Cyclic loading of low carbon cold drawn wires - the possibility to stabilize the yield stress

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Abstract:

Metal working industry is facing, among other problems, also with one of the instability of yield stress of the work material. In special cases (bending, stretching,…) it has an enormous affect on the final geometrical shape of the finished part. A research work in the field of cold drawn wire forming showed by appropriate presetting of the wire straightener, it is possible to influence the bending process, which follows. Repositioning of the straightening rollers depend upon current yield stress of wire which fluctuates during the process run. The first part of the paper presents a numerical analytical system for the characterization of the yield stress during wire straightening process. These data are used in the second part in the stabilization algorithm, which defines new positions of the rollers. Finally the principle has been experimentally verified in the production of leverarch mechanisms for maps and files.

Keywords: straightening, Bauschinger phenomena, bending, numerical modeling

I. INTRODUCTION

Stabilization of mechanical properties of the wire material seems to be unavoidable in modern wire processing lines. It is a precondition for stable production, which is reflecting above all, in stable geometrical parameters of finished products. Keeping the geometrical parameters of the semi products in narrower tolerance field would mean much less problems during automatic assembling lines and technological processes that follows. Overall efficiency of the production equipment would be higher, which means a certain advantage in the market position of the company.

Normally, fluctuation of input mechanical properties is presented in every material, but it is even more expressed in relatively low cost materials designed for mass production, such as leverarch mechanism for maps and files which are made in millions.

It has been presented by Patel et.al.[1] that consistent mechanical properties depends mainly on the metallurgical treatment of material. Investigations about the possibility of stabilizing the material parameters from the metallurgical point of view are therefore very important.

Presented paper discusses the possibility for the stabilization of mechanical properties of input material on the forming principle. Cold drawn wire is normally first bent on a coil and then delivered to another company for further processing. Therefore, prior to whatever forming process, the wire has to be straighten, which is done by using different kinds of wire straighteners. At this process, wire is subjected to alternating tensile and compression stress states which have an affect not only on the final straightness of wire, but also on its mechanical properties. The most important for bending processes, which normally follow, is the yield stress of wire.

II. BAUSCHINGER EFFECT

Cold drawn materials normally exhibit cyclic softening while being exposed to alternating plastic deformation. The phenomenon has been described first by Bauschinger [2,3,4]. Many efforts have been made than in the field of building appropriate models for a successful description and integration into numerical models capable to describing this effect [5-11]. Huml et.al [12,13,14] did some experiments showing the possibility of influencing the yield stress of wire material towards softening or hardening. Steel materials normally harden when being exposed to continuous plastic deformation, but when being exposed to alternating tensile and compressive stress states softening could occur. The amount of cyclic softening depends on the strain increment, which material is exposed to (Fig.1).

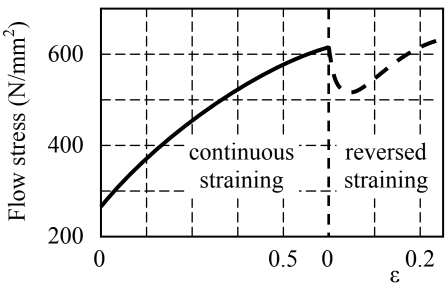


Figure 1: Schematically representation of the material hardening at continuous straining and softening at reversed straining [12]

III. CONSTITUTIVE MODEL FOR CYCLIC LOADING

The stress - strain diagram presented in Fig.1 can mathematically be expressed by the combination of isotropic hardening and kinematic hardening [3]. The yield surface expands and its center is moving in the space (Fig.2). Such constitutive model requires a definition of several parameters describing isotropic and kinematic hardening. Isotropic hardening part can be expressed by the following equation:

$$\sigma_0 = F\left\{\int \overline{d\varepsilon}^{p}\right\} \tag{1.}$$

Basic equation describing kinematic hardening rule involves a backstress tensor, which shifts the yield surface in space:

$$f(\sigma_{ij} - \alpha_{ij}) = k^2 \tag{2.}$$

Where σ_{ij} is stress tensor, α_{ij} represents backstress tensor, k^2 is according von Mises criterion equal to the second invariant of the deviatoric stress tensor J_2.

