Required Energy Calculation by Hot Rolling of Tubes and of the Main Drive Motors Power for a Stretch Reducing Mill

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Abstract: - This work shows the methodology regarding the calculation of the deformation resistance and of the required energy and power for hot reducing of tubes on a stretch reducing mill (SRM) with the final aim of an optimal sizing of the mill drives. Effective calculations are shown as methodology examples for the case of stretch reducing of a Φ123x3.9mm blank into a Φ 49x3.25mm tube. In order to evaluate the validity and accuracy of the suggested calculation methodology, the calculation results regarding the required reducing energy have been compared with the experimental data collected at a SRM in operation on which the research has been performed as well as with the experimental data presented in the literature.

Key-Words: - stretch reducing mill, hot reducing tubes, energy, drive motor

1 Introduction

The hot reducing process (or reduction) is a specific hot rolling method for tubes [1]. Further on the calculation methodology of all power, energy and thermal parameters is shown, that intervene in the hot reducing process of tubes with or without tension between the stands (calipers) [2]. As an application example of this methodology further down are shown also the calculation steps of the previous parameters based on a reducing regime practiced in a plant near Saint-Germain (France) of ∅123x3.9x12000 mm to ∅49.25 mm made of non alloy steel with 0.15% carbon [3]. We have chosen this calculation example for tube practical reasons i.e. [4]:

- the processing condition (calipers dimensions hence also the applied reducing, temperature, rolling speed at the beginning and chemical composition of the steel) are shown in detail;
- a modeling concerning the deformation resistance variation of the reducing process is done using for heat a plastometer consisting of a spinning machine (of SETARAM type) [5].

2 Calculation Methodologies

The calculation of energetic and power parameters includes the following steps [5], [6]:

- dimensional pipe featuring in each rolling stage as well as of the performed deformation regime;
- determination of required deformation resistance and mechanical work for performing the rolling operation;
- determination of the required power for performing rolling in each caliper of the reducer;

- comparison of the required energies for tubes deformation in each caliper, with experimental determined values of another reducer;
- evaluation of pipe heating level (temperature increase) based on the calorific equivalent of the required mechanical work for performing the rolling operation [7].

2.1 Modeling of Ø 123x3.9 mm tubes reducing regime to Ø 49x3.25 mm tubes

Using a plastometer (consisting of a hot spinning machine of Setaram type) modeling of the rolled tubes reducing process has been done according to the rolling regime. The used machine allowed a lab simulation (reproduction) of the following conditions existing in the rolling mill:

- deformation temperature equal to 900^0 C;
- deformation coefficient in each caliper;
- required time for tube passing from one caliper to the next as well as the total rolling time.

By construction, the plastometer could not reproduce exactly the effectively applied natural deformation speed in each caliper of the reducer but only a speed with about a size grade smaller. The obtained experimental data regarding the measured tensions under these conditions are synthesized in figure 1 and the digital values read on this diagram are mentioned in Table 1.

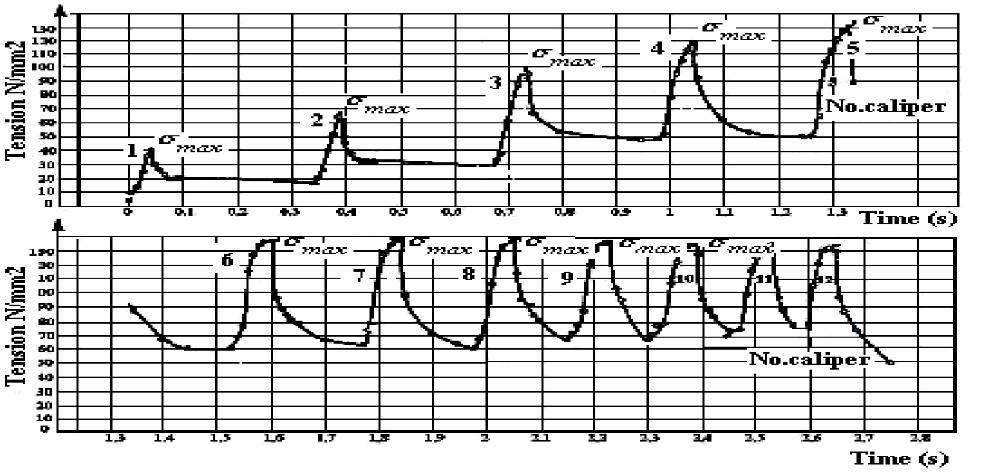

Fig. 1. Variation of monoaxial tension that appears in the steel during modeling in a hot reducing process of pipes from Φ123x3.90mm to Φ49x3.25mm. Deforming temperature 900°C.

