UDK 621.771:519.68
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
MTAEC9, 40(2)61(2006)

DETERMINATION OF THE DEFORMATIONAL ENERGY DURING SLAB-WIDTH ROLLING ON AN EDGER MILL

DOLOČANJE DEFORMACIJSKE ENERGIJE PRI VALJANJU SLABOV NA KRČILNEM OGRODJU

Franci Vode[1], Anton Jaklič[1], Roman Robič[2], Anton Košir[2], Franci Perko[2], Jani Novak[2]

[1]Inštitut za kovinske materiale in tehnologije, Lepi pot 11, 1000 Ljubljana, Slovenia
[2]Acroni d.o.o. Jesenice, Kidričeva 44, 4270 Jesenice, Slovenia
franci.vode@imt.si

Prejem rokopisa – received: 2005-09-01; sprejem za objavo – accepted for publication: 2006-01-29

The production of hot-rolling strips of known dimensions requires planning of the slab dimensions and the dimension-change traction of slabs along the production line. A combination of an edger-roll gap measurement and the deformational energy consumed to achieve the desired slab width on the edger enable a rough estimation of the slab widths during rolling. The paper is focused on an automatic calculation of the deformational energy consumed for slab-width rolling on the basis of existing edger measurements. For the calculation of the deformational energy consumed for slab-width rolling a mathematical model of an unloaded edger was built. The edger roller was treated as a stiff, rotary-driven body. The model calculates the consumed power for the velocity changes of the unloaded edger using the velocity input signal. The constructed model has enabled an estimation of the power consumed for the slab-width rolling only. The integration of the power over every pass through the edger yields the deformational energy. The acquired information is instantly written in a database, where they can be accessible for an estimation of the slab width during rolling.

Key words: steel, hot-rolling strips, deformational energy, edger, mathematical model

Proizvodnja toplo valjanih trakov znanih dimenzij zahteva načrtovanje dimenzij slabov in spremljanje dimenzij obdelovanega slaba med valjanjem. S kombinacijo meritev nastavne širine krčilnega ogrodja in deformacijske energije, porabljene za valjenje širine slaba s krčilnim ogrodjem preko vseh valjarskih prevlekov ogrodja bluming, je možno grobo ocenjevanje poteka širjenja slabov med valjanjem.

Delo je osredinjeno na avtomatizirano določanje deformacijske energije na krčilnem ogrodju iz obstoječih meritev krčilnega ogrodja. Za računanje energije, vložene v valjanje širin slabov, je bil zgrajen matematični model vrtenja neobremenjenega krčilnega valjarskega stroja. Krčilni valjarski stroj smo obravnavali kot togo, rotirajoče gnano telo. Model iz meritve hitrosti računa moč, vloženo v spreminjanje hitrosti vrtenja neobremenjenega krčilnega stroja. Dobljeni model je omogočil ocenjevanje moči, vložene samo v valjanje širin slabov. Integracija moči preko vsakega prevleka daje njegovo deformacijsko energijo. Pridobljene informacije se sprotno zapisujejo v podatkovno bazo, kjer so na voljo za ocenjevanje poteka širin slabov med valjanjem.

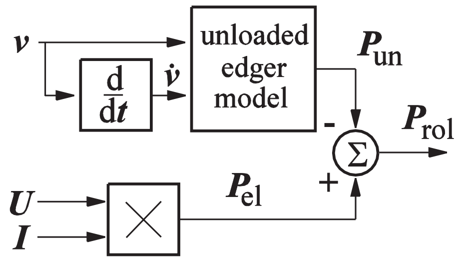
Ključne besede: jekla, toplo valjani trakovi, deformacijska energija, krčilno ogrodje, matematični model

