire's flow stress and the product geometry is clear. It can be concluded that the forming properties of wire have a major impact on the subsequent bending process, as wel as having an influence on the wire's diameter. The fluctuation in the wire's diameter has no significant influence on the bending process, since it is too small.

### 1.1 Osnovna zamisel stabilizacijskega algoritma

Osnovna zamisel je v tem, da bi z ravnalnim postopkom, pri katerem se material obremenjuje izmenično v nateznem in tlačnem področju, vplivali na mejo plastičnosti na izstopu iz ravnalke. Osnova razmišljanju je eksperimentalno potrjeno dejstvo [2], da je meja plastičnosti žice odvisna od velikosti povečanja plastične deformacije, bodisi v nateznem ali tlačnem področju. Za dosego zastavljenega cilja je najprej treba imeti dober model ravnalnega postopka, zato si bomo najprej ogledali njegovo modeliranje.

### 1.1 The main idea of the stabilization algorithm

The main idea is to use the straightening process, where the material is exposed to cyclical deformation in the tensile and compressive regions, to influence the wire's yield stress at the end of the straightening process. The basis for this is an experimentally verified fact [2]: that the yield stress depends on the total amount of cyclical deformation in the tensile or compressive region. To achieve this we have first to have a good model of the straightening process, so the modeling will be presented first.




Sl. 3. *Odvisnost med geometrijsko obliko izdelka in mejo plastičnosti žice*
Fig. 3. *Correlation between the product geometry and wire's yield stress*

## 2 MODELIRANJE RAVNALNEGA POSTOPKA

Pred nadaljnjo obdelavo žice na žično krivilnem avtomatu je le to treba izravnati v ravnalnih napravah ([3] in [4]). Glede na tip preoblikovalnega postopka, ki sledi, poznamo več vrst ravnalnih naprav, ki jih delimo predvsem po kontinuirnem ali prekinjanem načinu dela. V našem primeru se bomo omejili le na prekinjane ravnalne naprave, ki se uporabljajo pri izdelavi loka spenjanja prikazanega na sliki 1.

Najprej je treba uspešno modelirati ravnalni postopek, ki bo dovolj hiter, da ga bomo kasneje lahko uporabili v algoritmu za stabilizacijo preoblikovalnih lastnosti žice. Prav zaradi tega smo se deloma umaknili iz povsem numeričnega postopka v analitično numerični popis dogajanja, ki omogoča hitrejše računanje.

### 2.1 Reološki model

Reološki model preoblikovanja materiala, ki ga bomo uporabili v računskem modelu, je bistven za natančno modeliranje. Bistveno pri ravnanju žice je, da material izmenoma obremenjujemo v plastičnem področju, s čimer dosežemo na koncu čim večjo ravnost žice. Obnašanje jekla pri takšni deformaciji je opisano z diagramom napetost - deformacija pri izmenični obremenitvi ([5] do [7]), ki jo je treba definirati s preizkusi. Malooglljična poprej hladno deformirana jekla, kakršna žica tudi je, izkazujejo pri tovrstni obremenitvi Bauschingerjev pojav [8], ki pomeni nižanje meje plastičnosti pri spremembi smeri obremenjevanja. Natančna simulacija ravnalnega postopka zaradi tega zahteva poznavanje obnašanja jekla pri izmenični obremenitvi. To pomeni poznavanje diagrama $\sigma-\varepsilon$ (sl. 4), ki pa ga je za primer žice z debelino 4 mm eksperimentalno težko definirati.

Ena od možnosti je obrnjen postopek prek modeliranja upogibnega preizkusa, v našem primeru pa smo se odločili za poenostavitev in v Pragerjeve enačbe [9] za popis zveze med napetostjo in

## 2 MODELING OF THE STRAIGHTENING PROCESS

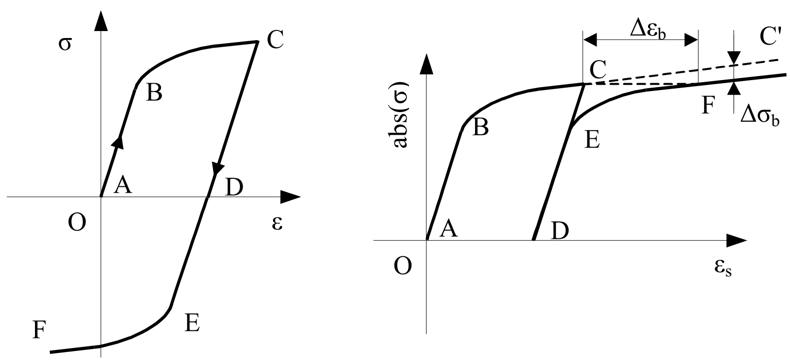
Prior to any further wire processing on the bending machinery it is necessary to straighten the wire in wire straighteners ([3] and [4]). Depending on the type of process that follows the straightening, many different types of straighteners can be applied. They can basically be divided into continuous and non-continuous types. We will confine ourselves to discontinuous wire straighteners, which are used in the production of the arch presented in Figure 1.

First, it is necessary to develop a numerical model of the wire straightener that will be fast enough to calculate the required repositionings of the rollers mounted in the straightener. This was the reason for using an analytical numerical approach rather than a purely numerical simulation of the straightening process.

### 2.1 Constitutive model

A constitutive model of the material that will be used in the model is essential for accurate modeling. The core of the straightening process is a cyclic, plastic deformation of the wire, which results in the final straightness of the wire. The material response for such deformations is characterized by the $\sigma-\varepsilon$ diagram during cyclic deformation ([5] to [7]), which has to be defined during the experimental testing. Low-carbon cold-drawn steels exhibit the Bauschinger phenomena when they are cyclically deformed into the plastic region. This means lowering the yield stress when the material is deformed in the opposite direction. A reliable simulation of the straightening process, therefore, requires a knowledge of the material's response during cyclical deformation. When presenting this in one dimension it is necessary to know the parameters of the diagram presented in Fig.4. In the case of wire with a diameter of 4 mm it is not a simple task to define this diagram.

One possibility is an inverse approach, by modeling the bending test. In our case we chose a simplification, therefore an extended form of Prager's [9] equation was used to describe the material's




Sl. 4. *Shematski prikaz Bauschingerjevega pojava [8]*
Fig. 4. *Schematic representation of the Bauschinger phenomena*

deformacijo vnesli še dodaten koeficient $D_{cyc}$, s katerim je dana možnost spreminjanja meje plastičnosti žice iz enega nihaja v drugega.

Diferencialne enačbe Pragerjevega modela so:

behavior during straightening. In order to capture the softening of the material, an additional term $D_{cyc}$ was added to allow for it.

