ОПРЕДЕЛЯНЕ НА ИЗРАЗХОДВАНАТА ЕНЕРГИЯ ЗА ДЕФОРМАЦИЯ ПРИ ГОРЕЩО ВАЛЦУВАНЕ НА ДЕБЕЛОЛИСТНА СТОМАНА

MATHEMATICAL MODEL FOR DETERMINATION OF CONSUMED ENERGY DURING THE FLAT HOT ROLLING OF STEEL PLATES

ОПРЕДЕЛЕНИЕ ЗАТРАЧЕННОЙ ЭНЕРГИИ НА ДЕФОРМАЦИЮ В ПРОЦЕССЕ ГОРЯЧЕЙ ПРОКАТКИ ЛИСТОВ ИЗ СТАЛИ

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Abstract: *In this work a mathematical model for estimation and optimization of the required consumption energy for the flat plate rolling of the group of Grade 0003 steel is presented. A design of experiments was performed. The key geometrical parameters namely, the thickness, the programmed plate width and the length are considered as independent parameters, in two levels of variation. The relation between these variables to the consumed rolling energy as a dependent changeable is described through the derived model of the plan matrix. A great number of data, collected in a four-year period were selected, filtered and processed statistically. Based on the model, graphs were obtained showing the dependence of the consumed rolling energy from the slab thickness and the programmed plate width and length. The results show that energy savings of about 11 percent can be achieved by operating the mill under optimal conditions.*

Keywords: Mathematical Model, Hot Rolling, Energy, Consumption, Plate, Slab, Steel.

Introduction

Energy consumption substantially influences the market price of the metallurgical production and exerts significant impact on the overall financial effectiveness of the companies.

Nowadays, the energy saving and diminution of the fuel consumption is recognized as a most important worldwide problem concerning both the industry and the society. The fact that the most expensive energy is the one that is uselessly dispersed, along with its high price nonetheless, and that these are the factors directly connected with the production costs and successful marketing of the products, has changed the attitude towards this problem. The maximum rationalization of all kinds of consumed energy has become utterly reasonable during the last decade in global frameworks and it is especially evident in the production environment.

The search for novel ways to increase the utilization of consumed energy without compromising the quality of the metallic products is performed relentlessly at A. D. Makstil - Skopje. One of the most effective achievements is the implementation and application of a Quality Management System (QMS). The careful analysis of proposals made by employees and the continuously technological improvements aim to maximize the energy utilization and further to rationalize its consumption in conjunction with the high production quality. The presented paper is a part of the work in this direction.

The main goal is to examine the consumed rolling energy for programmed plate dimensions independence of the type of slab (section) used.

Calculations of consumed rolling energy

The consumed rolling energy (CRE_{tot}) depends on the applied normal rolling force and on the rolling piece length obtained by a given reduction [1, 2]. As the normal rolling force has an impact on a certain position of the roll shaft, it can be said that the direct dependence of the consumed rolling energy is a function of the rolling moment. Accordingly, the coefficients for mechanical and electrical efficiency, the position of normal force rolling action and the geometrical indicators for calculating the CRE can be adopted from literature [1, 2]. The following formulas apply:

$$CRE = Torq_{total}\ 9{,}81\ H_{Entry}\ Len_{piece} / (R\ H_n\ Cos(g)),\ [KJ] \qquad (1)$$

where, H_{Entry} and Len_{piece} are the initial thickness and the length of the piece, respectively; R is the radius of the work rolls, and H_n is the piece thickness in the neutral plane in roll bite.