Their analyses shows that the maximum tension (σ_{max}) appeared in the first calipers in the tube are increasing and than either it remains constant or it decreases. The appearance of this phenomenon is caused by two factors: reducing regime variation (of coefficient λ) and continuous modification of the balance between the hardening determined by deformation and the softening due to restoration processes and dynamic recrystallization.

One can observe that in the first calipers the resistance decrease after deformation (expressed by the mono axial tension value) includes two steps i.e. a short but intensive one followed by a slower one, both taking place in the period of time in which the tube passes from one caliper to the next caliper. The deformation resistance (respectively the mono axial stress tension) has in this point a minimum value (σ_{min}).

During the rolling operation, due to a continuous increase of the deformation speed, the passing time of the tube from one stand to the other decreases and is becoming sometimes so small that the slow softening (evidenced at reduction in the first calipers) can not take place anymore. For this reason the static softening (due to restoration and recrysatallizing process) is performed in a much smaller measure, so that while the tube is passing through the reducer the minimum tension value σ_{min} is increasing continuously, this phenomenon being evidenced by the variation of ratios σ_{min} /σ_{max} , which generally are under 0.45 and over this limit (up to 0.59) at the last passes (Table 1).

2.2 Calculation of required tensions for tube reducing from Ø 123x3.9 mm to Ø 49x3.25 mm

Based on the elements shown we are presenting the modality for using the experimental data (tension variation at the Setaram machine) for determining the rolling tension in each caliper of the reducer. In Table 1 we can see that the natural deformation speed has varied during the experiments done on Setaram between 0.250 and 2.238 sec^{-1}, while the effective natural deformation speed applied at the reducer was between 0.73 and 13.9 sec^{-1} (Table 2).Never less in order to be able to determine the tensions that appear at greater natural deformation speeds than those experimented on the Setaram spinning machine, we have proceeded as follows:

Table 1. Variation of monoaxial tension that appears in the steel during modeling (at a Setaram type spinning machine) in a hot reducing process of pipes from Φ123x3.90mm to Φ49x3.25mm. Deforming temperature 900°C

Caliper number n	Natural deformation coefficient $\ln\lambda=\ln A_{n-1}/A_n$	Deformation speed $\dot{\varepsilon} = \ln\lambda=\ln' h_{n-1}/h_n$	At exit from caliper $\sigma_{max,n}$ N/mm2	At inlet in caliper $\sigma_{min,n}$ N/mm2	Ratio $\sigma_{min,n}/\sigma_{max.n}$
0			0	10	
1	0.0095	0.25	40	17	0.425
2	0.045	1.125	66	24.5	0.371
3	0.0583	0.971	101	48	0.475
4	0.0803	1.338	119	51	0.429
5	0.0995	1.809	131	57.5	0.439
6	0.1324	1,814	135	62	0.459
7	0.1343	2.238	140	60	0.429
8	0.1342	1.789	139.5	66	0.473
9	0.1334	1.906	138	66	0.478
10	0.1251	1.668	136	74.5	0.548
11	0.0919	1.351	133	79	0.594
12	0.067	1.34	133	50	0.376

- the correspondence between experimental determined tensions and deformations (on the Setaram type spinning machine) has been placed on a semi-logarithmic diagram shown in Figure 2;
- based on these data, a regression line has been traced (representing the correlation between the experimental determined mono axial stress tension and the applied natural deformation speed);
- this line has then extrapolated for natural deformation speed by about one size grade higher.

One can see that the inclination of this line (its tangent) is very close to that shown in Figure 2.

As already mentioned before all the other tube reducing process conditions have been reproduced in lead experiments. Consequently the differences between the deformation tensions determined in laboratory (on the Setaram machine) and those that appear effectively during the rolling process are exclusively due to the differences between the natural deformation speeds.

