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# Rational Exploitation of the Machines for Straightening Steel Plates and Strips Intended for the Manufacture of Static Equipment from Petroleum Refineries and Petrochemical Plants

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## Abstract

*This paper analyses and resolves the extremely complex problems of performing the technological operation of straightening of the steel plates and strips intended for the manufacture of static equipment, of the type pressure vessels and storage tanks, for petroleum refineries and petrochemical plants. The procedure and software product developed by the authors for the design of the technological operation of straightening of the steel plates and strips on straightening machines with multiple rollers highlights the parameters describing the regime for the straightening operation and the modalities for the adequate selection of their values, as well as the factors influencing the shape precision of the straightened semi-products and the energy input needed to perform the straightening operation. The information from the present paper is extremely useful for the selection and rational exploitation of the straightening machines and, in this manner, for the appropriate quality assurance of the semi-products intended for the construction of static equipment, with special technical parameters (big overall dimensions and masses, high operating pressures, high or low operating temperatures, aggressive working fluids etc.), from the petroleum and gas processing plants.*

**Key words:** *straightening of steel plates and strips, straightening machines with rollers, straightening regime*

## Introduction

The Petrochemical Equipment (PE) of the type storage tanks and pressure vessels are welded structures, constructed starting from semi-products of the type plates and rolled strips made of different steel grades, the highest weight being held by non-, micro- and low-alloy weldable steels, from the category HSLA (High Strength Low Alloy) steels. Straightening (levelling) is the technological operation that corrects the errors of shape (primarily, out-of-flatness) generated during the manufacturing process or caused to these semi-products during their transportation, storage and handling before usage. This operation is required, because marking and processing semi-products with such errors is difficult and leads to obtaining a reduced shape precision of PE components, which creates technological problems difficult to solve regarding the attainment of the stage of assembly for welding and of the welding stage.

The straightening operation is necessary especially for semi-products with reduced stiffness, which could get (both during their manufacturing and also by means of inadequate or accidental actions, occurred during their transportation, storage and handling before usage) residual deformations (of plastic nature), general or local, which affects their shape precision. Such precision for plates and rolled strips made of HSLA steels comply (at delivery) with the requirements summarised in Table 1, which includes also statistical data regarding the percentage $p_{ni}$, of the semi-products that must be straightened from each delivered batch (before using them to manufacture PE components) [1-4].

**Table 1.** Shape precision of plates and rolled strips from din HSLA steels and statistical data regarding the necessity of straightening these semi-products before using them to manufacture PE

| Semi-product thickness *s*, mm | | [3;5) | [5;8) | [8;15) | [15;25) | [25;40) |
|---|---|---|---|---|---|---|
| Tolerances on thickness Class C a), mm | lower | 0 | 0 | 0 | 0 | 0 |
| | upper | +1.0 | +1.2 | +1.4 | +1.6 | +2.0 |
| Normal tolerances b) on flatness (N) for steel type L c) semi-products and *ML* d) = | 1000 | 9 | 8 | 7 | 7 | 6 |
| | 2000 | 14 | 12 | 11 | 10 | 9 |
| Special tolerances b) on flatness (S) for steel type L c) semi-products and *ML* d) = | 1000 | 5 | 5 | 3 | 3 | 3 |
| | 2000 | 10 | 10 | 6 | 6 | 6 |
| Normal tolerances b) on flatness (N) for steel type H c) semi-products and *ML* d)= | 1000 | 12 | 11 | 10 | 10 | 9 |
| | 2000 | 17 | 15 | 14 | 13 | 12 |
| Special tolerances b) on flatness (S) for steel type H c) semi-products and *ML* d)= | 1000 | 7 | 7 | 7 | 7 | 7 |
| | 2000 | 14 | 13 | 12 | 11 | 11 |
| Minimum percentage of semi-products from a batch that must be straightened, $p_{ni}$ | plates | 90 | 75 | 50 | 10 | 2 |
| | strips | 100 | 90 | 60 | 25 | 10 |

a) See tolerances on thickness in EN 10029; b) All tolerances on flatness are in mm; c) Steel type L – steel semi-products with a specified minimum yield strength $R_{p0.2} \leq 460$ MPa, neither quenched nor quenched and tempered semi-products; Steel type H – steel semi-products with a specified minimum yield strength $R_e > 460$ MPa and all grades of quenched and quenched and tempered semi-products; d) *ML* – measuring length, mm; if the wave pitch (distance between the points of contact of the straight edge and the semi-product – see fig. 1) is shorter then 1000 mm the permissible deviation from flatness shall comply with following requirements: „for distances between the points of contact of two waves between 300 mm and 1000 mm, the maximum flatness tolerance is 0.5 % of the wave pitch for steel L and 1% of the wave pitch for steel H, but not exceeding *b* the values in Table 1".