The rolling moment, on the other hand, is calculated according to:

$$Torq=2\ F_n \psi\ (R\ (H_{Entry} - H_{Exit}))^{0,5} / 1000000),\ [t.m] \qquad (2)$$

while the total moment is calculated by:

$$Torq_{total} = Torq / Efic_{Mec},\ [t.m] \qquad (3)$$

Using the value for $Torq_{total}$, the power P can be calculated by:

$$P = 1{,}027\ Torq_{total}\ RPM / Efic_{Elec} \qquad (4)$$

The adopted coefficients for mechanic and electrical efficiency are $Efic_{Mec}$= 85% and $Efic_{Elec}$= 95%. The factor determining the position of normal rolling force is accepted as ψ = 0,5. The total consumed rolling energy is a sum of the separate CRE from each pass and/or CRE_{tot}. Table 1 summarizes the measured production data as well as CRE of rolling the plate with dimensions of 10x3000x24000mm of manganese steel grade S355J2.

Processing of the experimental data includes a full-factorial design of linear type effecting the mixed action between the factors of “2^3” type, whereas the number 3 indicates review of three influential factors upon consumed rolling energy.

The design of the experiments requires preliminary to specify the intervals of variation of each factor. The successful derivation and obtained results can give a mathematical model and/or a regressive equation for k =3 factors of the type:

$$Y_{reg} = b_o+b_1X_1+b_2X_2+b_3X_3+b_{12}X_1X_2+b_{13}X_1X_{3+}+b_{23}X_2X_{3+}+b_{123}X_1X_2X_3$$

Table 1. Technological data for rolling plates

Pass #	Piece Thickness mm	Piece Width mm	Piece Length mm	%ε	T°C	Normal Force tonns	Torq Nm	Total Torq Nm	Total Power KW	CRE MJ	Rolling Speed m/s
1	221,3	2120	1719	12	1039	1836	223	263	10159	11	1,84
2	198,5	2120	1900	10	1070	1623	172	202	7050	9	1,66
3	174,4	1929	2318	12	1050	1727	188	221	8550	13	1,84
4	152,6	1929	2636	13	1048	1587	164	193	7215	13	1,77
5	136,0	1929	2957	11	1043	1413	127	150	6203	11	1,96
6	114,3	3094	2212	13	1030	2542	262	309	8355	17	1,29
7	94,2	3094	2656	18	1023	2626	260	306	10712	20	1,66
8	75,7	3094	3299	20	1019	3066	292	343	17402	28	2,41
9	58,9	3094	4239	22	1026	3199	291	342	17630	38	2,45
10	45,6	3094	5503	23	1023	3238	261	307	17037	44	2,63
11	35,3	3094	7153	23	1037	3124	222	261	16105	48	2,93
12	27,3	3094	9286	23	1025	3172	198	233	15414	55	3,14
13	21,2	3094	11974	23	1032	3204	176	207	15639	63	3,58
14	16,4	3094	15371	23	995	3403	165	194	14931	76	3,66
15	13,6	3094	18616	17	991	2703	99	117	8954	52	3,63
16	12,1	3094	21428	12	934	2219	62	73	5797	35	3,79
17	11,1	3094	23482	9	896	1609	35	42	3197	21	3,64
18	10,4	3094	25003	6	854	1571	28	33	2058	18	2,94

CRE_{tot} = 571[MJ]

Having a database of collected data from the rolling process parameters (slab/plate) gives an opportunity to determine the consumed rolling energy (Y) at the processing conditions dictated by the experimental matrix of independent factors (Z_1, Z_2, Z_3). The plan matrix is given in Table 2.

Table 2. Experimental matrix of natural values

Exp. #	SLB_THK Z_1, mm	PLT_WID Z_2, mm	PLT_LEN Z_3, mm	CRE_{tot} Y_{med},MJ
1	250	3000	24000	569
2	170	3000	24000	512
3	250	2000	24000	434
4	170	2000	24000	392
5	250	3000	12000	320
6	170	3000	12000	253
7	250	2000	12000	229
8	170	2000	12000	200

In order to determine the regression coefficients the factors are coded according the following formulas [3, 4]:

$$Z_j^o = (Z_j^{max} + Z_j^{min})/2, \quad (5)$$

$$\Delta Z_j = (Z_j^{max} - Z_j^{min})/2, \quad (6)$$

$$X_j = (Z_j - Z_j^o)/ \Delta Z_j \quad (7)$$

where, $j = 1, 2, \ldots\ldots, k$

Table 3 presents the experimental plan matrix with the coded values (X_1, X_2, X_3), corresponding to the slab thickness (SLB_THK), plate width (PLT_WID) and plate length (PLT_LEN).