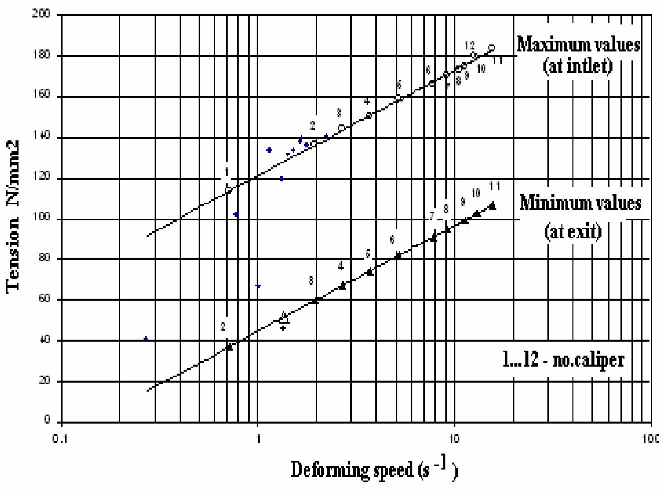

Fig. 2. Tension values σ at mono axial stress, depending on deformation speed, for a non alloy steel with 0.15% carbon.

Table 2. Calculation of deformation resistance and of necessary energy for pipe reducing

Caliper No.	Uniaxial deformation tension			Deformation resistance	Volume in focus	Stretching coefficient	Necessary deformation work			Natural deformation speed
	At inlet in caliper $\sigma_{min,n}$	Exit from caliper $\sigma_{max,n}$	Medium value* $\sigma_{med,n}$	$k_{fn}=1.15\sigma_{med,n}$	$V_{fn}=A_{mn}\cdot l_n$	$\lambda_n=A_{n-1}/A_n$	For deformation in focus $E_{1n}=V_{fn}\,k_{fn}\ln\lambda_n$	Friction overcoming $E_{2n}=0.4\,E1_n$	Total $E_{def\,n}=E_{1n}+E_{2n}$	$\dot{\varepsilon}=\ln\lambda_n/\Delta T_n$
		N/mm²		N/mm²	mm³		N m			s^{-1}
0	10.00		87.25	100.3375						
1	10.00	113	78.67	90.47	26370.18	1.0096	25.21	10.08	35.30	0.7343
2	39.04	136	104.50	120.18	48359.57	1.0466	264.70	105.88	370.58	1.9498
3	60.95	142.5	116.63	134.13	47820.03	1.0601	374.18	149.67	523.86	2.7052
4	68.29	150	127.74	146.90	45769.62	1.0836	539.69	215.88	755.57	3.6955
5	75.29	157	134.82	155.05	41319.26	1.1047	637.67	255.07	892.74	5.1258
6	82.63	167	144.07	165.68	35909.18	1.1415	787.44	314.98	1102.42	7.9744
7	92.55	171	148.91	171.24	30494.96	1.1438	701.46	280.58	982.04	9.54
8	96.57	174	153.64	176.68	25231.21	1.1436	598.20	239.28	837.48	11.4993
9	100.76	179	158.39	182.15	20816.22	1.1428	505.96	202.38	708.34	13.8764
10	104.97	182	161.69	185.94	17082.31	1.1333	397.33	158.93	556.26	15.7836
11	107.86	180	161.24	185.43	14228.42	1.0955	240.61	96.25	336.86	13.5791
12	104.49	174.5	157.84	181.52	11507.50	1.0626	126.78	50.71	177.49	11.0018

*The mean tension value is calculated by the relation: $\sigma_{mn} = \left(3\sigma_{max,n} + \sigma_{min(n-1)}\right)/4$