1 INTRODUCTION

The production of hot-rolling strips in Acroni has the following stages after the prepared liquid steel. Slab casting on a continuous caster, optional slab-surface cleaning and whetting, reheating of the slabs, rolling of the slabs on a rougher-mill and rolling of the transfer bar on a finishing-mill to the final thickness. In order to reduce production costs the final width of the hot-rolled strips should be as little as possible over the desired customer-dependent width. The first measured width in the production line appears on the finishing mill. It is clear that it is not an easy task to hit the desired width of hot-rolled strip from a slab. On a continuous caster a cold-slab width is calculated from known material parameters and caster settings. The possibility of a slab-width determination from existing edger measurements was investigated. On the edger the following measured signals are available: edger roll gap, edger current, edger voltage and edger speed. These four signals represent a possible source of additional information about the slab width during rolling on the rougher-mill. The problem with these data is that it is not an easy task to say from the measured signals whether the edger has rolled the slab side or not. As mentioned previously, the first measure of the strip width is mounted on a finishing-mill, which is the final rolling machine, where the strip width cannot be adjusted anymore. The purpose of this work is to extract additional slab-width information from the edger measurements. The first information we are interesting in is whether the edger has rolled the slab for each pass through the edger. If the edger has not rolled the slab, then we know that the slab width was narrower than the edger roll gap. If the edger has rolled the slab, the next question is how much wider was the slab than the edger roll gap. This question can be answered only partly, with the energy consumed for the slab width-rolling – the deformational energy. This energy gives us rough information about the actual slab width. With the answer to both the above questions we get information about the initial slab width and information about how the edger roller is working. From the slab-width-flow through the rolling process it is possible to make a conclusion about the suitability of the initial slab width, and further, to adjust the slab width on the continuous caster.

2 MATHEMATICAL MODEL OF EDGER

The basis for the extraction of the desired information is a mathematical model of the edger. Actually, we need an edger model that describes the rotational movements of the unloaded edger. The idea can be seen in **Scheme 1**.



Scheme 1: Basic idea for determining the power consumed for the slab-width rolling. The edger velocity v / (m/s) measure is used as the model input. The product of the voltage $U(t)$ / V and current $I(t)$ / A of the edger motor is measured as the electrical power. Subtraction of the model output from the measured value of the electrical power yields the power consumption for the deformation of slabs with the edger.

Shema 1: Osnovna ideja za določitev moči, vložene v valjanje širin slabov. Obodna hitrost valjev krčilnega stroja v / (m/s) je vhod v model. Produkt napetosti $U(t)$ / V in toka $I(t)$ / A na motorju krčilnega stroja je merjena vrednost električne moči. Razlika porabljene električne moči in moči neobremenjenega krčilnega stroja daje moč, ki se trenutno vlaga v krčenje širine slaba.

All three input variables v, U and I are measured values. First, we develop a dynamical model of the unloaded edger, where the model input is the edger velocity and the output is the power consumption of the unloaded edger $P_{un}(t)$. The model calculates the power needed for the rotation of the unloaded edger. The product of the other two measured variables, $U(t)$ and $I(t)$, which are DC values, is the present electrical power consumption $P_{el}(t)$. If we subtract the calculated power of the unloaded edger (model output) from the measured value of the electrical power being consumed by the edger motor, the result is the power being consumed at the moment for the side rolling of the slab – $P_{rol}(t)$. The integration of $P_{rol}(t)$ over a time belonging to a slab-pass through the edger roller yields the energy consumption for the slab-side rolling of the particular pass, which is equal to the deformational energy.

The unloaded edger can be seen as stiff rotating body[3]. This approximation does not generate an important systematic error. The electrical power on the edger motor is transformed to the mechanical power

$$P_{el}(t) = P_{meh}(t) \tag{1}$$

Considering the definition of power for a rigid rotating body[3] and with the definition of electrical power $P_{el}(t) = U(t) \cdot I(t)$ results in the following equation

$$U(t) \cdot I(t) = M(t)\omega(t) \tag{2}$$

The moment M is defined as $M = \mathrm{d}(J\omega)/\mathrm{d}t$ [3], ω is defined as $\omega = v/r$ and the associated differential $\mathrm{d}\omega/\mathrm{d}t = (1/r)(\mathrm{d}v/\mathrm{d}t)$. Substituting the above relations into equation 2 and changing the velocity derivative notation $(\mathrm{d}v/\mathrm{d}t) = \dot{v}$ yields