The differential equations of Prager's model are:

$$C = \left[ \left(1+K\right) \cdot \sigma - E \cdot K \cdot \varepsilon \right] \tag{1}$$

$$d\sigma = E \cdot d\varepsilon \qquad C \geq 0 \tag{2}$$

$$d\sigma = E \cdot \left[ 1 - \frac{1}{Y^{2n} \cdot \left(1+K\right)^{3n}} \cdot \left[ \left(1+K\right) \cdot \sigma - E \cdot K \cdot \varepsilon \right]^{2n} \right] \cdot d\varepsilon \qquad C \leq 0 \tag{3}$$

$$Y_i = Y_0 \cdot D_{cyc.}^{\;i-1} \tag{4}$$

Pri tem so:

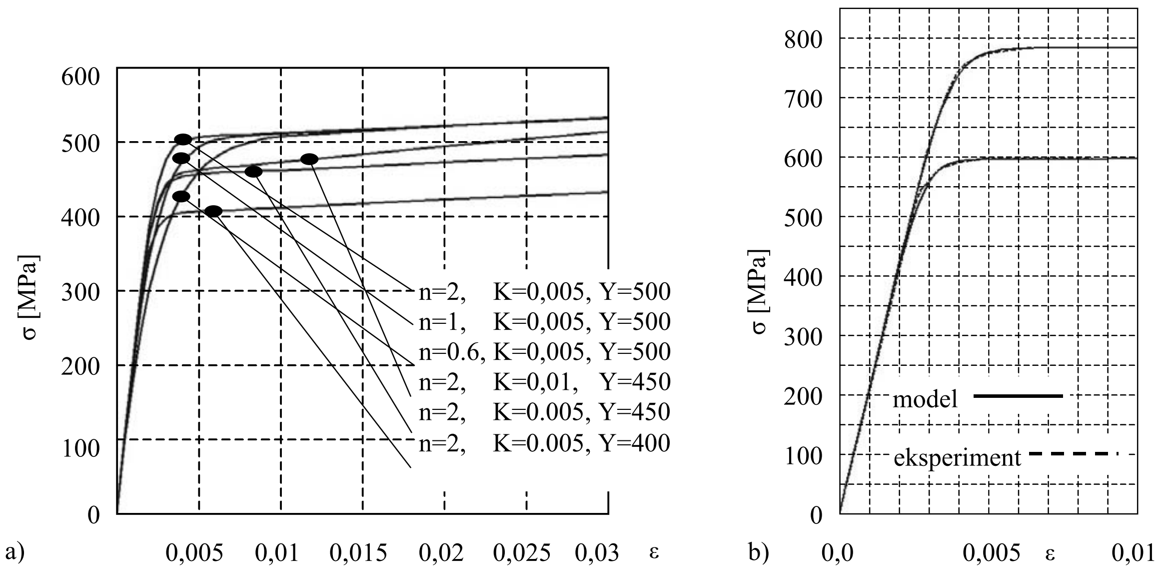
- $E$ - modul elastičnosti (MPa)
- $Y$ - meja plastičnosti v i-tem ciklu (MPa)
- $\sigma$ - napetost (MPa)
- $\varepsilon$ - deformacija
- n - faktor prehoda
- $K$ - limita strmine v plastičnem področju (MPa)

Vzrok, da smo se odločili prav za Pragerjev model zveze med napetostjo in deformacijo žice, je v tem, da ob pravilni izbiri parametrov n in $K$ izredno dobro popiše obnašanje materiala med enoosnim nateznim preizkusom. Glede na to, da je plastična deformacija žice v ravnalni napravi za področje preoblikovanja izredno majhna (< 1%), je za pravilno modeliranje ravnalnega postopka pomemben prav prehod iz elastičnega v plastično področje. Navadno pri obravnavanju postopkov preoblikovanja upoštevamo Hookov zakon v elastičnem področju ter funkcijsko odvisnost meje plastičnosti od primerjalne plastične deformacije v plastičnem področju. Takšen popis pa predstavlja v področju prehoda iz elastičnega v plastično področje lomljeno krivuljo, ki ni primerna za popis zveze med napetostjo in deformacijo pri modeliranju preoblikovalnih postopkov, kakršen je ravnanje žice.

Where:

- $E$ - Young's modulus (MPa)
- $Y$ - yield stress in the i-th cycle (MPa)
- $\sigma$ - stress (MPa)
- $\varepsilon$ - deformation
- n - transition factor
- $K$ - plastic slope limit (MPa)

The reason why Prager's model was used for the description of relationship between the stress and the deformation is that when appropriate values of the parameters n and K are chosen, a tensile-test experiment can be modeled very accurately. Since the material deformation during roller straightening is very low (< 1%), the transition region from the elastic to the plastic stress state is very important for accurate modeling. Normally, when forming processes are modeled we use Hooke's law in the elastic region and a certain functional relationship between the equivalent plastic deformations and the yield stress in the plastic region. Such a description results in a transition field with a non-smooth curve that is not appropriate for modeling the stress-strain relationship for processes such as wire straightening in the roller straighteners.




Sl. 5. *Pragerjev reološki model a) in primerjava s preizkusi b)*

Fig. 5. *Prager's flow rule a) and a comparison with the experiments b)*

Primerjava diagrama $\sigma$–$\varepsilon$, dobljenega z enoosnim nateznim preizkusom ter modeliranega diagrama s Pragerjevim modelom je prikazana na sliki 5. Prikazan je tudi vpliv parametrov n in $K$ na obliko krivulje prehoda iz elastičnega v plastično področje.

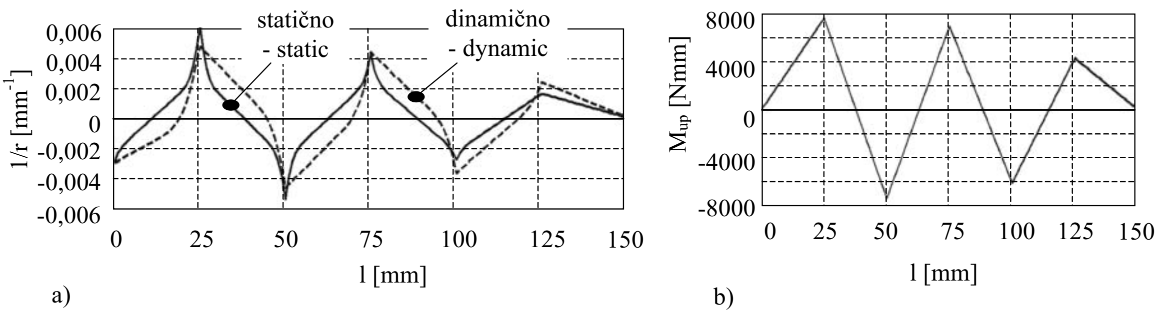
A uniaxial tensile test diagram is compared with the one modeled by Prager's flow ruler in Fig.5. The influence of the parameters n and $K$ on the form of the elastic-plastic transition curve is presented as well.

**2.2 Upogibni moment - ukrivljenost**

**2.2 Bending moment – curvature**

Naslednji korak pri modeliranju ravnalnega postopka je pravilen popis zveze med ukrivljenostjo žice vzdolž ravnalne naprave ter upogibnim momentom [10], ki deluje na žico. V praksi se lege ravnalnih valjev nastavijo tako, da začetni valji deformirajo žico približno na dvakratno vrednost ukrivljenosti v kolutu, toda v nasprotni smeri. Nato pa se ukrivljenost postopoma zmanjša do teoretične vrednosti nič na izhodu iz ravnalne naprave. Izhajamo torej iz diagrama, ki popisuje vrednosti ukrivljenosti žice na posameznem ravnalnem valju (sl. 6) in je dobljen na podlagi izkušenj.