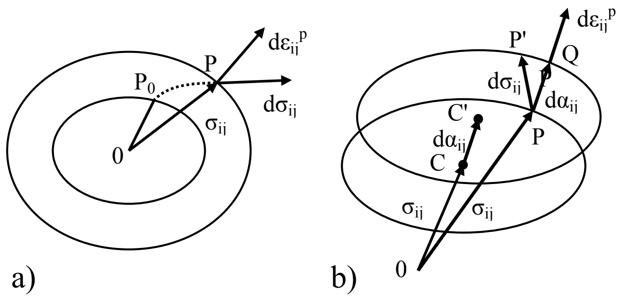


Figure 2: Geometrical representation of the hardening rule in the stress space a) isotropic hardening, b) kinematic hardening

III.I Simplification of the constitutive model

A reasonable simplification, which will be needed for use in a production control system and is accurate enough, is to represent the problem in one dimension only is discussed in this section. While the wire is straighten in the straightener the major stress acts only in the direction of wire length and it is assumed that all other stresses can be neglected. The Prager's flow rule has been introduced accordingly:

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

$$d\sigma = E\cdot d\varepsilon \qquad C \geq 0$$

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

Equations represent a one-dimensional model of the general constitutive model for cyclic plasticity. The parameters, which are needed to define the material characteristics according to the model in Eq.3, are as follows:

- Y - yield stress,
- E - modulus of elasticity,
- K - plastic hardening coefficient,
- n - elastic plastic transient coefficient.

The presented model is capable to predict material properties at cyclic loading, but it is not capable to include material hardening (softening) from cycle to cycle, however it is of a great importance for an accurate modeling.

Since cold drawn wire material exhibit cyclical softening when being exposed to reversed elastic-plastic deformation, it is necessary for a modification of the Prager's rule to include a term, which will allow for softening or hardening during cyclic loading. This possibility has been given by including an additional term in the Prager's equation:

$$Y = Y_0 \cdot D_{cyc}^{n} \tag{4.}$$

With the included additional term in the Prager's equation it is possible to variate the yield stress of wire in two directions. This equation is used for on-line material properties assesing, where the only parameters, which could change, are yield stress and the hardening exponent.

III.II Material characteristics

Wire material with his chemical composition has the main affect onto the behavior during cyclic loading, but also the amount of cyclic deformation plays an important role for cyclic behavior of metals. It has an affect on the yield stress after straightening. For two materials of steel wire used in the production the relationship between cyclical deformation and its yield stress is presented in Fig.3.

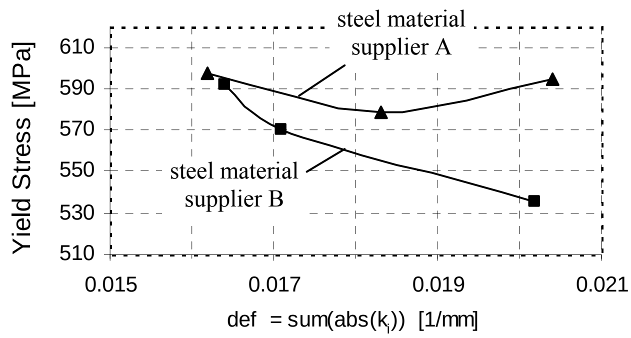


Figure 3: Material characteristics at cyclic loading for two different material producers.

Table 1: Chemical composition of the wire material

C %	Si %	Mn %	P %	S %
0.05	0.12	0.46	0.011	0.025

IV. ON-LINE ASSESSING OF THE MATERIAL PROPERTIES

Special measuring equipment for on-line data assessing has been constructed by the authors [15,16]. At the same time it should also be capable to influence the wire yield stress. The measuring equipment is based on the wire straightener platform (actually, it is a modification of the seven roller wire straightener which has load cells mounted onto the straightening rollers) since it is characterized by low cycle alternating plastic deformation and it is also possible to change the amount of reversed plastic deformation, which is essential for the yield stress stabilization.

It is possible to measure the yield stress of wire on-line. A production cut out of such a measurement is presented in Fig.4. It shows the scaled values of the yield stress and part geometry according the following equation:

$$b_{rel} = \frac{b(l) - b_{min}}{(b_{max} - b_{min})} \qquad Y_{rel} = \frac{Y(l) - Y_{min}}{(Y_{max} - Y_{min})} \qquad (5.)$$

It can be realized that the fluctuation of the material parameters are relatively low (only 4% to the reference value), but the fluctuation has the same frequency as the fluctuation of the geometrical parameters of the finished product which is made out of this wire. It can be easily concluded and explained that wire material parameters have the main impact onto the geometrical shape of the product, especially when bending operations are concerned. The reason for this is that bending processes are influenced by spring back, which depends on the yield stress of the wire material.