Table 3. Calculation of the required power *P* for tube reducing

Caliper number	Deformation speed in focus, v		Chord length	Rolling duration through focus	Natural deformation speed	Required rolling power				Total required power for deformation
						for deformation in focus	for friction overcoming			
	exit	average					in focus	in transmission mechanisms	at no load functioning	
			$l_n=(R\Delta d_n)^{1/2}$	ΔT_n	$\dot{\varepsilon}_n=\ln\lambda_n/\Delta T_n$	$P1_n=E1_n/\Delta T_n$	$P2_n=0.40\,E1_n$	$P3_n=0.05(P1+P2_n)$	$P4_n=0.75P1_1=ct.$	$Pt_n=P1_n+P2_n+P3_n+P4_n$
	(m/s)		(m)	(s)	(s^{-1})		kW			
0										
1	1.4	0.7	0.018	0.026	0.7343	0.972	0.389	0.068	0.729	2.157
2	1.465	1.433	0.034	0.024	1.9498	11.079	4.432	0.776	0.657	16.943
3	1.553	1.509	0.036	0.024	2.7052	15.844	6.337	1.109	0.657	23.947
4	1.683	1.618	0.037	0.023	3.6955	23.888	9.555	1.672	0.657	35.773
5	1.859	1.771	0.036	0.020	5.1258	31.282	12.513	2.190	0.657	46.642
6	2.122	1.991	0.035	0.018	7.9744	44.503	17.801	3.115	0.657	66.077
7	2.427	2.275	0.034	0.015	9.54	46.688	18.675	3.268	0.657	69.288
8	2.776	2.602	0.032	0.012	11.4993	48.120	19.248	3.368	0.657	71.393
9	3.172	2.974	0.031	0.010	13.8764	49.329	19.732	3.453	0.657	73.170
10	3.595	3.384	0.028	0.008	15.7836	47.187	18.875	3.303	0.657	70.021
11	3.938	3.767	0.026	0.007	13.5791	34.265	13.706	2.399	0.657	51.027
12	4.185	4.062	0.023	0.006	11.0018	22.304	8.922	1.561	0.657	33.444
Sum				0.193	97.47	375.460	150.184	26.282	7.955	559.883

Reducing regime constant $C = v \cdot Vf = 0.0020225$ m3/s

In order to solve this problem we have figured the deformation speed values of each caliper on the X-X axis in the diagram of Figure 2 and the corresponding values on axis Y-Y represent the tension values that are effectively developed at reducing. The values obtained in this way are put down and the diagram in the figure according to the item (current number of the caliper in the reducer).

Because the minimum tension values depend on the natural deformation speed like the maximum values too, the correlation between them has been graphically represented in an identical way, their regression line being traced in parallel with the line regarding the maximum tensions variation. The minimum tensions values *(σ_{min})* achieved during the rolling operation have been determined in the same way.

Further on, as an example, we are presenting the calculation of the maximum respectively minimum tensions at the 5th pass:

- the maximum mono axial tension ($\sigma_{max,n}$) for n=5 determined on the plastometer for a natural deformation speed $\acute{\varepsilon}$ =0.0995 s^{-1} is $\sigma_{max,5}$ = 131 N/mm^2;
- the minimum mono axial tension ($\sigma_{min,n}$) for n=4, (with which the tube enters the caliper 5) determine in the same way for a natural deformation speed $\acute{\varepsilon}$ = 0.0803 s^{-1} is $\sigma_{max,5}$ = 51 N/mm^2;
- the natural deformation speed values have been $\acute{\varepsilon}$ = 5.126 s^{-1} in caliper 5 and $\acute{\varepsilon}$ =3.69 s^{-1} in caliper 4.

Using diagram we can obtain for these deformation speeds the following mono axial tension values that are really developed in the rolling line:

$\sigma_{max,5}$ =157 N/mm^2

σ_{min4} =68.29 N/mm^2

2.3 Calculation of deformation resistances

As already said before, the tube is hardening during the deformation by rolling so that the tension in minimum at the inlet in the caliper, reaching a maximum value at the end of the rolling. One can see that after entering in the caliper, the tension of one point of the tube that enters in the deformation focus is increasing very fast. By following the curve rate of the tension distribution in the deformation focus we have come to the conclusion that its average value can be calculated by the following empiric relation:

$$\sigma_{mn} = \left(3\sigma_{\max,n} + \sigma_{\min,(n-1)}\right)/ 4 \qquad (1)$$

where $\sigma_{min,(n-1)}$ is the minimum tension value at the tube exit from caliper 4 and $\sigma_{max,,n}$ is the maximum tension value at tube inlet in caliper 5. The results of these calculations, performed for all reducer calipers, are shown in Table 2.