$$U(t) \cdot I(t) = \frac{J}{r^2}\dot{v}(t)v(t) \tag{3}$$

In equation 3, J and r^2 are unknown model parameters. Both are constant and therefore the ratio J/r^2 = konst = k is constant. The second model input signal is $\dot{v}$, which can only be numerically derived from v. Derivation of the signals increases the signal noise; therefore, we use the following numerical derivation. The left and right differences are calculated as $\dot{v}_L = (v_k - v_{k-1})\Delta t$ and $\dot{v}_R = (v_{k+1} - v_k)\Delta t$. The average value of them is used as the derivative value $\dot{v}$ at time k $\dot{v}_{t=k} = (v_L + v_R)/2$. The numerical derivation is the weakest point of modeling, apart from the high sample time, 0.5 s.

Equation 3 has a single unknown parameter k, which can be found using the least-squares method[2]. Both side data need to be available and must originate from a part where the edger was unloaded and where the motion of the edger was sufficient, etc. [2]

3 THE EDGER MODEL AS A SOURCE OF ADDITIONAL INFORMATION AND OBTAINED RESULTS

As described in the previous section, the mathematical model presents a basis for the extraction of additional information from edger measurements.

The first task was fitting the model parameters. The measured data from rougher-mill were available for several rolled slabs in separated ASCII files. From all the different long-slab steel grades, altogether 20 random slab-rolling files were used, and on each a parameter fitting was performed and the resulting model parameter was stored. This was done for two reasons: to verify the repeatability of the obtained parameters, and also to see the model-extrapolation ability. Each of these parameter-fitting tasks was visualized and verified to exclude possible unsuitable data files, e.g., errors in data files, unsuitable dynamics, etc. The average of these 20 model parameters was used as a model parameter in the subsequent analyses. The model parameter value was determined as $k = 43 \cdot 10^3$. Verification of the model can be seen in **Figure 1**, on the upper graph from timestamp 110 s to 140 s, where the edger is unloaded. The signal P_{el} in a particular time interval is a measured value and can be seen as a true value of the model output. Agreement between the model power-prediction $P_{\underline{un}}$ and the measured value of the power P_{el} is satisfactory, taking into account the sample time. The second plot in **Figure 1** presents P_{rol}, which is the base signal for additional analyses.

For a determination of the slab width rolled/not rolled the following empirically obtained integral criterion is used.

$$R=\frac{\int_{t_{\mathrm{pass}}}\left|UI\right|\,\mathrm{d}t}{\int_{t_{\mathrm{pass}}}\left(UI\,\frac{1}{2\dot{v}+0.08}\right)^{2}\mathrm{d}t}\cdot 10^{6} \tag{4}$$

R is always positive and determines:

$$\left\{\begin{array}{l} 0\le R\le 1;\ \text{Edger rolled slab} - \text{width} \\ R>1;\ \text{Edger did not roll slab} - \text{width} \end{array}\right\}$$

The criterion is calculated for every slab pass through the edger. The lower integral sums the power along the pass and accents the power contributions where the velocity is not changing rapidly and vice verse, the power contribution of samples with a rapid velocity is reduced. The ratio of both integrals is independent of the slab-length/number of samples. The part in the denominator $1/(2\dot{v}+0.08)$ accents the power contributions according to the acceleration in the nonlinearly. The constant 0.08 defines the magnification of the power contributions at zero acceleration of the edger. Note that for the calculation of the R-characteristic the measured value of the power is used and no model results are needed.

The next calculated characteristic for each pass through the edger is the energy consumed for the rolling. This value can be obtained simply with an integration of P_{rol} over the whole pass. The following integration is performed

$$E_{\mathrm{rol}}=\int P_{\mathrm{rol}}\,\mathrm{d}t, \tag{5}$$

where $P_{\mathrm{rol}} > 0.02\ P_{\mathrm{max}}$ and $|P_{\mathrm{rol}}| > 3\ P_{\mathrm{un}}$.