Straightening is achieved by means of plastic deformation (usually, cold-working) of the semi-product, causing its bending to the contrary of the curvature corresponding to the out-of-flatness that it has. The schemes and diagram from Figure 1 present the manner of defining and determining the flatness of steel plates and strips, together with the principle of achieving straightening for this type of semi-products: a) the semi-product has in its initial state a local curvature $\rho_0 = -1/r_0$; b) to straighten the semi-product, a bending moment $M$ is applied, with the intensity gradually increased up to a value $M_i$, which achieves the elastic-plastic deformation of the semi-product to the contrary of the curvature $\rho_0$; c) once the bending moment reaches the value $M_i$, the curvature of the semi-product attains a value $\rho_i = 1/r_i$, established such that, when the moment $M_i$ stops acting (the semi-product is taken out from the straightening machine) and the elastic relaxation of the semi-product takes place, the curvature will get the value 0 (the semi-product is straightened).

## Multiple Rollers Machines for Straightening Semi-products

The straightening of semi-products of the type steel plates and rolled strips, used particularly for manufacturing PE, is made on special machines (Straightening Machines – SM), which have a great number of rollers (for semi-products used normally to manufacture PE components, with the thickness $s = 8\dots16$ mm, straightening machines with $n = 9\dots13$ rollers are used).

These SM can be characterized as follows: a) the rollers are disposed on two superposed cross-bars; b) the rollers from the lower cross-bar are usually the driving ones, being powered by an electrical motor by means of a speed reduction unit and an appropriate mechanical transmission; c) the cross-bars on which the SM rollers are disposed can be inclined, the upper cross-bar being inclined in relation to the lower cross-bar at a dihedral angle $\alpha = 3...5^{o}$, which allows for a progressively decreasing deformation of the material of the semi-product subjected to straightening; d) the SM rollers, with the diameter $D_r$, are manufactured from surface quenched steel (high frequency quenching at the hardness 50...60 HRC) or from cast iron with hard surface; e) the distance between the rollers from the same row is $t = (1.0...1.1)D_r$, and the diameters of the pins supporting the rollers on the liners of the slide bearings from their ends have the value $d_r = (0.78...0.80)D_r$; f) the deformation pattern of the semi-products when passing between the SM rollers (with the cross-bars being inclined) is presented in the scheme from Figure 2, and the main technical and operational parameters of some modern SMs for straightening plates and strips are shown in Table 2 [6, 7].

It has been established (experimentally and theoretically) that the straightening process takes place while the semi-product goes between the first 4...5 rollers of the SM, when passing between the other rollers only the extension (stretching) of the semi-product and the relaxation of the residual stresses generated in the straightening process will occur [3, 4].