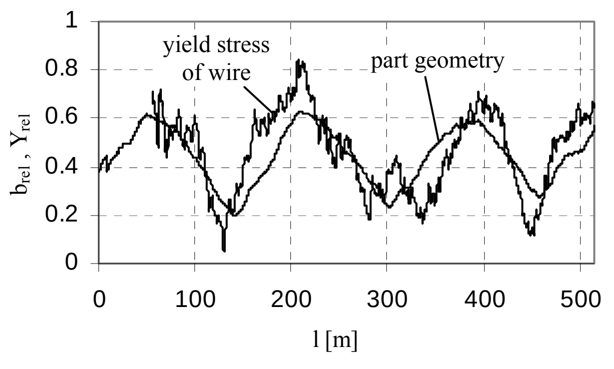


Figure 4: Fluctuation of the part geometry and comparison to the fluctuation of the yield stress of wire (scaled values)

An analytical model of the wire straightener has been developed using MatLab environment. It is capable to calculate the residual curvature of wire coming out of the straightener and transverse forming forces acting on the rollers. The model can be presented by the following equation:

$$(F_1...F_7, k_{res}) = f(d_x, d_y, E, Y_0, n, K, D_{cyc}, k_{ini}) \qquad (6.)$$

Parameters of the equation are:

- d_x - wire diameter in x direction (mm),
- d_y - wire diameter in y direction (mm),
- M - modulus of elasticity (MPa),
- Y_0 - initial yield stress of wire (MPa),
- K - hardening coefficient (MPa),
- n - transient elastic-plastic coefficient (-),
- D_{cyc} - factor for cyclic hardening (softening) (-),
- k_{ini} - initial curvature of wire (m^{-1}),
- $F_1...F_7$ - transverse roller forces (N),
- k_{res} - residual curvature of wire (m^{-1}).

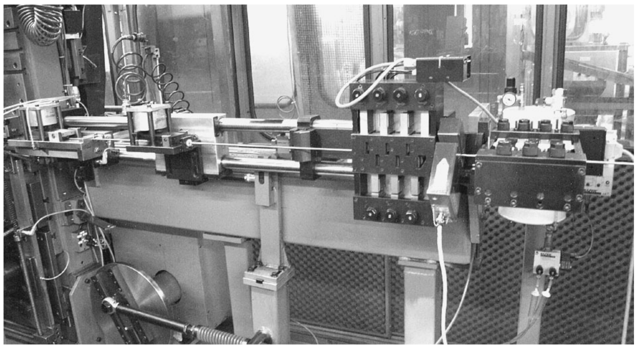


Figure 5: Experimental wire straightener mounted on a bending machine

The inverse of the presented model can then be used for on-line assessing of the material parameters of the wire.

IV.I Material properties assessing algorithm

The transverse forming force can be measured on every of the five rollers in seven roller straightener (two of the rollers are not included in the measurement algorithm). It can be assumed based on the experimental verification that some of the material parameters are not fluctuating within the length of the coil (d_x, d_y, E, n, K, E, k_{ini}). k_{res} is also not dependent on the transverse forming forces and can be abandoned in the equation. Therefore, the Eq.6 can be rewritten in the following form:

$$(F_1...F_5) = f(Y_0, D_{cyc}) \qquad (7.)$$

Eq.7 represents the transverse forming forces acting on the roller and final curvature of the wire as being dependent only on the initial yield stress of wire and the cyclic hardening (softening) coefficient. An inverse model can therefore be presented as follows:

$$(Y_0, D_{cyc}) = f^{-1}(F_1...F_5) \qquad (8.)$$

There are actually too many measurable parameters and the system is over defined. The problem can be avoided by taking the fact of measurement inaccuracy in account. There is always some noise presented in the experimentally observed values, therefore it is appropriate to treat the results in a statistical way. Introducing the linearization about the working point one would get Eq.9.

$$\begin{Bmatrix} Y_0 \\ D_{cyc} \end{Bmatrix} = \begin{bmatrix} \frac{\partial F_1}{\partial Y_0} & \frac{\partial F_1}{\partial D_{cyc}} \\ \cdot & \cdot \\ \cdot & \cdot \\ \cdot & \cdot \\ \frac{\partial F_5}{\partial Y_0} & \frac{\partial F_5}{\partial D_{cyc}} \end{bmatrix}^{-1} \cdot \begin{Bmatrix} \Delta F_1 \\ \Delta F_2 \\ \Delta F_3 \\ \Delta F_4 \\ \Delta F_5 \end{Bmatrix} + \begin{Bmatrix} Y_{0,ini} \\ D_{cyc,ini} \end{Bmatrix} \qquad (9.)$$