For example for caliper 5 (hence n=5) these values are the following:

σ_m = (3x 157+ 68.29) /4 = 134.82 N/mm^2

As it is well known, in fact the tube stress in the caliper is not mono axial but complex (three-dimensional) and therefore it is necessary to use therefore the equation of von Misses or Treska, that show that between the deformation resistance symbolized by k_f and the mono axial (main) tension σ *is* the following correlation k_f =1.15σ_{mn} for caliper 5 where n=5:

k_f =1.15x134.82=155.05N/mm^2

2.3.1. Calculation of required energy for deformation

The required energy for deformation as such, (reduction in focus), marked with E_1, is calculated by the relation:

$$E_{1,n} = k_{f,n} V_{f,n} \ln \lambda_n \qquad (2)$$

where the meaning of the symbols in the specified formula are known and their values for all reducer calipers as well as the results of the calculations performed in this sense are shown in table 2 [3].

For example, the required energy for tube deformation in caliper 5, is calculated as follows:

$$E_{1,5} = k_{f,5} V_{f,5} \ln \lambda_5 = 637.67 \text{ J}$$

2.3.2. Calculation of the required energy for overcoming the friction in calipers and of total required deformation energy

Because of the speed differences that appear between the tube that passes through the focus (the tube has in the caliper a variable travel speed- smaller at the inlet and greater at the exit than the rolling cylinder speed, that has a constant peripheral speed), (an unavoidable incongruity for each rolling process), at the contact surface between roll and tube appear friction posts. The performed experiments [2] have shown that for the rolling (with traction between calipers) of tubes on stretch reducing mills required energy for overcoming these forces is equal to 40% of the required deformation energy.

Therefore in this paper, the required energy value for overcoming the friction (symbolized by E_2) has been considered to be equal with 40% of the required deformation energy. The results of the calculations done in this sense are shown in Table 2.

For example, in caliper 5, the value of these forces will be equal to the one resulting:

$E_{2,5}$= 255.07 Nm

Therefore, the required total energy for performing the deformation as well as for overcoming the friction in caliper n, will be the sum between $E_{1,n}$ and $E_{2,n}$, allowing us to write the following relation:

$$E_{def,n} = \left(E_{1,n} + E_{2,n}\right) \qquad (3)$$

The results of these calculations are shown in Table 2.For caliper 5 the above relation becomes as follows:

$$E_{de\,f,5} = 892.74 \text{ J}$$

2.4 Calculation of the drive motors power

2.4.1 Calculation of the required power for tube deformation in calipers

Like in all other similar cases, the required power is calculated by dividing the required energy for performing the respective deformation to the time in which it has been done. By dividing the required energy for tube reducing in any of the reducer calipers, to the respective operation time the result is the power (marked with P) [9]. The results of the calculations performed in this respect regarding the required powers for achieving the deformation as well as for overcoming the friction forces between caliper and rolled tube are shown in Table 3.

For example, the required power for pipe rolling in caliper 5 will be:

$$P_{def,n} = \left(E_{1n} + E_{2n}\right) / \Delta T_n \qquad (4)$$

with $E_{15} =$ 637.67 J , E_{25} = 255.07 J, ΔT_n = 0.02 s.

As a consequence, we have the following results:

P_{15} = 31.28 kW

P_{25} =12.53 kW

2.4.2 Calculation of the required power for overcoming the friction in transmission elements and for no-load running

Practical determinations regarding the friction in transmission elements and in no-load running of the reducer are not available and therefore in this calculation we have used valued that have been determined at other rolling mills. Thus we have consider that the required power for overcoming the friction in all transmission elements is of 5% from the required deformation power and for the no-load run the estimated power, which is constant, was about 75% of the required tube deformation power (in the first caliper (in which the reducing being very small the greatest part of the power is consumed for the no-load running). These are orientation values but their weight in the analyzed problem assembly is relatively little significant.

The results of the calculations performed in this sense are shown in Table 3.