The next step in the numerical simulation of the wire straightener is the definition of the connection between the wire curvatures and the bending moment acting on the wire along the straightener [10]. Initially the wire straightener is preseted to the know-how values so that the wire is initially deformed to double the initial curvature in the opposite direction. Normally, the curvature fades out towards the end of the straightener. The diagram describing the wire curvature (Fig.6) is therefore the basis for further calculations. It is based on the experiences of the company personnel.




Sl. 6. *Ukrivljenost žice a) ter upogibni moment b) vzdolž ravnalke*
Fig. 6. *Wire curvature a) and bending moment b) along the straightener*

Upogibni moment, s katerim je treba delovati na delček žice, če hočemo, da bo njegova ukrivljenost enaka $k_i$, je definiran z integralom zmnožka med napetostjo in ročico po prerezu žice (en. 5):

In order to obtain curvature $k_i$ a certain bending moment has to be applied in the cross-section of the wire. It is defined by the numerical integration of the normal stress multiplied by the distance from the neutral plane over the cross-section of the wire (Eq.5).

$$M_i = 4 \cdot \int_0^{d_0/2} \sigma\left(k_i y\right)\sqrt{d_0^2/4 - y^2}\, y\, dy \qquad (5),$$

kjer je $k_i$ ukrivljenost žice v legi, ko se le ta dotika i-tega ravnalnega valja, $\sigma(k_i, y)$ pa je dobljena z uporabo diferencialnih enačb Pragerjevega modela. Upogibni moment na prvem ravnalnem valju je enak nič, saj se na njem deformacija žice še ne pojavi. Dejstvo je, da ravnalni valji delujejo na žico le v določenih singularnih točkah, zato je porazdelitev upogibnega momenta vzdolž ravnalne naprave lahko samo linearna. Izračunamo jo s pomočjo definiranih točk (en.5) na način:

where $k_i$ represents the wire curvature when interacting with the i-th roller, $\sigma(k_i, y)$ represents the material data obtained by Prager's flow rule. The bending moment on the first roller is zero, since no deformation occurs there. Since the rollers are acting on the wire only at singular points the distribution of the bending moment from one roller to another is linear. This means that it is possible to calculate the bending moment distribution on the wire traveling through the roller straightener (Eq.5):

$$M\left(x\right) = M\left(x_i\right) + \frac{M\left(x_{i+1}\right) - M\left(x_i\right)}{x - x_i} \qquad x_i \le x \le x_i + 1 \qquad (6).$$

Kljub temu, da je porazdelitev upogibnega momenta vzdolž ravnalne naprave linearna, pa porazdelitev ukrivljenosti ni odsekoma linearna

As the moment is linearly distributed over the length of the roller straightener the wire curvature is not. Wire is locally subjected to a small amount of funkcija, čemur botruje dejstvo, da je žica deformirana v plastično področje. Ukrivljenost je določena z enačbo (7), le da ne iščemo upogibnega momenta, temveč ukrivljenost, katere rezultat je želen upogibni moment.

plastic deformation, which causes a nonlinear distribution in the curvature along the wire straightener. It is defined by Eq.7, where the curvature at which the desired bending moments occur is looked for.

$$M(x)=4\int_{0}^{d_0/2}\sigma\left(k(x)y\right)\sqrt{d_0^2/4-y^2}\,y\,dy \quad k(x)=U\left(M(x)\right) \qquad (7).$$

Poleg zveze med napetostjo in deformacijo je ukrivljenost žice odvisna še od tega, ali le ta v ravnalki miruje ali pa se giblje. Ker je ravnalni postopek dinamičen, bomo obravnavali le primer, pri katerem se žica vzdolž ravnalne naprave giblje. Primer upogibnega momenta in ukrivljenosti žice je za žico z debelino 4 mm podan na sliki 6. Številčne vrednosti ukrivljenosti in upogibnega momenta pa so prikazane v preglednici 1.

Apart from the stress–strain relationship, the wire curvature depends on whether it is traveling through the straightener or it is stopped within the straightener. Since the straightening process is dynamic, it will be focused only on the case where the wire is moving through the straightener. An example of the bending moment and the curvature for a wire with 4-mm diameter is represented in Fig.6. The values are listed in Table 1.

Preglednica 1. *Številčne vrednosti momenta in ukrivljenosti*
Table 1. *Bending moment and wire curvature*

| valj / roller | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| ukrivljenost v $mm^{-1}$ curvature [$mm^{-1}$] | -0,0025 | 0,0048 | -0,0045 | 0,0034 | -0,0031 | 0,0030 | 0,00 |
| upogibni moment v Nmm bending moment [Nmm] | 0 | 8397 | -7950 | 7679 | -6837 | 6311 | 0 |

Izračunane vrednosti upogibnega momenta in ukrivljenosti uporabljamo za izračun položaja ravnalnih valjev in s tem poti žice skozi ravnalno napravo ter velikosti prečnih sil, ki delujejo na žico v ravnalki. Definicija lege žice v ravnalki temelji na numerični integraciji izraza za ukrivljenost vzdolž ravnalne naprave, definicija prečnih sil pa izhaja iz porazdelitev upogibnega momenta.

Based on the calculated values for the bending moment and the wire curvature, it is possible to define the roller position of the wire straightener and the roller force acting on each roller. The definition of the position is based on the numerical integration of the wire curvature term along the straightener axis. Roller forces are based on the bending moment distribution.

### 2.3 Numerična integracija ukrivljenosti

Ukrivljenost žice je dobljena z enačbami (5) do (7) in je osnova za nadaljnji preračun. Ker je odvisnost ukrivljenosti le odsekoma gladka krivulja, analitičen postopek integracije praktično ni mogoč. Zato je potrebno uporabiti numerično intergacijo izraza za ukrivljenost žice vzdolž ravnalne naprave.

V splošnem je matematični izraz za ukrivljenost definiran z enačbo:

### 2.3 Numerical integration of the curvature

The presented equations (5-7) describe the technique for obtaining wire curvature, which is the basis for the calculation of the roller positions within the wire straightener. The function describing the wire's curvature is smooth only in the interval between two adjacent rollers. This is the reason why it is not possible to integrate the wire's curvature analytically. Thus it is necessary to use numerical integration of the curvature term along the straightener.