The right hand side of the Eq.9 represents five independent linear equations for two unknowns. System is over determined therefore, any two equations among five will be enough for determining the current yield stress Y_0 of wire and its softening factor D_{cyc}. There are 10 different possibilities for defining both values and every of them depend onto the measured values F_i. Final values are therefore defined according the Eq.10:

$$Y_0 = \frac{1}{10}\sum_{i=1}^{10} Y_{0\,i} \qquad D_{cyc} = \frac{1}{10}\sum_{i=1}^{10} D_{cyc\,i} \qquad (10.)$$

An example of this measurement is presented in fig.3, which shows the fluctuation of yield stress of wire along the coil. One minute time on the x-axis corresponds to 18.5 m. Total amount of wire being bent on a coil depends mainly on the type of coil and characteristics of further production line. In our case there were approximately 4900 m of wire in one coil.

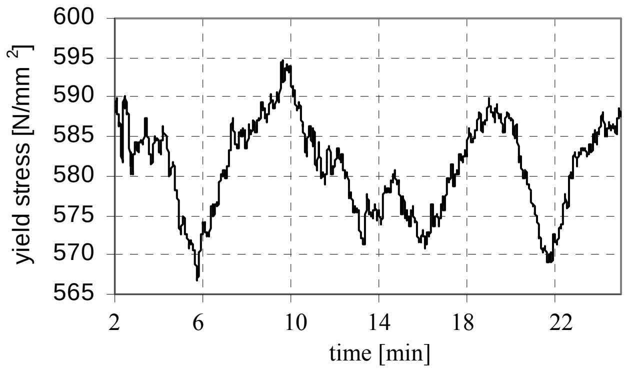


Figure 6: Fluctuation of the flow stress of wire within the length of the coil

V. STABILIZATION OF THE MATERIAL PROPERTIES USING ROLLER STRAIGHTENER

In the next paragraph we would like to give some more emphasis onto the possibility to stabilize such a fluctuation of yield stress of wire as presented in Fig.6.

V.I Wire characteristics

First measurement, which has to be done prior to introducing the stabilization algorithm, serves us with the needed data about wire characteristics. Yield stress of wire does depend on the amount of cyclic deformation, but there is a difference between several wire producers (Fig.3). Therefore, the characteristic has to be measured for every producer separately. The first problem, which arises in bending, is the definition of the reference value for the amount of cyclic deformation. It cannot be the relative displacement of fibers within wire material, since the cross section of wire is not uniformly deformed. We have decided to introduce the wire curvature, since it is equal for all points in a specified cross section.

During straightening in the roller straightener, the wire is bent sequentially from positive towards negative curvature values. The total amount of deformation has therefore been expressed as sum of absolute values of maximal curvature within one single bend (Eq.11).

$$def = \sum_{i=2}^{n-1} \left| k_i^{max} \right| \qquad (11.)$$

Where:

- def - total curvature change within straightening (1/m),
- k_i - peak curvature in a single bent (1/m),
- n - number of straightening rollers.

By changing the value of def, which is normally done by the resetting the positions of the rollers, the yield stress of wire changes as well and it depends on a wire manufacturer. The diagram in Fig.3 shows wire characteristics for two different wire suppliers.

V.II Stabilization algorithm

The stabilization algorithm for wire material properties is based on the fact that it is possible to influence the fall of flow stress of wire. In the case of wire supplier B, the higher total deformation, lower is the final yield stress of material and vice versa. The system detects current yield stress of wire in a way described in the section IV. At this point the positions of the rollers in a roller straightener are set to the operating point so that the wire is straight when coming out from the straightener.

The variable *def* defined by the Eq.10 has at this point a value of 0.0173 mm^{-1}. When increasing it to 0.0193, the flow stress of wire of wire supplier B would fall for apr. 20 MPa, (diagram in Fig.3) The positions of the rollers are changed accordingly (Table 2). The sum of the curvature is increased when the yield stress is rising and decreased when it is falling. Since the initial flow stress of wire is fluctuating within the cycles lasting for 8-10 minutes, there is enough time to react.