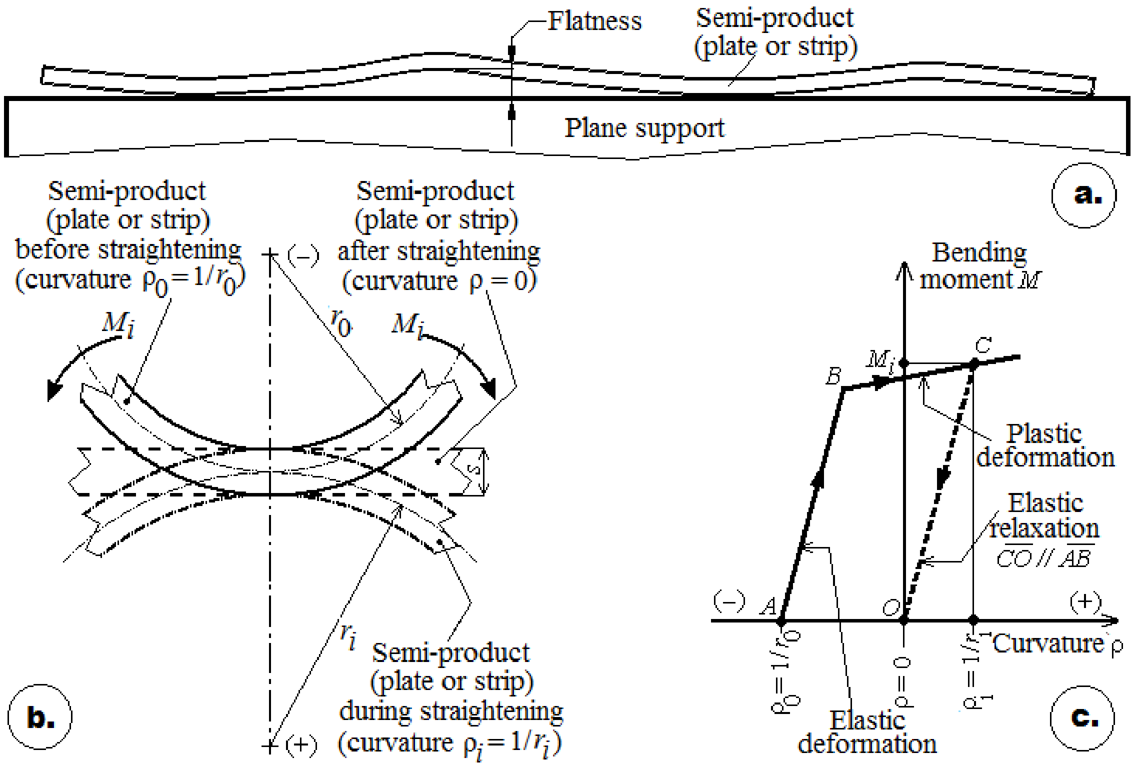

**Fig. 1.** The principle of achieving the straightening of semi-products of the type plate or strip

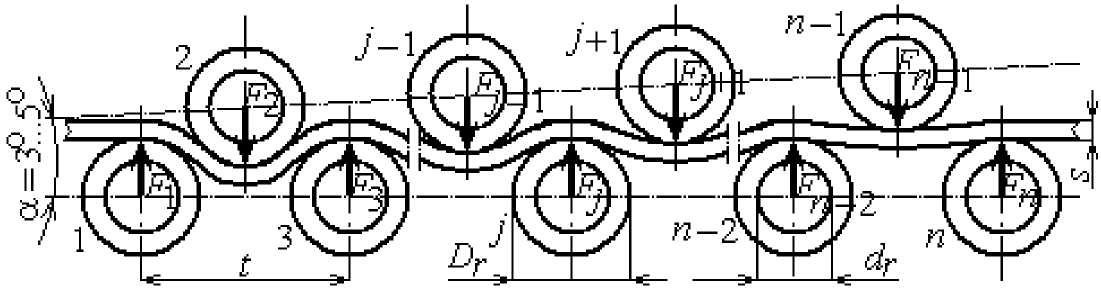

**Fig. 2.** Deformation pattern for plates and strips when straightening them on a SM

**Table 2.** Technical parameters of some SMs for plates and strips

| Machine type | SM technical parameters $^{a)}$ | | | | | | Straightening accuracy max, mm/m |
|---|---|---|---|---|---|---|---|
| | $s \times B$ $^{b)}$ max, mm × mm | $n$ | $D_r$, mm | $t$, mm | $v_s$, m/min | $P_m$, kW | |
| W43G | 2 × 2500 | 15 | 50 | 56 | 15 | 7.5 | 0.5 |
| | 6 × 2000 | 15 | 105 | 110 | 20 | 45 | 1.0 |
| | 8 × 2000 | 13 | 165 | 175 | 20 | 45 | 1.0 |
| | 10 × 2000 | 13 | 165 | 175 | 20 | 55 | 1.0 |
| | 12 × 2000 | 13 | 165 | 175 | 16 | 75 | 1.0 |
| | 16 × 2500 | 11 | 220 | 260 | 12 | 110 | 1.0 |
| | 20 × 2500 | 11 | 260 | 300 | 9 | 160 | 1.0 |
| | 25 × 2500 | 9 | 280 | 320 | 8 | 185 | 1.0 |
| JPG | 3 × 1600 | 15 | 90 | 98 | 30 | 22 | 1.5 |
| | 6 × 2000 | 13 | 140 | 150 | 18 | 45 | 2.0 |
| | 10 × 2000 | 11 | 160 | 175 | 12 | 75 | 2.0 |
| | 12 × 2000 | 11 | 180 | 195 | 10 | 100 | 2.0 |
| | 16 × 2000 | 9 | 220 | 235 | 9 | 110 | 2.0 |
| | 20 × 2500 | 9 | 240 | 240 | 8 | 150 | 2.0 |

a) Significance of technical parameters: $n$ – number of straightening rollers; $D_r$ – diameter of straightening rollers; $t$ – distance between straightening rollers; $v_s$ – straightening speed; $P_m$ – main motor power; b) the machine can process steel semi-products with maximum thickness $s$ and width $B$ if the yielding strength is maximum 450 MPa