In general the curvature of a mathematical function is expressed by the following term:

$$k(x)=\frac{\frac{\partial^2 y}{\partial x^2}}{\sqrt{\left[1+\left(\frac{\partial y}{\partial x}\right)^2\right]^3}}=\frac{1}{r(x)} \qquad (8),$$

kjer sta:
$k(x)$ - ukrivljenost žice
$r(x)$ - polmer ukrivljenosti

Izraz (8) je nelinerana diferencialna enačba drugega reda, ki jo je mogoče na podlagi dejanskih

where:
$k(x)$ - wire curvature
$r(x)$ - bending radius

This is a second-order nonlinear differential equation, which can be simplified based on special geometrijskih značilnosti še nekoliko poenostaviti. Ker je prvi odvod funkcije (poti žice skozi ravnalko) praktično enak nič, ga lahko zanemarimo, s čimer se izraz za ukrivljenost poenostavi v:

geometrical characteristics. Since the first derivative of the function is small, it can be neglected, which means that the mathematical curvature term can be simplified:

$$k(x)=\frac{\partial^2 y}{\partial x^2} \qquad (9).$$

Napaka, ki jo naredimo pri neupoštevanju prvega odvoda funkcije, je za primer izravnavanja žice z debelino 4 mm manjša od 1 odstotka, kar je zanemarljivo in torej lahko za nadaljnji preračun uporabimo kar enačbo (9). Dvojna integracija vzdolž ravnalke da iskano lego, ob tem pa moramo upoštevati dve konstanti, ki se pojavita ob vsakokratnem integriranju in določata lego žice na prvem in zadnjem ravnalnem valju.

Dejansko se v praksi nastavlja lega ravnalnih valjev in ne ukrivljenost. Ta je le posledica lege, poleg tega pa so ravnalke navadno nastavljene tako, da so valji, nameščeni na eni strani, pritrjeni, na drugi pa jih je mogoče premikati. Pravilna rešitev integracije je torej tista, ki da pot žice takšno, da se le ta dotika ravnalnih koles. Zato je na tem mestu potreben iterativen postopek točnega določanja začetne ukrivljenosti žice na posameznih ravnalnih valjih. Nekaj možnosti poti žice skozi ravnalko je prikazanih na sliki 7.

## 2.4 Prečne sile na ravnalne valje

Prečne sile na ravnalne valje uporabljamo za inverzen izračun trenutne meje plastičnosti žice, kar je temelj za stabilizacijski algoritem. Njihov izračun sloni na momentnem ravnotežju sil, ki delujejo v sistemu žica - ravnalni valji. Postopek izračuna je shematično prikazana na sliki.8.

## 2.5 Eksperimentalno testiranje simulacije

Predstavljen numerični model ravnalnega postopka je bil testiran na žici, na kateri smo poznali napetost tečenja. Izmerjene in izračunane vrednosti

A numerical error that originates from the neglecting of first derivative is calculated for the wire of 4 mm, and represents less than 1%, which can be neglected. For the further calculation, Eq.9 can be used instead. Double integration along the straightener axis gives the results, but it is necessary to consider both constants from the integration. They define the position of the wire on the first and last roller.

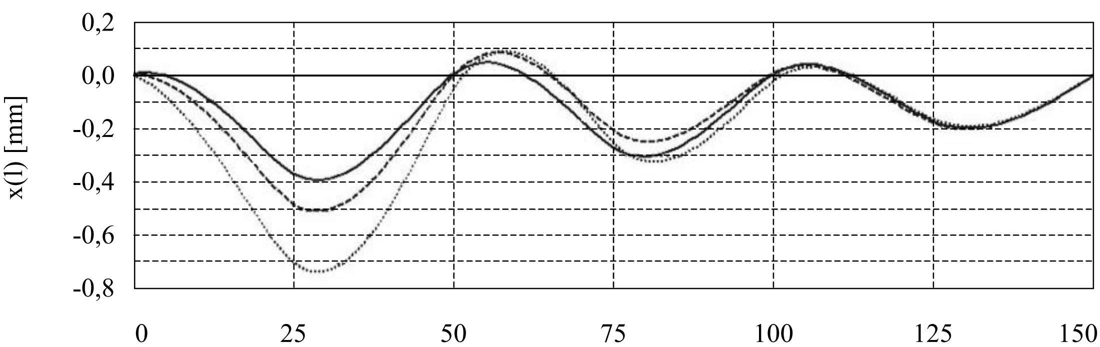
In pratice the position of the rollers is changed. The wire's curvature change is only a consequence of changing the roller positions. Apart from this, the position of the four upper rollers normally stays constant, but it is possible to change the positions of the rollers on the opposite side. A correct solution of the numerical integration is the one where the wire exactly touches the rollers. Therefore, an iterative approach is necessary to define accurate initial curvatures of the wire on each roller. Some possibilities are presented in Fig.7.

## 2.4 Transverse roller forces

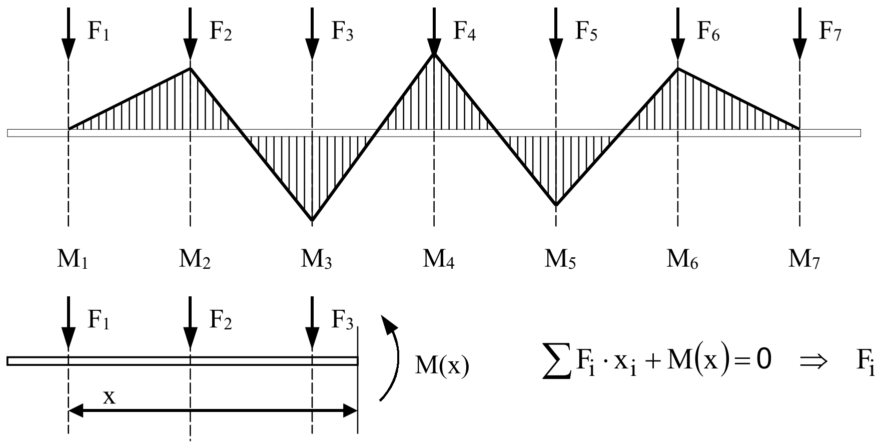
The transverse roller forces are needed for the inverse calculation of the current yield stress of the wire, which is the basis for the stabilization algorithm. The calculation is based on the moment equilibrium in the system of wire and straightening rollers. The procedure is schematically represented in Fig.8.

## 2.5 Experimental testing of the simulation

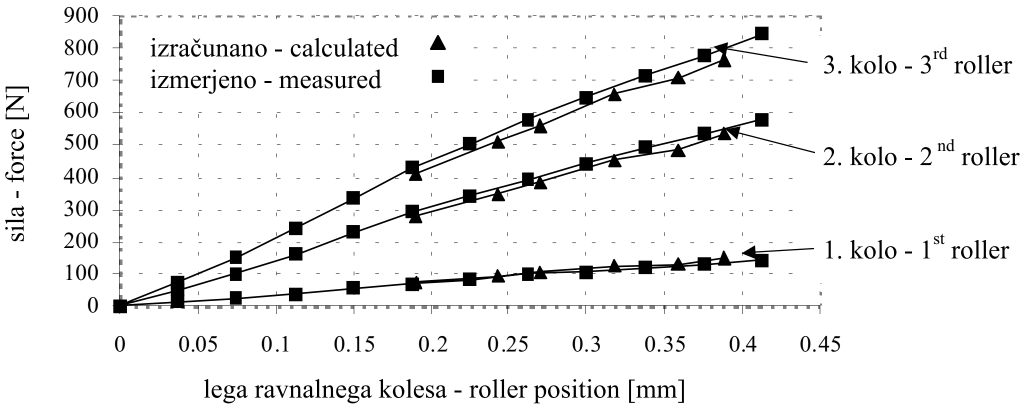
The numerical model of the wire straightener was tested on a wire with known yield stress. The measured and calculated values for the roller forces were practically the same (Fig.9). This means that the