2.4.3. Calculation of the required total power for performing tube reducing

The total required power (P_{tot}) for deformation is calculated [10] by summarization of:

- required deformation power (P_1);
- required power for overcoming the friction in caliper (P_2);
- required power for friction in transmission elements (P_3);
- required power for no-load run (P_4);

Therefore we can write the following relation

$$P_{tot} = P_1 + P_2 + P_3 + P_4$$

The results of this calculation are shown in Table 3.

3. Comparison of required calculated energy for tube reducing from Ø123x3.9mm to Ø49x3.25mm with the experimentally measured energy on SRM

Strictly theoretically speaking (when the reduction coefficient, deformation temperature and the chemical composition of steel are identical or only similar) the specific energy required for deformation by rolling (hence also for tube reduction) does not depend on the place or type of equipment on which the respective deformation is done. The same thing can be sad regarding the friction forces that appear between the material (reduced tube) and rolls. Therefore a comparison of the calculation results performed (based on considerate reason with theoretical character with determination performed effectively at the reducer), representt a checking of their correctness, especially if the experiments the same steel grade has been used and the heating before tube reducing has been done at the same temperature.

Such determinations (measurements) of the required energy for reduction have been presented by Burianov [2] who has performed its experiments under the following conditions:

- used steel grades: 10, 20 and 45 (non alloyed steels with an average carbon content like the one specified before);
- number of stands (calipers) of the reducer used in the experiments: 12;
- tap (blank) diameter: 140 mm;
- reduced tubes diameter: 102-83 mm
- wall thickness: 2.75- 20 mm;
- heating temperature for reducing: 900^{0}C;
- reduced tube speed at inlet in the first stand (caliper) of the reducer: 1-2 m/s;
- applied section reducing (Δd /d) at each stand:
  - 3.5-4.5 % for wall thickness under 5 mm
  - 2.0-3.0 % for wall thickness over 5 mm

It can be seen that from several points of view (steel grades, rolling temperature, tube diameters and caliper numbers) the experimenting conditions are similar to those used at tube reducing from Ø123 mm to Ø 49 mm.

Therefore, the comparison of calculations concerning the specific energy presented in this paper for reduction with the practical data obtained at the reducer allows an objective evaluation of the relevant calculations correctness.

Based on determinations performed in this sense in the plant, Figure 3 shows the dependence curve between stretching coefficient *(λ)* and the specific energy required for performing the reducing operation. On the same curve are indicated the specific energy values corresponding to the stretching coefficients used at tube rolling from Ø123 mm to Ø 49 mm.

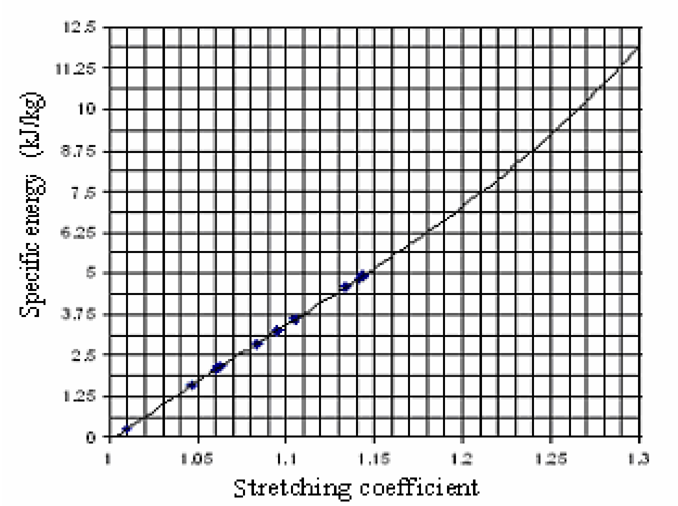

Fig.3. Specific energy consumption variation required for reduction in 12 calipers, of a none alloy steel, from Φ140mm la Φ83...102mm

The obtained results are shown in Table 4. Comparing them with the specific energies determined by calculation we can find out a good correspondence (see Figure 4). Thus, we can see that the average difference between the calculated and the determined energies on the experimental curve are of maximum ±30%. As a general remark we can see that the determined values are in all cases slightly higher than the determined values. These differences can be explained by the different processing conditions.