## Initial Data Required to Define the Technological Regime for Straightening

The definition of the technological regime needed to perform the straightening operation for steel plates and strips requires the knowledge of the following categories of initial data:

- Technical parameters of the SMs available: number of SM active rollers, $n$; diameter of SM working rollers, $D_r$; diameters of the pins supporting the rollers on the liners of the slide bearings from their ends, $d_r$ (as previously mentioned, for the majority of SMs, $d_r = (0.78...0.80)D_r$); pitch / distance between the axis of the rollers placed on the same row, $t$ (as previously mentioned, for the majority of SMs, $t = (1.0...1.1)D_r$); peripheral speed of the SM rollers (straightening speed), $v_s$; the efficiency of the mechanical transmission from the SM driving motor to the rollers that achieve straightening, $\eta$ (most SMs ensures efficiency values of $\eta = 0.75…0.85$); nominal power of the SM driving motor $P_m$ (see fig. 2 and table 2).

- The characteristic dimensions of the semi-product subjected to straightening: the thickness of the semi-product, *s*; the width of the semi-product, *B*.
- The mechanical properties of the semi-product: longitudinal modulus of elasticity (Young's modulus), $E$; yield strength, $R_y$ (upper yield strength, $R_{eH}$, proof strength, plastic extension, $R_{p0.2}$, or proof strength, total extension, $R_{t0.5}$); tensile strength, $R_m$; percentage elongation after fracture, $A$; stress – strain characteristic curve, conventional/nominal, $\sigma = f(\varepsilon)$, or true/effective, $\sigma = g(\varepsilon)$. The values for the parameters $E$, $R_y$, $R_m$ and $A$ (at the environmental temperature, $t_a$) are taken from the standard of the steel from which the semi-product is made of or they are determined by the tensile testing of some specimens cut from the semi-product, and the curves $\sigma = f(\varepsilon)$ and $\sigma = g(\varepsilon)$ are drawn by means of processing the force – extension curve, determined by tensile testing, using, for instance, the procedure presented in [5], their analytical expressions being shown in Table 3. If it is desired or it is imposed (on grounds regarding the technical parameters of the available SMs) to achieve straightening at a temperature $t > t_a$, the mechanical properties of the semi-products at this temperature (Young's modulus, $E_t$, and yield strength, $R_{yt}$), needed to define the technological regime for the straightening operation, will be calculated with formulas of the type: $E_t = E\,K_{E,t}$ and $R_{y,t} = R_y\,K_{Ry,t}$; for the semi-products made of HSLA steels and $t \in [100^{\circ}\mathrm{C};1000^{\circ}\mathrm{C}]$, the values of the factors $K_{E,t}$ and $K_{Ry,t}$ can be determined using the information presented in Figure 3 (for a conservative evaluation of the power required for straightening, it is recommended to use the maximum values for $K_{E,t}$ and $K_{Ry,t}$ – see fig. 3) [8-14].

**Table 3.** Analytical expressions of the effective stress – strain curves for steel plates and strips and the formulas of the factors $Q_{b,j}$ and $Q_{t,j}$ used to define the technological regime for the straightening operation