Sl. 7. *Različne izračunane poti žice skozi ravnalko*
Fig. 8. *Different calculated wire paths through the straightener*




Sl. 8. *Izračun prečnih sil na ravnalne valje*
Fig. 8. *Calculation of the transverse roller forces*




Sl. 9. *Eksperimentalno testiranje simulacije ravnanja [11]*
Fig. 9. *Experimental verification of the straightening simulation [11]*

Preglednica 2. *Simulacija ravnalnega postopka*
Table 2. *Simulation of the straightening process*

| številka ravnalnega valja / roller no. | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| položaj / roller setting [mm] | 0 | -0,69 | -0,05 | -0,25 | -0,02 | -0,17 | 0 |
| prečna sila na valj / transverse roller force [N] | 325 | 940 | 1230 | 1200 | 1130 | 805 | 255 |

sil, ki delujejo na ravnalno kolo so bile praktično enake (sl. 9). To pomeni, da je model dovolj natančen in da ga lahko uporabimo v obrnjeni metodi določanja trenutne meje plastičnosti žice.

Rezultati simulacije so lege ravnalnih koles ter prečne sile na ravnalne valje in so za primer žice s premerom 4 mm prikazani v preglednici 2.

## 3 STABILIZACIJSKI ALGORITEM

Prikazan numerični model ravnalnega postopka je jedro algoritma za stabilizacijo meje plastičnosti žice. Poleg tega pa je pred samo vpeljavo sistema treba izpolniti še nekatere robne pogoje.

Obnašanje žice pri izmenični deformaciji je najbolj pomemben parameter, ki dejansko pove, ali je z ravnalnim postopkom mogoče stabilizirati mejo

developed numerical model is accurate enough and can therefore be used as an inverse method for the characterization of the flow properties of the wire passing through the roller straightener.

The result of the simulation is the roller position and the roller forces. For the wire with a diameter of 4 mm they are presented in Table 2.

## 3 STABILIZATION ALGORITHM

The above-presented numerical model of the wire-straightening process serves as the basis for the stabilization of the yield stress of the wire. Certainly, there are some preconditions, which have to be fulfilled in order that the flow stress stabilization can be carried out.

The wire's behavior under cyclic deformation is the most important parameter, which tells whether it will be possible to stabilize the yield stress or not.

plastičnosti ali ne. Obnašanje dveh različnih vrst žice je prikazano na sliki 9. Diagram prikazuje mejo plastičnosti žice po ravnanju v odvisnosti od celotne plastične deformacije [11], ki smo jo za potrebe stabilizacijskega algoritma definirali z izrazom:

The behavior for two different wire types is presented in Fig.10. It presents the yield stress of the wire after being straightened with respect to the total amount of wire curvature [11], which has been for the purpose of the stabilization algorithm defined as:

$$k^{TOT} = \sum_{i=2}^{n-1} |k_i| \qquad (10).$$

Izraz pomeni vsoto absolutnih vrednosti ukrivljenosti žice na posameznem ravnalnem valju in je mera za velikost izmenične plastične deformacije.

Malooglji čna jekla navadno izkazujejo izmenično mehčanje (krivulja B na sl. 10). To pa je odvisno od velikosti prirasta plastične deformacije. Če je le ta večji, se material lahko zopet utrjuje (krivulja A na sl.10). Sprememba meje plastičnosti je torej odvisna od materiala in prirasta plastične deformacije. Za primer jekla B na sl.10 je mogoče z nadzorom velikosti prirasta plastične deformacije (nastavitve ravnalnih koles) uspešno izvesti stabilizacijo meje plastičnosti.

Glavna zamisel stabilizacije je v tem, da z numeričnim modelom ravnanja, predstavljenega v prejšnjem razdelku, definiramo mejo plastičnosti žice, ki je trenutno v ravnalki. Na podlagi eksperimentalnih podatkov s slike 10 se nato izračunajo potrebne popravke nastavitev ravnalnih koles. Posledica tega je izpostavitev žice drugačnim izmeničnim deformacijam, kar povzroči tudi drugačno vrednost meje plastičnosti po ravnanju. Dejstvo je, da se meja plastičnosti žice ne spreminja v dolžini, manjši od dolžine ravnalne naprave. Z meritvami je bilo ugotovljeno, da je frekvenca spreminjanja meje plastičnosti približno 8 do 10 min, kar pomeni približno 180 m žice (sl. 11).

It represents the sum of the absolute values of the wire's curvature on a single straightener roller and it is a measure of the total cyclic plastic deformation.

Low-carbon cold-drawn wire materials normally exhibit cyclic softening (curve B in Figure 10). This depends on the plastic increment. If the plastic increment is higher, it is possible that the material will harden again (curve A in Figure 10). The change of the flow stress depends on the material and on the increment of the plastic deformation. In the case of material B from Fig.9 it is possible that the mechanical properties of the wire are stabilised by controlling the plastic increment, which comes from controlling the positions of the straightening rollers in the roller straightener.

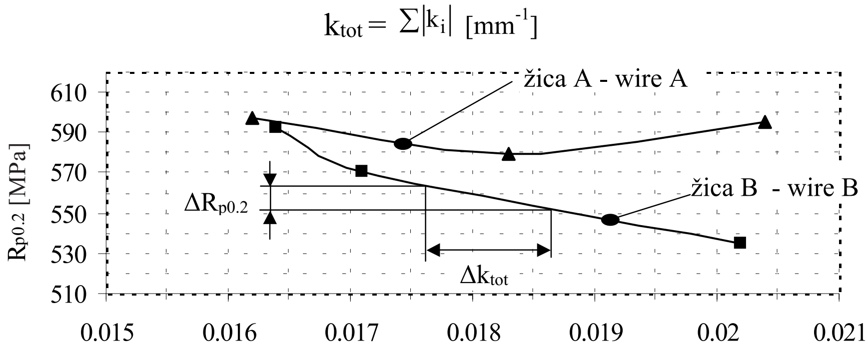
The basic idea of the stabilization is that by using a numerical model of the wire straightener, described in the previous paragraph, the wire's yield stress passing the roller straightener is calculated. By combining the data from Figure 10, the necessary adjustments of the wire's curvature are calculated afterwards. This means that the wire is exposed to different amounts of cyclic deformation, which means a different yield stress of the wire after straightening. The yield stress of wire does not fluctuate over short time periods. It was confirmed from measurements that the cycle time of the flow-stress fluctuation is 8–10 min, which means approximately 180 m, as shown in Fig. 11.