Table 3. Experimental matrix of coded values

Exp. #	X_1	X_2	X_3	CRE_{tot} (Y_1)	CRE_{tot} (Y_2)	CRE_{tot} (Y_3)	Y_{med}
1	+1	+1	+1	565	575	568	569
2	-1	+1	+1	513	511	512	512
3	+1	-1	+1	459	415	427	434
4	-1	-1	+1	405	383	388	392
5	+1	+1	-1	344	290	326	320
6	-1	+1	-1	268	233	257	253
7	+1	-1	-1	243	218	226	229
8	-1	-1	-1	192	204	204	200

To determine all of the regressive coefficients, the experimental matrix is extended to include the effect of interaction with mutual multiplication of variables, with all possible combinations including triple action. In this way, calculation of the regression coefficients is made easier, and can be expressed simply as:

$$b_i = N^{-1} \sum_{i=1}^{N} (X_{ji} Y_i) \quad (8)$$

where, $i = 1, 2, \ldots\ldots$, N and $j = 1, 2, \ldots\ldots, k$

This formula is valid in states where the orthogonality criterion is met, meaning that the sum of all X columns is separately equal to zero, which in our case was satisfied.

In order to come to calculations of regression coefficients there is firstly a need to determine the homogeneity of the results and/or their dispersion, from the number of repeated measurements (k_y). In our case, three repeated results were used for each of the total consumed rolling energy and for each measuring point. The dispersion S^2 is determined by the formula:

$$S_i^2 = (N-1)^{-1} \sum_{i=1}^{N} (Y_{ij} - Y_i med)^2 \quad (9)$$

where, $i = 1, 2, \ldots\ldots$, N, and $j = 1, 2, \ldots\ldots, k_y$

The homogeneity value is then calculated as:

$$G_{max} = S_{max}^2 / \Sigma S^2 \quad (10)$$

and compared to the tabulated Cochren's criteria. If the calculated value of G_{max} does not exceed the table value, then the regression coefficients can be calculated by the formula (8).

Once the regression coefficients are calculated, their error dispersion is tested in order to evaluate the regressive coefficients S_b according to the "Student's test'. The dispersion S_b^2 is determined by the following formula:

$$S^2 = N^{-1} \sum_{i=1}^{N} S_i^2 \quad (11)$$

Dispersion for each coefficient separately is calculated as:

$$S_{bi}^2 = N^{-1} S^2/(k_y-1) \quad (12)$$

The calculated Student criteria "t-test" is calculated as:

$$t_i = |bi| / S_{bi} \quad (13)$$

The obtained separate dispersions of error are then compared with tabulated Student criteria data for k_y-1 free degrees. If the value of calculated Student's criteria does not exceed the tabulated value, for a given number of free degrees and probability, then the coefficient is insignificant and it is rejected.

In order to test the adequacy of the model, also considered was Fisher's criteria. The data obtained according to the regressive equation, in which only the significant coefficients are retained, is tabulated. The dispersion error is determined from the medium value of the inlet results and dispersion values obtained from a regressive equation calculated with the following equation:

$$S_i reg^2 = (N-L)^{-1} \sum_{i=1}^{N} (Y_i med - Y_i reg)^2 \quad (14)$$

where, $i = 1, 2, \ldots\ldots, N$

L – number of significant coefficients

$$F_{crit} = S_i reg^2 / S^2 \quad (15)$$

If the calculated critical Fisher's criteria (F_{crit}) is less than the tabulated one, then the model is considered adequate.