| Type of curve $\sigma = g(\varepsilon)$ for semi-product | | Without strain hardening (Prandtl) | With strain hardening [a)] | |
|---|---|---|---|---|
| Analytic formula of $\sigma = g(\varepsilon)$, if $\varepsilon$ is: | $\varepsilon \le \varepsilon_e$ | $\sigma = E\varepsilon$ | $\sigma = E\varepsilon$ | $\sigma = K\varepsilon^m$ |
| | $\varepsilon > \varepsilon_e$ | $\sigma = R_y = R_{eH}$ | $\sigma = K\varepsilon^m$ | |
| $Q_{b,j}$ factor in formula for bending moments $M_{b,j}$ | | $Q_{b,j} = 1 - \frac{k_j^2}{3}$ | $Q_{b,j} = \frac{2}{m+2}\left[\frac{1}{k_j^m} - \frac{(1-m)k_j^2}{3}\right]$ | $Q_{b,j} = \frac{2}{m+2}\frac{1}{k_j^m}$ |
| $Q_{t,j}$ factor in formula for torsion moments $M_{tdp,j}$ | | $Q_{t,j} = \frac{1}{k_j} + \frac{k_j}{3} - 1$ | $Q_{t,j} = \frac{2}{(m+1)(m+2)}\frac{1}{k_j^{m+1}} + \frac{2(1-m)}{3(m+2)}k_j - \frac{1-m}{1+m}$ | $Q_{t,j} = \frac{2}{(m+1)(m+2)}\frac{1}{k_j^{m+1}}$ |

a) $\varepsilon_e = R_y/E$; the strain-hardening exponent $m$ is determined with the method from ASTM E646 or is evaluated using the formulas proposed in [8], while the strength modulus / coefficient $K$ is given by the formula $K = E\varepsilon_e^{1-m}$.

## The Technological Regime for Straightening Semi-products

The preparation of the straightening operation (for a batch of steel plates or strips having the characteristics listed as initial data) commonly consists of the selection of the SM with rollers (among the machines available in the factory in which the operation is executed) and the verification of the possibility of performing the operation on the chosen machine; to that purpose, by, the calculation steps detailed below should be performed.

A. The values of the bending moments $M_{i,j}$, $j = 1...n$, required to bend the semi-product when passing in front of the rollers of the SM, are determined by applying the formulas (obtained considering the calculation scheme shown in Figure 4) [13-17]:

$$M_{i,j} = \int \sigma y \mathrm{d}S \text{ and } \mathrm{d}S = B\mathrm{d}y \;\Rightarrow\; M_{i,j} = 2B\int_0^{\frac{s}{2}} \sigma y \mathrm{d}y \;\Rightarrow\; M_{i,j} = \frac{R_y B s^2}{4} Q_{b,j}, \qquad (1)$$

in which $\sigma = g(\varepsilon)$ has one of the analytical expressions indicated in Table 3, $\varepsilon = y/r_j$, because it is accepted that the deformation of the semi-product at the radius $r_j$, when it passes in front of the roller $j$, is made in compliance with the plane sections hypothesis, and $Q_{b,j}$ has, as a function of the type of the curve $\sigma = g(\varepsilon)$, one of the analytical expressions from Table 3. The values of the elastic area coefficient of the semi-product, elastic-plastically deformed at its passage in front of the roller $j$, $k_j$ (which intervene in the analytical expressions of $Q_{b,j}$), defined with the formula $k_j = 2(y_0/s) = 2(r_j/s)(R_y/E)$, are obtained as a function of the value $k_3$ (the coefficient of the elastic area of the semi-product elastic-plastically deformed at its passage in front of the roller 3), assumed based on the indications from Table 4 or calculated (if the local curvatures of the semi-product subjected to straightening, $\rho_s = 1/r_s$, $r_s = k_c s$, are known) as a root of the equation [1-3, 12]:

$$\frac{6}{m+2}\left[\frac{1}{k_3^m} - \frac{1-m}{3}k_3^2\right] = \frac{2}{k_3} - \frac{1}{k_c}\frac{E}{R_y}; \qquad (2)$$