### 3.1 Postopek stabilizacije

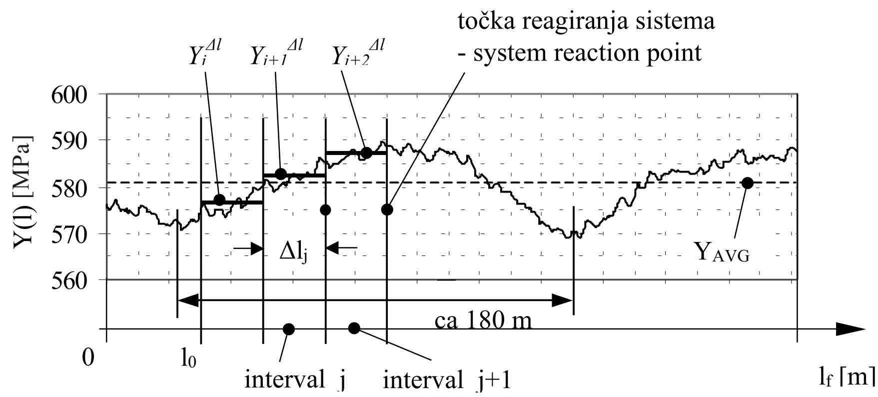
Ravnalna naprava stalno meri sile na ravnalna kolesa. Z numerično simulacijo smo sile na ravnalna kolesa izrazili kot neko funkcijo, ki je odvisna od več parametrov postopka (meja plastičnosti, premer žice, lege koles itn.). Ob predpostavki, da se spreminja samo meja plastičnosti, lahko zapišemo:

### 3.1 Stabilization procedure

The roller forces are constantly measured by the roller straightener. Using a numerical simulation the roller forces were expressed as a function that is dependent on material and process parameters (yield stress, wire diameter, roller positions, etc.). If only the yield stress fluctuates, the equation can be expressed as:




Sl. 10. *Meja plastičnosti za žici dveh različnih proizvajalcev v odvisnosti od* $k^{TOT}$
Fig. 10. *Yield stress of the wire, from two different suppliers, depending on* $k^{TOT}$




Sl. 11. *Spreminjanje meje plastičnosti ter prikaz točk, kjer ukrepamo [11]*
Fig. 11. *Fluctuation of the flow stress of the wire and the reaction points [11]*

$$F_i = f(Y(l)) \qquad (11).$$

Enačba inverznega postopka pa je na podlagi en. (11) naslednja:

Based on Eq.11, the inverse is:

$$Y(l) = f^{-1}(F_i(l)) \qquad (12).$$

Razlika med trenutno mejo plastičnosti in povprečno vrednostjo v določeni količini žice se izračuna kot:

The difference between the current yield stress and the average yield stress of the wire is calculated as:

$$\Delta Y_j = Y_j^{\Delta l} - Y_{AVG} = \frac{1}{\Delta l_j}\int_{\Delta l_j} Y(l)dl - \frac{1}{l_f}\int_0^{l_f} Y(l)dl \qquad (13),$$

pri čemer sta:
$\Delta l_j$ - opazovani korak (sl.11)
$l_f$ - celotna dolžina žice od začetka merjenja

Potrebno popravo parametra $k^{TOT}$ za bolj enakomerno mejo plastičnosti žice po ravnanju dobimo z uporabo diagrama na sliki 10. Potrebna poprava izhaja iz velikosti odstopanja trenutne vrednosti meje plastičnosti $\Delta Y_j$ od povprečne vrednost $Y_{AVG}$. V obliki funkcije:

where:
$\Delta l_j$ - measured interval (Fig.11)
$l_f$ - cumulative length of the wire

In order to stabilize the yield stress in the next step, j+1, it is necessary to correct the value $k^{TOT}$ according to the findings presented in Fig.10. The necessary correction is defined by the difference between the current value of the yield stress, $\Delta Y_j$, and the average value of the yield stress $Y_{AVG}$. The function is:

$$k_{j+1}^{TOT} = u^{-1}(Y_{AVG} - \Delta Y_j) \qquad (14)$$

$$\Delta k^{TOT} = k_{j+1}^{TOT} - k_j^{TOT} \qquad (15).$$

Novo izračunano vrednost $k^{TOT}$ je nato treba enakomerno porazdeliti na vse ravnalne valje hkrati, in sicer tako, da izpolnimo robne pogoje (žica se mora dotikati ravnalnih valjev, pri tem pa lahko spreminjamo le lege drugega, četrtega in šestega ravnalnega valja). Prav tako ni mogoče spreminjati ukrivljenosti na vseh ravnalnih kolesih. Prvo je namreč določeno z ukrivljenostjo žice v kolutu, zadnje pa je odvisno od ravnosti žice na izstopu. Prav tako je ukrivljenost na predzadnjem ravnalnem valju odvisna od ravnosti žice na izstopu. Torej je v ravnalni napravi s sedmimi ravnalnimi kolesi ($n$=7) v eni ravnini mogoče poljubno spreminjati ukrivljenost na štirih ravnalnih valjih.

The new calculated value of $k^{TOT}$ is necessary to distribute uniformly on every roller in such a way as to fulfill all the boundary conditions (the wire should touch the roller, but only the second, fourth and sixth rollers can be changed). Furthermore, it is not possible to change the curvature on all rollers. The first one, $k_1$, is defined by the coil curvature, and the last one should be zero. The one before the last is defined by the zero condition on the last roller as well. A seven-roller wire straightener (n=7) allows for curvature adjustments on four of the rollers. The correlations between the adjacent curvatures

Razmerja med posameznimi nastavitvami morajo ostati enaka. Referenčno vrednost predstavlja drugo ravnalno kolo, ukrivljenosti na preostalih treh pa izrazimo kot:

should remain constant. The second roller is taken for reference and the curvature on the others is expressed as:

$$k_{ij} = k_{2j} \cdot q_{2i} \qquad i = 3..(n-2) \qquad \text{j-ti korak / j-th step} \tag{16}$$

$$k_{ij+1} = k_{2j+1} \cdot q_{2i} \qquad i = 3..(n-2) \qquad \text{j+1-korak / j+1-step} \tag{17}$$

Koeficienti $q_{2i}$ so v ravnalnem postopku nespremenjeni in pomenijo razmerja med nastavitvijo na drugem ravnalnem kolesu in preostalimi (tremi - v primeru ravnalke s sedmimi ravnalnimi kolesi). En. (15) lahko sedaj izrazimo kot:

The coefficients $q_{2i}$ are constants in a certain roller-straightening process and represent the ratios between the curvature on the second roller and the other three (in the case of the seven-roller straightener). Eq.15 can be expressed as:

$$\Delta k^{TOT} = k_{2j+1} \cdot \left(1 + \sum_{i=3}^{n-2} q_{2i}\right) - k_{2j} \cdot \left(1 + \sum_{i=3}^{n-2} q_{2i}\right) \tag{18}$$

Nova ukrivljenost na drugem ravnalnem kolesu je:

The new, wire curvature on the second roller is:

$$k_{2j+1} = k_{2j} + \frac{\Delta k^{TOT}}{\left(1 + \sum_{i=3}^{n-2} q_{2i}\right)} \tag{19}$$

Preostale tri ukrivljenosti $k_{3j+1}$, $k_{4j+1}$ in $k_{5j+1}$ določimo z enačbo (17). Nove lege ravnalnih koles so določene s postopkom, opisanim v prejšnjem poglavju o numerični simulaciji ravnalnega postopka. Odvisnost lege od ukrivljenosti lahko zapišemo z uporabo odvisnosti:

