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Algorithms for Automatic Billet Straightening Machine

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Abstract. This scientific contribution presents current results of cooperation focused on the automatic billet straightening machine development. An experimental study of three-point bending is shortly presented to explain basic ideas of the straightening. Main variants of straightening are briefly described. Some material parameters have to be properly determined for a new material in the straightening process, what is solved by creation of software for their estimation from a mapping regime of straightening.

Introduction

There are many applications requiring straightening of a long metallic material, for example billets [1], elevator guide rails [2] or more general long linear guideways [3].

In technical practice, two methods of straightening profile bars are usually used. The first possibility is continuous straighteners [4, 5], which is however problematic for straightening of large cross-sections, mainly due to the need to use large bearings.

The billet straightening, which is described in this contribution, is necessary operation done in ironworks before grinding of billets. Straightening by means of three-point bending is more accurate and flexible in terms of straightened cross-sections than continuous straightening. The billet straightening by 3-point bending is usually done manually by operators in manual regime based on human vision and joystick control [1]. In the automatic straightening machine an algorithm must be adapted with respect to the input curvature of the profile bar (e.g. single-arc shape, "S" shape or shape with multiple vertices [6]). This is usually the so-called multi-step straightening mechanism [3, 6]. For a multi-step straightening mechanism, it is then necessary to correctly determine, for example, the number of straightening steps, the distance of supports, the size of the straightening force / straightening stroke, with different settings, differently aligned bars can be obtained [2]. The crucial thing is an accurate prediction of springback [7].

The aim of this contribution is to present results currently gained in the frame of a long term project focused on the development of automatic billet straightening machine. The machine has been constructed by KOMA Industry company for Třinecké železárny. The camera vision and visualisation of straightening was developed by experts from Elcom company. The main aim is to show basic ideas of the newly proposed algorithm and to explain the necessary optimisation procedure to get some process parameters for reliable straightening.

Three-point Bending

For better understanding of the basic idea of algorithm the terminology should be introduced. The irreversible deflection w_{pl} remaining after unloading will be called the plastic deflection, see Fig. 1. This quantity is also important input for the algorithm and is measured by a camera system in the developed automatic straightening machine.

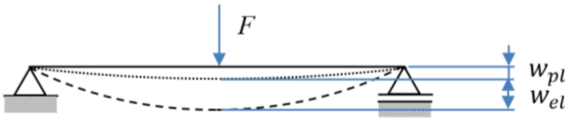

Fig. 1: A scheme of 3-point bending case

Then, the total deflection w is composed of the plastic deflection w_{pl} and the elastic deflection w_{el}, thus

$$w = w_{el} + w_{pl} \,. \tag{1}$$

The plastic deflection w_{pl} can be calculated considering an elastic stiffness k_{el} and applied bending force F according to the analogy to Hooke's law

$$w_{pl} = w - w_{el} = w - \frac{F}{k_{el}} \,. \tag{2}$$

Experiments

First of all, an experimental study including tensile tests and 3-point bending tests performed on the 51CrV4 material will be presented. The bending tests were realised on specimens with the rectangular cross-section of variety of dimensions D and distances of supports L. An example of obtained force vs deflection diagrams is shown in Fig. 2. In order to visualise the difference of cross-section dimensions a photo of some specimens is presented in Fig. 3.

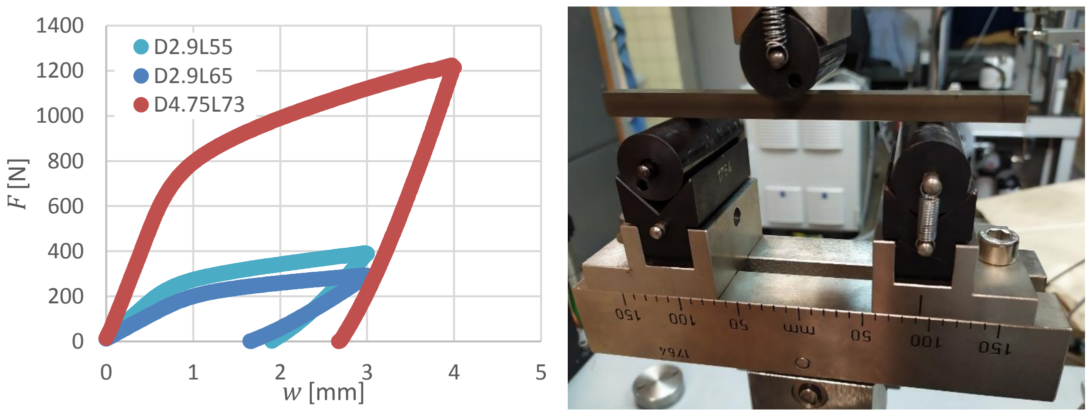

Fig. 2: Dependency of force on deflection from a bending test (left), a photo of measurement

Fig. 3: A photo of selected deformed specimens

For straightening of billets with different dimensions of a square cross-section it is important to investigate how the dependences of the total deflection on the plastic deflection differ for individual cross-sectional sizes. The main result of the experimental study is the graph in Fig. 4, where all the obtained dependences of the total deflection on the plastic deflection for individual dimensions of the cross-section are shown (e.g. the designation 2.9x2.9 corresponds to the dimension of the side of the cross-section 2.9 mm).