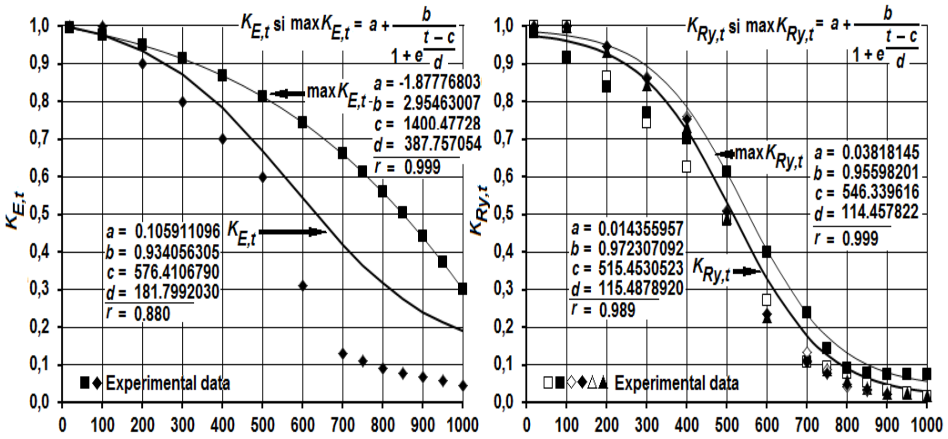

**Fig. 3.** Temperature variation diagrams for the factors $K_{E,t}$ and $K_{Ry,t}$

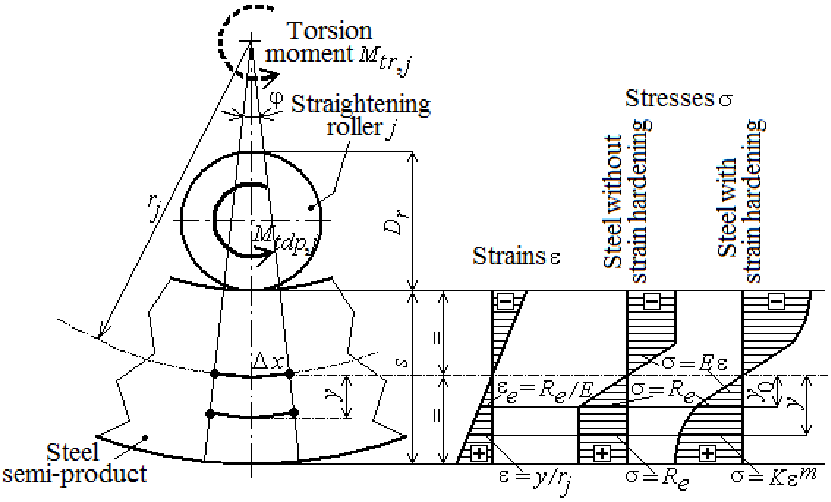

**Fig. 4.** Calculation scheme used for the definition of the elements of the technological regime for the straightening operation of semi-products

**Table 4.** Formulas for $k_j$ and $F_j$ when defining the technological regime for straightening semi-products

| Roller $j$ | $j = 1$ | $j = 2$ | $j = 3$ | $j = 3\ldots n\text{-}1$ | $j = n\text{-}1$ | $j = n$ |
|---|---|---|---|---|---|---|
| $k_j$ | $M_{i,1} = 0$ | $k_2 = 2k_3$ | $k_3$ $^{a)}$ | $k_j = k_3 + \frac{j-3}{n-4}(1-k_3)$ | | $k_n = 1$ |
| $F_j$ | $F_1 = \frac{2}{t}M_{i,2}$ | $F_2 = \frac{2}{t}(2M_{i,2} + M_{i,3})$ | $F_j = \frac{2}{t}(M_{i,j-1} + 2M_{i,j} + M_{i,j+1})$;<br>$F_{n-1} = \frac{2}{t}(M_{i,n-2} + 2M_{i,n-1})$; | | | $F_n = \frac{2}{t}M_{i,n-1}$ |

1. $k_3$ = 0.08…0.10 when straightening the semi-products (of the type steel plates and strips) with $s < 6$ mm and $k_3$ = 0.06…0.08 when straightening the semi-products with $s \geq 6$ mm [1-4].

Figure 5 presents, as an example, the selection diagram for $k_3$, obtained by resolving equation (2), for the case of plate batches made from the steels S235 (with $R_y$ = 250 MPa, $R_m$ = 400 MPa, $A$ = 22 %, $K$ = 527 MPa and $m$ = 0.111) and S355 (with $R_y$ = 400 MPa, $R_m$ = 640 MPa, $A$ = 20 %, $K$ = 844 MPa and $m$ = 0.120).