Curvatures $k_{3j+1}$, $k_{4j+1}$ and $k_{5j+1}$ are defined by Eq.17. The new positions of the straightening rollers are calculated using the numerical model of the straightener presented in the previous section. The position of the rollers can be expressed by the function:

$$x_{ij+1} = V(k_{ij+1}) \tag{20}$$

Zveza med lego ravnalnega kolesa in skupno ukrivljenostjo žice $k^{TOT}$ ni linearna in je za primer jekla B s slike 10 prikazana na sliki 12. Stabilizacijski algoritem za to jeklo pa lahko zaradi nižanja meje plastičnosti pri izmenični obremenitvi opišemo preprosto z naslednjimi enačbami:

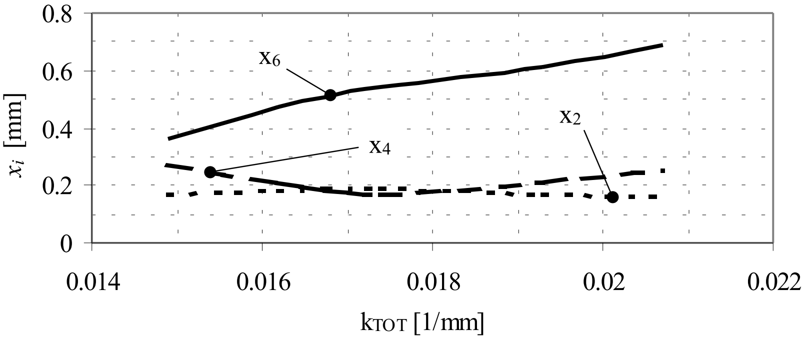
The connection between the roller position and total wire curvature, $k^{TOT}$, is not linear and is presented in Fig.12 (steel B from Fig.10) The stabilization algorithm for the steel B can be, due to the softening of the material during the total cyclic deformation, schematically presented by the equations:

$$\text{če/if} \quad Y_{j+1}^{\Delta l} \geq Y_j^{\Delta l} \Rightarrow k_{j+1}^{TOT} \geq k_j^{TOT} \tag{21}$$

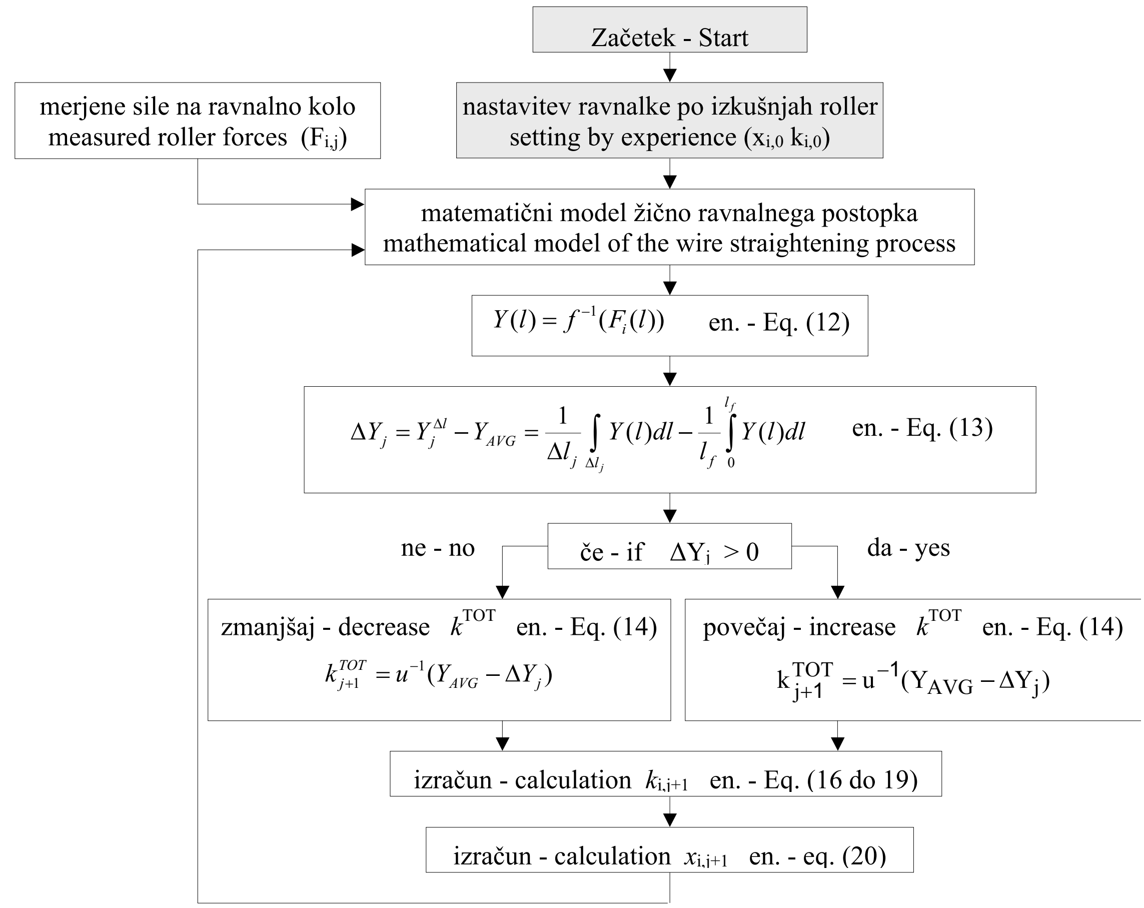
$$\text{če/if} \quad Y_{j+1}^{\Delta l} \leq Y_j^{\Delta l} \Rightarrow k_{j+1}^{TOT} \leq k_j^{TOT} \tag{22}$$

Če je meja plastičnosti v ciklu j+1 večja kakor v ciklu j, potem je treba vrednost $k^{TOT}$ povečati, če hočemo, da bomo dosegli nižjo mejo plastičnosti materiala.

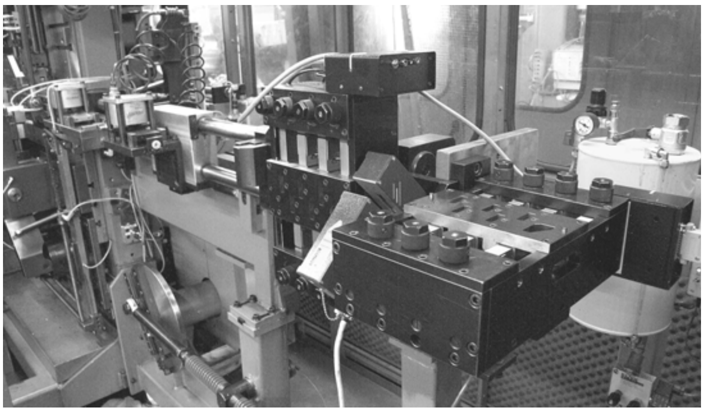
If the yield stress in the cycle j+1 is higher than in cycle j, then the value $k^{TOT}$ should be increased to soften the material.