The power is summed for those samples where P_{rol} is at least 2 percent of the maximum edger power P_{max}, and where the absolute value of P_{rol} is more than three times higher than the power of an unloaded edger. When both conditions are fulfilled the integration is performed. The sum of the time where the integration is performed is denoted as t_{roll}. The third characteristic is calculated with the following equation

$$\overline{P}_{\mathrm{rol}}=\frac{E_{\mathrm{rol}}}{t_{\mathrm{roll}}} \tag{6}$$

and represents an average value of the edger power during the actual rolling of the slab width. The $\overline{P}_{\mathrm{rol}}$ provides information about the edger loading, which is

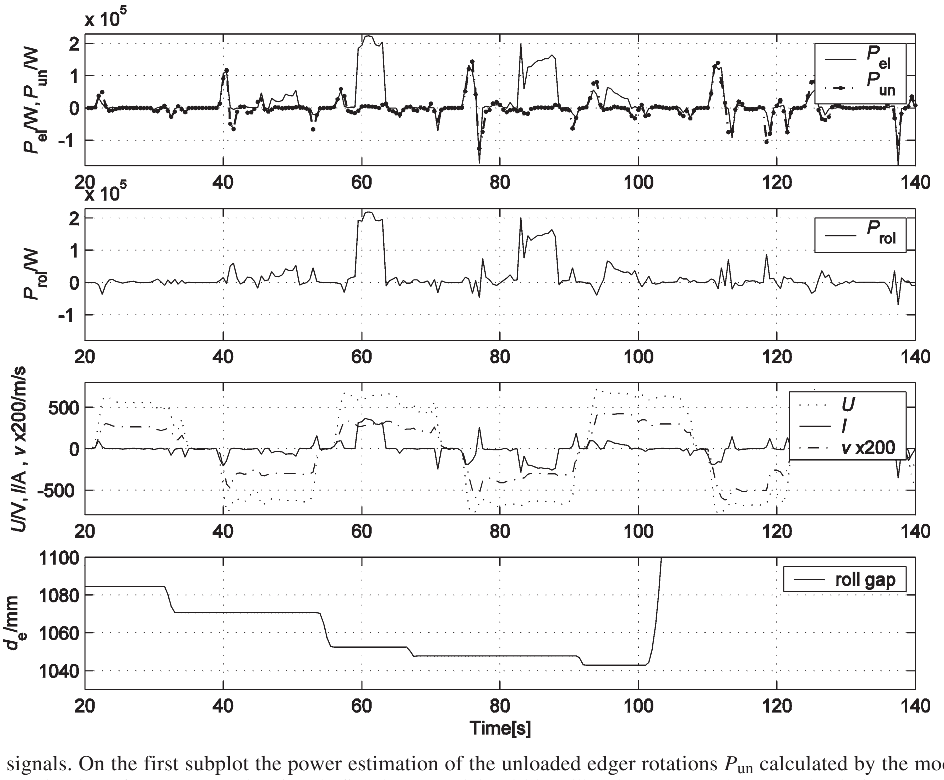


Figure 1: Example signals. On the first subplot the power estimation of the unloaded edger rotations P_{un} calculated by the model is presented in addition to the measured value of power P_{el}. The signals fit where no slab-width rolling is present. The second subplot presents the $P_{\mathrm{rol}} = P_{\mathrm{el}} - P_{\mathrm{un}}$ power consumed for slab-width rolling. On the third and fourth subplot the edger source-measurements are presented. The edger is removed after the timestamp 102 seconds on the fourth subplot.