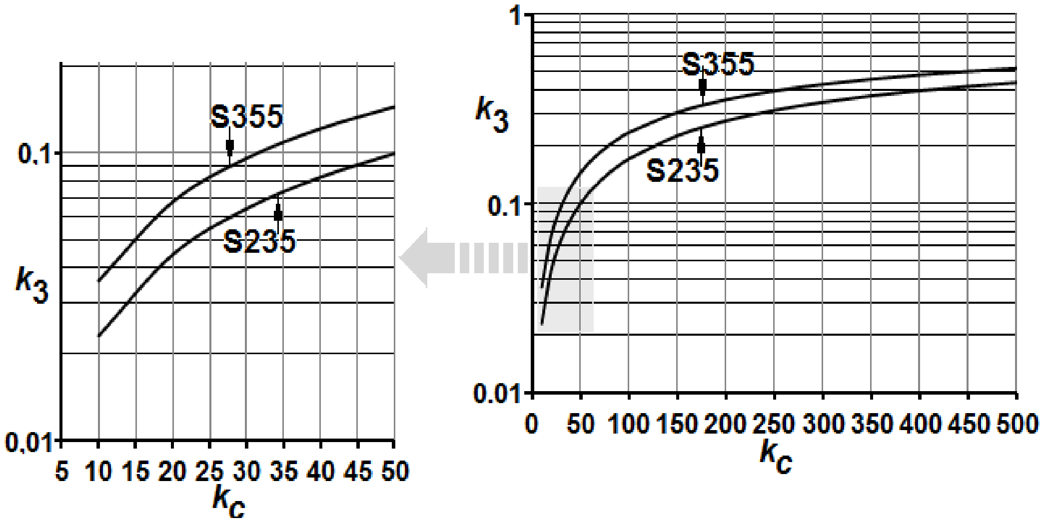

**Fig. 5.** Selection diagram for $k_3$ as a function of the local curvature radii of the semi-product, $r_s$=$k_c s$

B. The intensities of the forces $F_j$, $j$ = 1...$n$, that are acting upon the semi-product in front of each roller of the SM (see fig. 2), are calculated with the formulas indicated in Table 4, defined using a recurrent calculation method, based on calculation schemes of the type presented in Figure 6 [1].

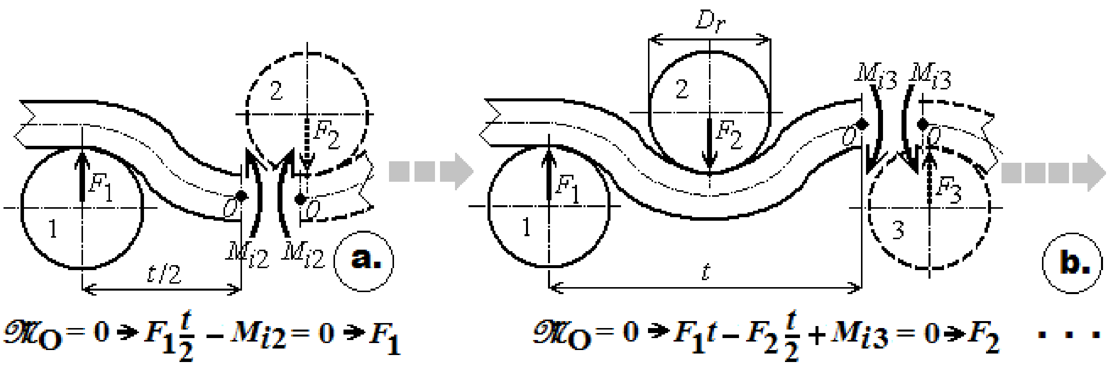

**Fig. 6.** Calculation schemes for the intensities of the forces $F_j$, $j$ = 1...$n$

C. The values of the torsion moments $M_{t,j}$, $j = 1...n$, that should be applied on the SM rollers to achieve straightening, are defined by the relationship:

$$M_{t,j} = M_{tdp,j} + M_{tfs,j} + M_{tfl,j} \ , \tag{3}$$

where $M_{tfl,j}$ and $M_{tfs,j}$ are the torsion moments needed to overcome friction in the bearings with which the roller $j$ rests on the cross-bar of the SM ($M_{tfl,j}$) and between the semi-product subjected to straightening and roller $j$ of the SM ($M_{tfs,j}$), while $M_{tdp,j}$ is the torsion moment necessary for the elastic-plastic deformation of the semi-product (bending of the semi-product at the radius $r_j$) when passing in front of roller $j$ [1-8, 12]:

$$M_{tfl,j} = F_j \mu \frac{d_r}{2}; \quad M_{tfs,j} = F_j f, \ M_{tdp,j} = \frac{R_y^2 D_r Bs}{4E} Q_{t,j}, \tag{4}$$