Results and Discussion

Tables 5 and 6 present the key data of the model. Table 5 comprises the achieved regressive coefficient, calculated values for significance Student test of the coefficients and values of significant coefficients for the final regressive equation (according the tabulated Student criteria: 2.12 for f = N(k_y-1) = 16 of free degrees for adopted probability of 95%). The tabulated Cochren criteria for a number of free degrees f_1 = (k-1) = 2 and f_2 = N = 8 free degrees of probability of 95%, amounts 0, 5157. Seeing that this is greater than the calculated value of 0,385, it confirms that the model is homogeneous.

Table 5. Model values of the regressive coefficient

Exp. #	Regressive coefficients		Calculated Student test		Standard Student criteria (P=95%)	Significant coefficients	
1	b_o	363,6	t_o	113,81	2,12	Ok	363,6
2	b_1	24,5	t_1	7,76	2,12	Ok	24,5
3	b_2	49,9	t_2	15,62	2,12	Ok	49,9
4	b_3	113,1	t_3	35,41	2,12	Ok	113,1
5	b_{12}	6,8	t_{12}	2,122	2,12	Ok	6,8
6	b_{13}	0,3	t_{13}	0,087	2,12	-	-
7	b_{23}	14,0	t_{23}	4,37	2,12	Ok	14,0
8	b_{123}	-2,9	t_{123}	0,92	2,12	-	-

Likewise, tabulated Fisher criteria for the number of degrees of freedom f_1 = (k-1) = 2 and number of degrees of freedom for dispersion of adequacy f_2 = N(k_y-1) = 16, for probability of 95%, amounts to 3,12. This is greater than the calculated value of 0,43, which also confirms the adequacy of the model.

Thus the regressive equation obtained with coded values of the variables with the significant coefficients has the following final form:

$$CRE_{tot}=363,6 + 24,5X_1 + 49,9X_2 + 113,1X_3 + 6,8X_1X_2 + 14,0X_2X_3 \quad (16)$$

Table 6. Regressive equation values

N	X_1	X_2	X_3	Y_1	Y_2	Y_3	Y_{med}	Y_{reg}
1	+1	+1	+1	565	575	568	569	572
2	-1	+1	+1	513	511	512	512	509
3	+1	-1	+1	459	415	427	434	431
4	-1	-1	+1	405	383	388	392	395
5	+1	+1	-1	344	290	326	320	318
6	-1	+1	-1	268	233	257	253	255
7	+1	-1	-1	243	218	226	229	232
8	-1	-1	-1	192	204	204	200	197

For convenience of the practical usage decoding of the regressive equation is performed, according to which the new equation with natural values has the following final form:

$$CRE_{tot}=33,9 - 0,23Z_1 - 0,05Z_2 + 0,007Z_3 + 3,4x10^{-4}Z_1Z_2 - 4,6x10^{-6}Z_2Z_3 \quad (17)$$

The derived regression formula (17) was validated using incidental conditions for independent variables with values ranging within previously established limits. The results are given in Table 7 where it can be seen that, at values outside the experimental design, the maximum error (i.e., difference between the measured CRE_{tot} and the calculated CRE_{tot}) is approximately 6%, which is tolerable.

The data calculated from the derived regression formula (17) are used for graphical interpretation and conclusions about consumed rolling energy during hot rolling processing of the investigated manganese steel

Table 7. Use of the model with incidental values

Slab Thickness mm	Plate Width, mm	Plate Lenght, mm	CRE_{tot}	CRE_{tot}-Calculated	Error, %
200	2500	14600	287	293	-2,28
		14600	299	293	2,09
		17000	341	339	0,69
		20000	418	395	5,85
		20000	412	395	4,39
		20000	404	395	2,30

A number of graphs have been made based on the model. Figure 1 illustrates the variation the total consumed energy for rolling plates in dependence of their width and length when using three different slab types (i.e. with thickness 170, 200 and 250 mm).