Sl. 12. *Zveza med lego ravnalnih koles in celotno ukrivljenostjo $k^{TOT}$*
Fig. 12. *The connection between the roller settings and the total curvature, $k^{TOT}$*




Sl. 13. *Shematičen prikaz stabilizacijskega algoritma [11]*
Fig. 13. *Schematic representation of the stabilisation procedure [11]*



Sl. 14. *Preizkusna ravnalna naprava*
Fig. 14. *Experimental wire straightener*

Celoten postopek stabilizacije je shematsko prikazan na sl.13.

### 3.2 Testiranje stabilizacijskega algoritma

Prikazan stabilizacijski algoritem je bil eksperimentalno preverjen na industrijskem primeru izdelave reber, sestavnih delov mehanizmov za registratorje in mape v podjetju NIKO Železniki. V skladu s predstavljenim algoritmom smo spremenili

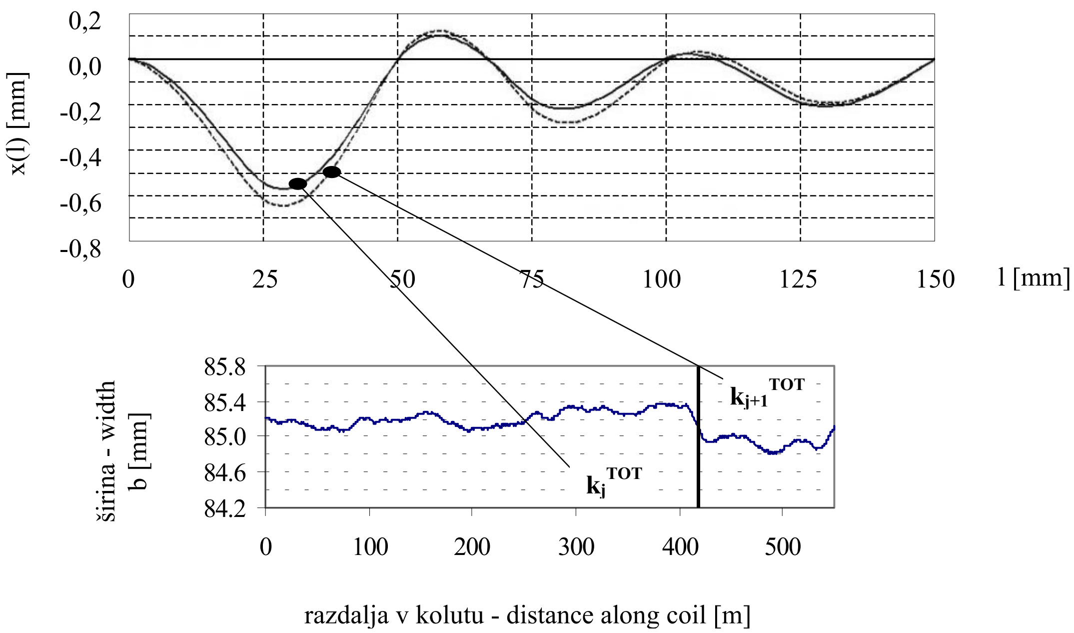
The whole stabilization procedure is schematically presented in Fig.13.

### 3.2 Testing of the stabilization algorithm

The presented numerical model of the stabilization algorithm was finally evaluated in the production of arches for leverarch mechanisms at a company called NIKO Železniki. According to the presented algorithm the roller positions were changed to

Preglednica 3. *Nastavitve ravnalnih koles*
Table 3. *Roller presetting*

| valj št. i<br>roller no. i | $x_{i,1}$<br>$k_{TOT}$ = 0,0174 mm$^{-1}$ | $x_{i,2}$<br>$k_{TOT}$ = 0,0193 mm$^{-1}$ | $\Delta x_i$ |
|---|---|---|---|
| 1,3,5,7 | 0 mm | 0 mm | 0 mm |
| 2 | 0,19 mm | 0,17 mm | -0,02 mm |
| 4 | 0,17 mm | 0,22 mm | 0,05 mm |
| 6 | 0,53 mm | 0,61 mm | 0,08 mm |




Sl. 15. *Preizkusno vrednotenje predlaganega modela: a) pot žice, b) širina izdelka (slika1) pred spremembo (nastavitev j) in po (nastavitev j+1) spremembi lege ravnalnih koles*
Fig. 15. *Experimental verification of the proposed model: a) wire path, b) product width (Figure 1) before (setting j) and after (setting j+1) presettings of the rollers*

lego ravnalnih valjev za izračunane vrednosti. Posledica tega je bila spremenjena pot žice skozi ravnalko in s tem tudi spremenjena meja plastičnosti žice. V končni fazi se je spremenila geometrijska oblika rebra, kot posledica spremembe meje plastičnosti žice. Na sliki14 je prikazana preizkusna merilna oprema, nameščena na žično krivilni avtomat.

S spremembo poti žice skozi ravnalko, ob čemer je bila žica še vedno ravna, se je spremenila širina izdelka, kot glavni geometrijski parameter izdelka (sl. 15b). Spremembe lege ravnalnih koles so prikazane v preglednici 3, pot žice skozi ravnalko pred spremembmo in po njej lege valjev pa na sliki 15a).

the calculated values. This means that the wire path through the straightener was changed as well, which means a certain difference in the flow stress of the wire that is coming out of the wire straightener. Because of this difference there is a clear change in the geometrical parameters of the finished arch. The experimental set-up mounted onto the bending machine is presented in Fig.14.

By changing the wire path through the straightener (wire remains straight), the width ,as the major geometrical parameter, changed as well (Fig.14.b). Table 3 presents the corrections performed on the straightening rollers. Figure 15 a) presents the wire path through the straightener before and after the roller presetting.

## 4 SKLEP

V prispevku je bil najprej prikazan numerični model ravnanja žice v ravnalni napravi, ki v nadaljevanju rabi kot jedro stabilizacijskega algoritma. Zamisel je bila preizkusno ovrednotena, s čimer smo potrdili, da je takšen način stabilizacije geometrijskih parametrov izdelkov iz žice mogoč, kljub temu, da so

## 4 CONCLUSION

A numerical model of the wire-straightening process has been presented, which serves as the core for the stabilization algorithm. The idea was experimentally verified, which confirmed that the stabilization of the geometrical parameters of the product made out of wire is possible, even though v njej prisotne spreminjajoče se materialne lastnosti. Pri tem nas ne zanimajo vzroki za te neenakomerne lastnosti materiala, temveč se osredotočimo na samo stabilizacijo.

Nadaljnje možnosti uporabe se odpirajo predvsem v smeri izdelave pločevinastih izdelkov. Kakršenkoli drug način poprave geometrijske oblike je zaradi večje zapletenosti izdelkov otežen. Postopek s stabilizacijo meje plastičnosti jekla pa ponuja tudi v tem primeru odlične možnosti.

the input material had an inhomogeneous yield stress. The reasons for the material inhomogenities are not a part of the discussion. We have only focused on the stabilization principle.

Further applications are also possible in the field of sheet-metal forming. Any other way of correcting the geometry of sheet-metal parts is more difficult because of the complex geometry. The material's yield-stress stabilization algorithm also promises good results in this field of production.

## 5 ZAHVALA

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