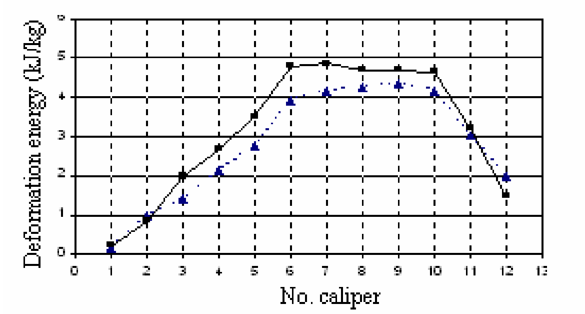

Figure 4. Comparison between the calculated deformation energy values for stretching applied at tube reducing from Φ123x3.9mm to Φ49x3.25mm and the resulting values from the performed measurements at tube reduction from Φ140mm to Φ83...102mm.

4 Conclusions

A methodology has been worked out for the calculation of the required energies and powers for tube deformation in each caliper of the reducing line.

For achieving this calculation, besides the influence of the chemical composition and the rolling temperature (data which for rolling operations performed in a sequential regime are sufficiently good well known) in the case of a continuous rolling, particularly of tubes, we must also know the following specific parameters:

- natural deformation degree (*ε*);
- natural deformation speed (ἑ)
- dynamic softening intensity (that appears during the deformation process) a static softening intensity (that takes place during the required time for tube passing from one caliper to the next successive caliper).

Because the present stage of the plastic deformation theory does not allow a relatively exact calculation of the concomitant influence of all previous specified factors, the only possibility to obtain such data (required for performing such a calculation), consist in the modeling of the analyzed reducing process by using a plastometer (like for example a Setaram type spinning machine).

By extrapolation of the experimental data (through adequate mathematic methods) they become usable for calculation of energetic and power parameters achieved also in similar technological conditions.

The calculation methodology presented in this paper has been exemplified in the version of tube reduction from Ø123x3.9mm to Ø49x3.25mm, at a reducer consisting of 12 stands.

For performing the respective calculation we have used experimental data obtained by modeling the relevant reducing process on a plastometer

The energetic parameters calculation method shown in this paper has been checked by comparing thus obtained required energy values with the experimental on a similar reducing mill determine average values.

Table 4. Comparison between necessary specific energy of tubes from Φ123x3.9mm to Φ49mm

Caliper	Deformation specific energy E_s , kJ / kg		Ratio between determined and calculated values	Difference between determined and calculated values	
	Calculated values at the tube reducing from Ø123mm to Ø49mm	Determined values from fig.6 at tube reducing from Ø140mm to Ø83...102mm		values	%
1	0.1716	0.2	1.17	0.0284	16.55
2	0.9824	0.85	0.87	-0.1324	-13.48
3	1.4045	1.98	1.41	0.5755	40.98
4	2.1164	2.66	1.26	0.5436	25.69
5	2.77	3.5	1.26	0.73	26.35
6	3.9359	4.8	1.22	0.8641	21.95
7	4.1289	4.86	1.18	0.7311	17.71
8	4.2554	4.7	1.10	0.4446	10.45
9	4.3626	4.7	1.08	0.3374	7.73
10	4.1748	4.65	1.11	0.4752	11.38
11	3.0353	3.2	1.05	0.1647	5.43
12	1.9771	1.46	0.74	-0.5171	-26.15
sum	33.32	37.56	-	-	-
Medium value	2.777	3.13	1.12	0.353	12.05

The obtained results have shown that between the two values there is a good conformity, the average difference being of 12%.

The experimentally determined deformation energy values present syntheses results of a series of determinations performed in plants, experiments where the influences they have from this view point – temperature, natural deformation speed and (dynamic and static) softening, appeared during the rolling and between the rolled stands, have not been evidenced.

Although, being practical average values, their use in various other calculations leads to orientate results which though not very precise, do not modify the size grade of the result.

The calorific equivalent of the mechanical work performed for tube reducing from Ø 123x3.9 mm to Ø49.25 mm have lead to an increase of the tube temperature (during its rolling) by 47.8 ^{0}C, this fact meaning that if they should not cool down, their final temperature would be 947.8 ^{0}C.

In reality the tube temperature at its exit from the last reducer stand is lower because of heat losses by radiation, convection (air, water) and thermal conductivity.

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