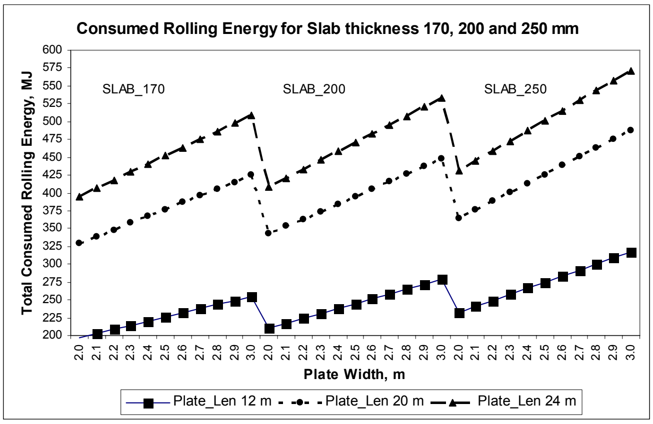

Figure 1. CRE_{tot} for different size slabs and plates

Figure 2 shows the dependence of CRE_{tot} for plates rolled from the three different slab types with increasing width of the plates from 2,0 up to 3,0 m at keeping constant plate length of 20,0 m. Here it can be seen again that with the enlargement of scheduled plate the total energy consumed during rolling increases. Higher energy is consumed for a plate of given width if it is obtained by a rolling of a thicker slab. It is clearly visible the faster increase of consumed rolling energy during deformation process of thicker slabs, especially at larger plate widths and 250 mm thickness slabs.

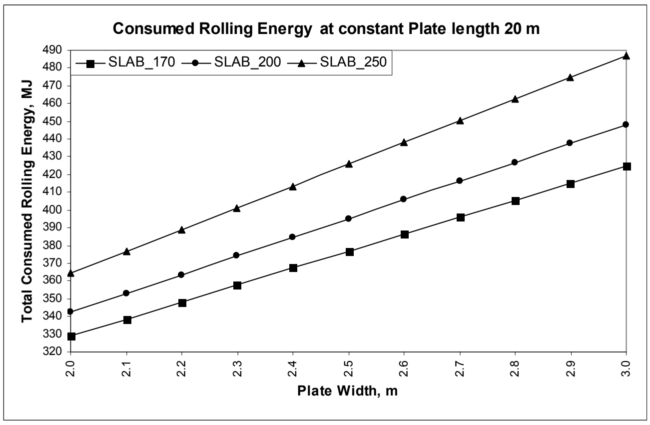

Figure 2. CER_{tot} as a function of plate width at constant length

The effect of a different slab type and geometrical plate parameters on the consumed rolling energy is similarly seen in the diagram, depicted in Figure 3. It is a section from the diagram in Figure 1, for a single width of plate 2,5 m. for rolling different length from 12 to 24 m.