Actually, due to the fluctuation of flow stress of wire, the outgoing curvature fluctuates as well, but normally it does not affect the following technological process very much. Normally this problem is solved by increasing the number of straightening rollers [17,18,19].

Table 2: The position of the rollers before and after curvature adjustments.

roller	position at def = 0.0173 mm^{-1}	position at def = 0.0193 mm^{-1}
x_1, x_3, x_5, x_7	0 mm	0 mm
x_2	0.19 mm	0.17 mm
x_4	0.17 mm	0.22 mm
x_6	0.53 mm	0.61 mm

Determining the new positions of the straightening rollers has to be done by using the application developed in MatLab. Peek curvatures corresponding to a specific roller are increased or decreased proportionally, to the old values, while the sum of all peek curvatures corresponds the values 0.0173 initially and 0.0193 after new presetting.

$$\Delta\text{def} = \sum_i k_{i\ \text{new}} - \sum_i k_{i\ \text{old}} = \\ = k_{2\,\text{new}} + k_{3\,\text{new}} + k_{4\,\text{new}} + k_{5\,\text{new}} \\ - k_{2\,\text{old}} - k_{3\,\text{old}} - k_{2\,\text{old}} - k_{2\,\text{old}} \qquad (12.)$$

Total difference has to be distributed proportionally to all four peek curvatures. Actually there are seven curvatures, which describe the behavior of the wire in the roller straightener, but it is not possible to influence on all of them. Wire curvature on the first roll depends on the wire curvature bent on coil. Since the curvature on the last roller has to be zero, so it is necessary to adjust the curvature on the sixth roller as well. Other four rollers can be adjusted independently. Boundary condition for the adjustment of the rollers is force needed for pulling the wire out of the straightener, which should stay reasonable low.

Total difference of *def* can therefore be expressed in the following way:

$$\Delta\text{def} = k_{2\,\text{old}} \cdot (1 + p_1 + p_2 + p_3) \\ - x \cdot k_{2\,\text{old}} \cdot (1 + p_1 + p_2 + p_3) \\ \Rightarrow x = \frac{k_{2\,\text{old}} \cdot (1 + p_1 + p_2 + p_3) - \Delta\text{def}}{k_{2\,\text{old}} \cdot (1 + p_1 + p_2 + p_3)} \qquad (13.)$$

VI. EXPERIMENTAL VERIFICATION

A simple experiment has been done then with the wire of supplier B. The positions of the rollers were changed manually so that the total wire curvature has been set from initially 0.0173 to final value of 0.0193. By the numerical model of the wire straightener the new positions of the rollers were calculated so that the wire remain straight when coming out of the straightener. Due to the change of mechanical properties of wire, which is a consequence of the increased amount of reversed plastic deformation, the geometry of the finished product changes as well in average for apr. 0.2 mm (Fig.7).

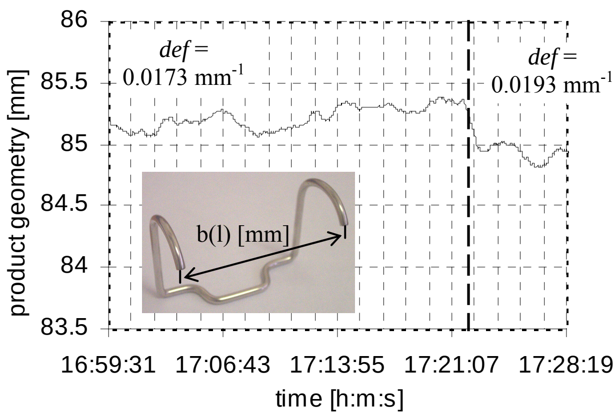
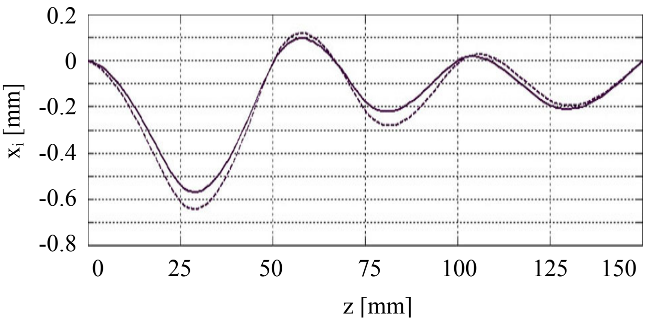


Figure 7: Product geometry change due to different presetting of roller within the roller straightener. New setting has been performed at 17:21:30 and the consequence is a change in the part geometry

Corresponding wire path in the wire straightener is presented in Fig.8. Relatively small change in the position of the straightening rollers can rather affect the final product geometry.