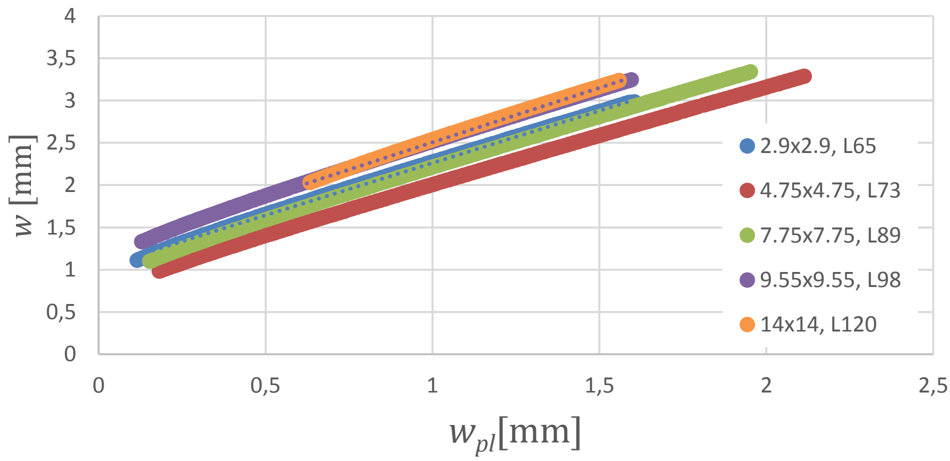

Fig. 4: Dependence of total deflection on plastic deflection from experiments performed in laboratory conditions at room temperature

An important finding from the performed experimental study is the fact that although the cross-sections are significantly different in cross-sectional dimensions, the slope of the dependence $\boldsymbol{w}(\boldsymbol{w_{pl}})$ remains approximately the same. The curves therefore differ only in the vertical offset. However, it is necessary to mention, that the distances of supports L were considered differently for each case based on a Finite Element simulations (for instance L65 in the legend of the graph in Fig.4 means L=65mm).

Material parameters

The straightening run is designed by dividing the billet into sections corresponding to the distance of the supports (e.g. L = 1000 mm) and for the measured deviation from the straightness w_{pl} the required stroke w is calculated from the relation

$$w = w_Y + k_w w_{pl} \,, \tag{3}$$

where w_Y, k_w are material parameters.

There are also two other material parameters w_{ignor} and w_{max}, which should be appropriately determined for given material. After estimation of stroke w, it is checked whether $w > w_{ignor}$ is valid in the individual sections. If the condition does not apply, the intervention is omitted in the given section. If $w > w_{max}$, the release is performed by three (or two only) strokes to prevent billet breaking. Estimation of the size of such particular strokes can be done by means of numerical analyses [8]. An application has been coded in Python, which is used for estimation of material parameters mentioned above, see Fig. 5. A mapping regime of straightening is necessary, when a new material should be straightened, to be able to apply equations (2) and (3).

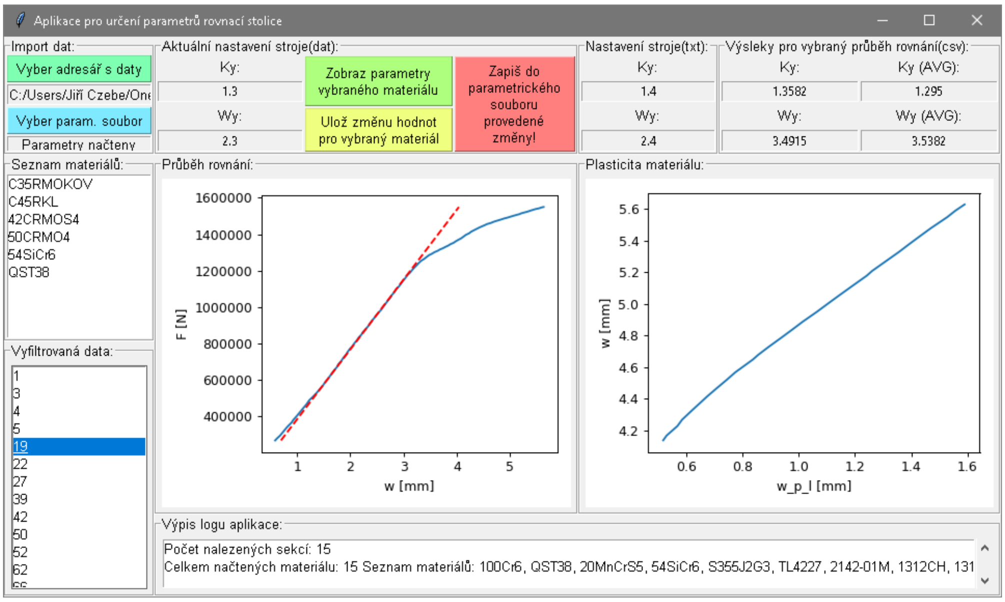

Fig. 5: User interface of software for material parameters identification (In Czech)