Slika 1: Primer signalov. Na prvem grafu je ocena moči neobremenjenega krčilnega stroja, računana z modelom P_{un}, poleg merjene vrednosti moči P_{el}. Signala se ujemata, kjer krčilni stroj ne valja širin slaba. Drugi graf prikazuje moč, porabljeno za valjanje $P_{\mathrm{rol}} = P_{\mathrm{el}} - P_{\mathrm{un}}$. Tretji in četrti graf prikazuje izvirne merjene signale. Krčilno ogrodje je razmaknjeno po času 102 s na četrtem grafu.

useful for a determination of the suitability of edger control during rolling.

All the above integrals are calculated numerically and therefore the discretely equivalent criteria are used.

The calculated integral criteria for the above sample rolling data are shown in **Table 1**.

Table 1: Calculated integral criteria for signals shown in **Figure 1**
Tabela 1: Izračunane vrednosti integralskih kriterijev za signale prikazane na **sliki 1**

Roll pass No.	1	2	3	4	5	6	7
R	21.25	0.64	0.20	0.11	0.76	8.51	42.74
E_{rol}/kWh	0	0.068	0.448	0.443	0.086	0	0
$\overline{P}$/kW	0	34.9	201.9	145.1	44.3	0	0

4 DISCUSSION

Let us comment on the example data. Seven passes through the edger roller are detected for the sample data. The presented integral characteristic R for the example data yields, in **Table 1**, the presented values. As mentioned previously, R greater than 1 means that the side rolling in the particular pass is not detected. From **Table 1**, looking at the R values, we can conclude that in 2, 3, 4 and 5-th passes the edger has rolled the slab along its width. This is also visible from **Figure 1**, signal P_{rol}. The $\overline{P}_{rol}$ is calculated using equation 6 and for the example data yields, in **Table 1**, the presented values. Note that $\overline{P}_{rol}$ is the average value of the signal P_{rol} over the actual rolling time.

The signal P_{rol} in **Figure 1** sometimes drops under zero. It always happens during high-velocity changes. This effect occurs partly due to the braking mode of the edger motor. Braking includes braking of the edger itself, besides braking of rolled slab, if it is rolled. This occurs quite often since every velocity change of edger, while the slab is width-rolled, partially includes braking/ accelerating of the whole rolled slab. The second reason for the negative values of P_{rol} is that the measured data are sampled only $\Delta t = T_s = 0.5$ s. This is quite slow, if we keep in mind that the average rolling speed is around 1 m/s for the first pass and that the shortest slab is around 4 m. In the worst case it means only 8±1 samples for the first pass. Sample time, therefore, influences the accuracy of calculations for the initial passes. Note that low sample time has a minor influence on the accuracy of the model calculated P_{rol} for low acceleration rates of the edger. Fortunately, during rolling the velocities do not vary much, and therefore the model yields relatively accurate results. The results are much more inaccurate when huge variations in the edger velocity are present.

The above data manipulations and computations are performed fully automatically using the C programming language. The extracted data are automatically stored in a MySQL database.

The obtained numerical data are used for additional analyses, where the width of the rolled piece is observed through the whole charge. The observation of R, E_{rol} and $\overline{P}_{rol}$ together with the obtained widths measured on the finishing mill collected in a surveyable combination of diagrams and tables observing slabs from a whole charge gives a clear overview of the suitability of initial slab widths and the suitability of edger control for the production of each slab. This information is successfully used to improve the production quality and decrease the production costs.

The implemented model and model-calculated characteristics have been in online use in Acroni d. o. o. since June 2005.

5 CONCLUSION

The presented edger model enabled a determination of three additional data for each slab pass through the edger of a rougher-mill. For each slab pass through the edger the following information was determined:

- Edger has/has not rolled the slab width
- Energy consumed for slab-width rolling
- Average value of edger power during the actual slab-width rolling

6 REFERENCES

[1] Strnad J., Fizika, Prvi del, Mehanika / Toplota, Društvo matematikov, fizikov in astronomov SRS, Ljubljana, 1987, 89
[2] Matko D., Identifikacije, Fakulteta za elektrotehniko, Ljubljana 1998, 101–107
[3] Karba R., Modeliranje procesov, Fakulteta za elektrotehniko, Ljubljana, 1999, 180–184