VII. CONCLUSION

This paper presents an algorithm for influencing the mechanical properties of wire by controlled cyclic deformation. In some technological operations, such as bending process, yield stress of the material has the main affect onto the final geometrical properties of the product. It is a consequence of different amount of spring back, which is especially important at bending operations. The undertaken experimental work proves that it is possible to influence the part geometry by different presetting of the rollers in the roller straightener, which means different amount of reversed plastic deformations.

Numerical procedure for stabilizing mechanical properties of wire material is presented thoroughly. Theoretical background has been first simplified to the point of being applicable into the real production. An analytical model of the wire straightener has been made using the extended form of Prager's equation supported by additional term, which allows for material softening from one cycle to another. Based on the model a stabilization algorithm has been developed and experimentally verified. It has shown that stabilization of material properties by controlled cyclic deformation is possible and can be successfully applied in industrial processes.

VIII. ACKNOWLEDGEMENTS

This work has been done in the frame of EUREKA E2382! The authors acknowledge the financial support by the Slovenian Ministry of Science and Technology. They also wish to thank the factory's personnel whose work is directly involved with the discussed issue.

IX. REFERENCES

[1] J.K.Patel, B.Wilshire, The Challenge to Produce Consistent Mechanical Properties in Nb-HSLA Strip Steels, J.Mat.Proc.Tech., 2002, vol 120, 316-321,

[2] S.Suresh, Fatigue of Materials, Cambridge University Press, 1998,

[3] R.Hill, The Mathematical Theory of Plasticity, Oxford, Clarendon Press, 1998,

[4] J.Chakrabarty, Applied Plasticity, Springer-Verlag New York, 2000

[5] Z.Mröz, H.P.Shrivastava, R.N.Dubey, A Nonlinear Hardening Model and its Application to Cyclic Loading, Acta Mech.,1976, vol.25, 51,

[6] W.Prager, A New Method of Analyzing Stress and Strain in Work-Hardening Plastic Solids, J.Appl.Mech, 1956, vol.23, 493,

[7] N.T.Tseng, C.C.Lee, Simple Plasticity Model of the Two-Surface Type, J.Engng.Mech.Trans. ASCE, 1983, vol.109, 795,

[8] J.T.Gau, G.L.Kinzel, A New Model for Springback Prediction in which the Bauschinger Effect is Considered, Int.J.Mech.Sci.,2001,vol.43, 1813-1832,

[9] K.C.Valanis, On the Foundation of the Endochronic Theory of Plasticity, Arch.Mech., vol 27, 659

[10] D.L.McDowel, A Two Surface Model for Transient Nonproportional Cyclic Plasticity, J.Appl.Mech.,1985, vol. 52, 298,303,

[11] N.Ohno, Y.Kachi, A Constitutive Model for Cyclic Plasticity for Nonlinear Hardening Materials, J.Appl.Mech.,vol53.,395,

[12] P.Huml, The Influence of Strain Path on Wire Properties, Advanced Technology Of Plastiticity 1987,Springer-Verlag, Vol.II,

[13] P.Huml, Utilization of Flow Stress in Metal Forming Calculations, Annals of the CIRP, 33, 1984, 147-149,

[14] H.P.Stűve, Einfluss von wechseln der Beanscpruchungsrichtung auf die Fliesspannung von Metallen, Berichte aus dem Inst.f.Umformtechnik, Nr.74.,Universität Stuttgart, 1983,

[15] M. Nastran, A contribution to the stability of the cold forming process of wire, PhD Thesis, University of Ljubljana, 2003

[16] M. Nastran, K. Kuzman, Stabilization of mechanical properties of the wire by roller straightening, J.Mat.Proc.Tech.,125-126:711-719,2002

[17] A.Eckehard, M.Schilling, Qualitätverbesserung in der Drahtverarbeitung, Draht 1/98,

[18] H.Schneidereit, M.Schilling, Bestimmung der Mindestrollenanzahl bei Drahtrichtapparaten, Draht 47(1996), 7/8, 398-400,

[19] W.Guericke, M.Paech, A.Eckehard, Simulation des Richtens von Draht, Draht, 47(1996) 1/2, 23 - 29.