Straightening algorithm

Two criteria are used to assess the straightness of the billet. The first direct access to the entire length of the billet, which is the sum of the heights and the minimum deviation from the linear regression equation. This value is denoted as p_1 in the algorithm. The second characteristic is the straightness per meter of billet length. This value is available as the sum of the payments and the minimum deviation from the regression line equation determined by the meter. This value is denoted as p_2 in the algorithm. The critical value of parameter p_1 will be marked as $p_{1\mathrm{crit}}$ and is generally dependent on the billet length. The critical value of parameter p_2 will be marked as $p_{2\mathrm{crit}}$ and influences also the output accuracy of straightening process. According to current state of experimental validation, the following variants of straightening are possible. The border between strongly crooked and slightly curved billets is p_0.

Variant 1 ($p_1>p_0$ and $p_2>p_{2\mathrm{crit}}$): This variant is usually the most effective for "snake-like" billets. The billet is divided into meter sections. In each section, a regression line is determined and the value of w is calculated. If $w>w_{ignor}$ then an intervention is performed in the given section. This variant is usually quite time consuming for a large number of interventions.

Variant 2 ($p_1<p_0$ and $p_2<p_{2\mathrm{crit}}$): It is assumed that the billet can have two possible shapes (single-arc shape or "S" shape). Then it is straightened by either two or one stroke. The same parameter p_0 is considered for all materials.

Variant 3 ($p_1>p_{max}$): This is a regime useful for very crooked billets (occurs usually for single-arc shape). The value of p_{max} is a limit of p_1 for the billet to be considered for this variant of straightening. The straightening is boosted based on experience with the given material. The same parameter p_{max} is considered for all materials.

Variant 4 ($p_1 < p_{1\mathrm{crit}}$ and $p_2 > p_{2\mathrm{crit}}$): This variant is very important in the case, when the billet is curved just in one place. The largest deflection is found and the stroke is proposed analogously as in the Variant 1.

The main program for determination of the position and stroke size proposal was developed in NI LabView. Selection of variants is done from the parent system.

Conclusions

The main finding of this scientific study is the importance of plastic hardening parameter k_w to be able to perform the automatic straightening for different cross-section size in technical practice. There is a possibility to increase the support distance with increasing cross-section size to keep the plastic hardening parameter k_w exactly the same. The second important parameter w_Y depends on the yield strength of the material and the cross-section dimensions of the billet. Both material parameters, k_w and w_Y must be identified for the considered material of billet at least on one selected cross-section size data.

Many numerical simulations were done based on Chaboche material model with two backstress parts [9] to propose the nature of algorithm described in this contribution [8]. The basic variants of straightening considering different shapes of the billet have been described. The algorithm was verified on chosen steels in The New Long Billet Treatment Plant of Třinecké železárny. The process and material parameters are optimised using a Python code. An example of one pass of the billet using variant 1 of the algorithm is shown in Fig. 6.

The next step of research is the application of rigid body movement calculations [3, 6] to speed up the straightening process (to minimize necessity of scanning).

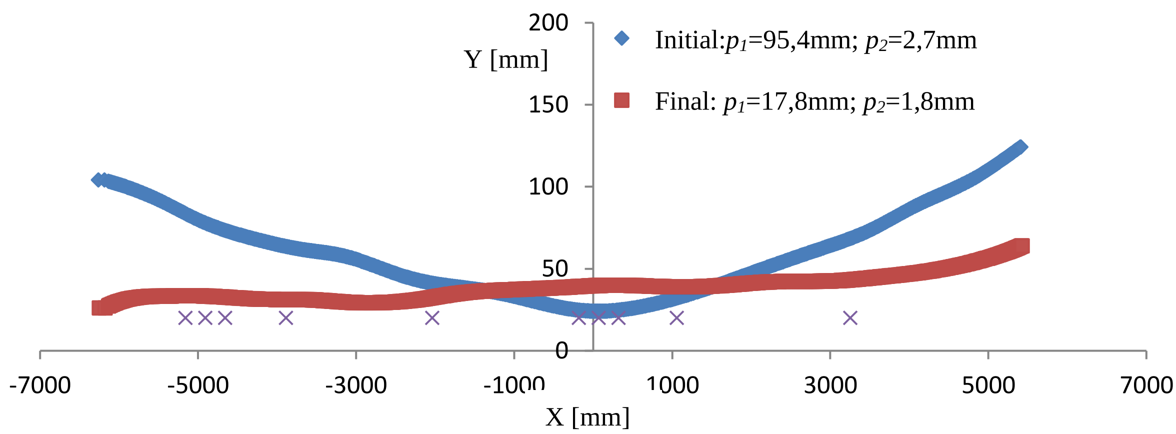

Fig. 6: Shape of the billet before (blue) and after (red) straightening by variant 1

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