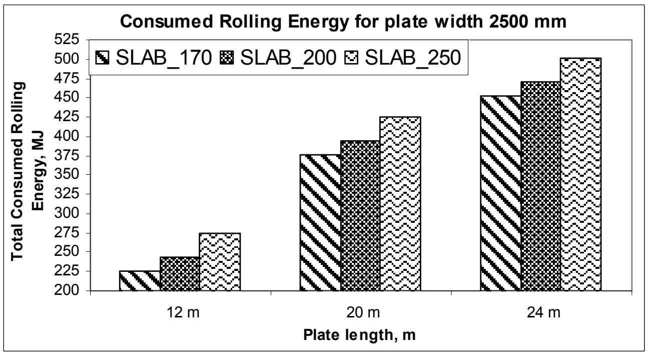

Figure 3. CER_{tot} for rolling plates of constant width

The difference (**ΔCER_{tot}**) between the total consumed rolled energy (CRE_{tot}) for plates rolled from a slab of thickness 250 mm and those, consumed for hot rolling plates from slabs of thickness 170 and 200 mm, are summarized in Table 8. The same data are depicted graphically in Figure 4. It is clearly seen the strong influence of slabs geometry. At a given plate dimensions, for example for a plate with programmed dimensions 10 x 2500 x 20000 mm, the consumption of energy, is lowest (lowest CRE_{tot}) if the plate is rolled from a slab with a thickness of 170 mm, and highest if the used slab has a thickness of 250 mm. The estimated difference in consumed energy is 11, 5%. This reveals that matching the right type of slab with the specified dimensions of the plate could make significant savings in energy.

Table 8. Expected energy consumption and potential savings

	CER_{tot} MJ	**ΔCER_{tot} MJ**	**Energy savings, %**
Plate dimensions **10x2500x12000 mm**			
SLAB_170	226	−49	17,8% less energy vs, Slab_250
SLAB_200	244	−31	11,3% less energy vs, Slab_250
SLAB_250	275	-	-
Plate dimensions: **10x2500x20000 mm**			
SLAB_170	377	−49	11,5% less energy vs, Slab_250
SLAB_200	395	−31	7,3% less energy vs, Slab_250
SLAB_250	426	-	-
Plate dimensions: **10x2500x24000 mm**			
SLAB_170	452	−49	9,8% less energy vs, Slab_250
SLAB_200	471	−30	6,0% less energy vs, Slab_250
SLAB_250	501	-	-

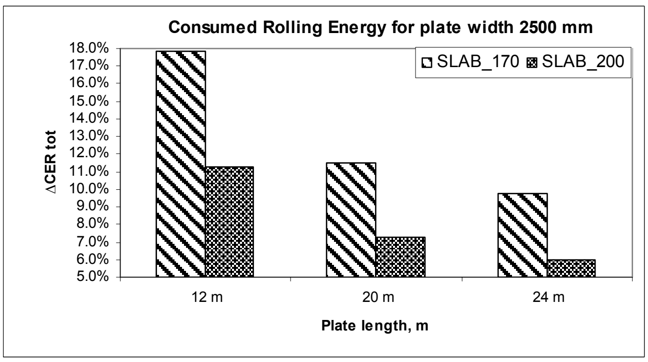

*Figure 4. **ΔCER_{tot}** Difference (Energy saving, %) in CER_{tot} from Slab_250 to Slab_200 and 170*

According to the presented results, it follows that during the hot rolling of steel plates, a greater quantity of energy is consumed if the used slab has a higher thickness. While this conclusion could be expected, however, some additional important relationships can be deducted which may contribute to appreciable lowering of the consumption of energy and thereby facilitate significant production cost decrease.

Careful analysis of the results processed in the presented method make relationships between the energy required for a particular plate size and the size of the slab, evident prior to the rolling operation, thus allowing this information to be used for optimal planning of the rolling process so as to facilitate lowering the cost of production. The results show that the developed mathematical model is a useful technique for transparent analysis of results and such or similar approach could be used for the analysis of other process parameters in situations where adequate data is monitored and recorded. Further work is under way.

Conclusions

1. The developed mathematical model describes the dependence of consumed energy in the hot rolling of steel plates as a function of slab and plate dimensions, using data from the production of manganese steels at A.D. Makstil - Skopje.
2. Mathematical process modeling enables collected production data to be used for making software instruments for process analysis by which approximate anticipation of the energy consumption is enabled, even for plate dimensions for which former data in not available. Thereby, a model significantly improves the possibilities for costs planning and prediction of the result, and hence rationalization of the fabrication and price decrease of the final product.
3. The derived model predicts that for manganese steel plates rolling from slabs with thickness 170 mm or 200 mm rather than 250 mm is beneficial in respect to energy economy. In this case energy saving of 10% to 18% can be expected for 10 mm plates with lengths from 12 to 24 meters.

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