$\mu$ being the sliding friction coefficient from the bearings of the roller $j$ ($\mu = 0.08 ... 0.10$), $f$ – the rolling friction coefficient between roller $j$ of the SM and the semi-product subjected to straightening ($f = 0.08$ mm...0.10 mm), and the factor $Q_{t,j}$ being given by the formulas indicated in Table 3, as a function of the type of the curve $\sigma = g(\varepsilon)$ of the semi-product material subjected to straightening; calculation formulas for $M_{tdp,j}$ have been developed considering the following reasoning sequence:

- by examining the calculation scheme from Figure 4, the following equations resulted:

$$\frac{M_{tr,j}}{r_j} = \frac{2M_{tdp,j}}{D_r + s} \ \Rightarrow \ M_{tdp,j} = M_{tr,j} \frac{D_r + s}{2r_j}, \tag{5}$$

in which $M_{tr,j}$ is a fictive torsion moment, which should be acting in the centre of an (imaginary) roller with the radius $r_j$, in order to perform the plastic deformation of the semi-product so that it coils on this roller; considering that, in a passage sequence of the semi-product over the SM roller $j$, the plastic deformation of the volume of material located between the planes which define the angle $\varphi$ (see fig. 4) is achieved, and, if $L_{m,j}$ is the mechanical work required to reach this deformation, the following relations result:

$$L_{m,j} = M_{tr,j}\varphi = M_{tdp,j} \frac{2r_j}{D_r + s}\varphi = M_{tdp,j} \frac{2\Delta x}{D_r + s} \tag{6}$$

and, since $s << D_r \ \Rightarrow \ D_r + s \cong D_r$, the last equation from (6) has been written under the form:

$$M_{tdp,j} = L_{m,j} \frac{D_r}{2\Delta x}. \tag{7}$$

- the mechanical work $L_{m,j}$, from equation (7), has been determined using the common formula:

$$L_{m,j} = \int \Delta L_{m,j} \mathrm{d}V, \tag{8}$$

where the material elementary volume in which the deformation occurs, d$V$, is, as it can be seen in Figure 4, $\mathrm{d}V = B\Delta x \mathrm{d}y$, and $\Delta L_{m,j}$ represents the mechanical work needed to attain the strains $\varepsilon$ in a unity volume from the material of the fibre positioned at the distance $y$ from the mean fibre of the semi-product subjected to straightening; $\Delta L_{m,j}$ has been determined by calculating the integral:

$$\Delta L_{m,j} = \int_0^{\varepsilon} \sigma \mathrm{d}\varepsilon = \int_0^{\varepsilon} f(\varepsilon)\mathrm{d}\varepsilon, \tag{9}$$

$L_{m,j}$ has resulted of the form:

$$L_{m,j} = \frac{R_y^2 Bs\Delta x}{2E} Q_{t,j} \tag{10}$$

and, introducing $L_{m,j}$ in (7), the formula for $M_{tdp,j}$ has been obtained – the last formula from the group (4).

D. The power required by the SM driving motor (to be able to perform the straightening operation of the semi-product), $P_{nec}$, is calculated by using the formulas:

$$P_{nec} = \frac{\omega \sum_{j=1}^{n} M_{t,j}}{\eta} = \frac{2v_i \sum_{j=1}^{n} M_{t,j}}{D_r \eta}, \tag{11}$$

in which $\omega$ is the angular speed of the rollers of the machine, and $v_i$ is the straightening speed: $v_i = \omega \frac{D_r}{2}$.

E. The power required, $P_{nec}$, is compared with the nominal power of the SM driving motor (selected, in the stage of defining the initial data, from the machines available or accessible to perform the straightening operation), $P_m$, and one of the following decisions will be taken:

- if $P_{nec} \le P_m$, the straightening of the semi-products can be achieved using the chosen SM;
- if $P_{nec} > P_m$, the straightening of the semi-products cannot be achieved using the selected SM and, as a consequence, the conditions of performing the technological operation of straightening should be modified (selection of another SM, straightening of the semi-products at $t > t_a$, diminution of the semi-products width, $B$, etc.).

## Adequate Selection and Rational Exploitation of the Straightening Machines

SM with multiple rollers are heavy and expensive installations and, as a result, any manufacturer of static equipment for petroleum refineries and petrochemical plants owns one or, at the most, two such machines, with which he must perform all the straightening operations for the steel plates and strips he is using as semi-products to manufacture the components of the equipment which is ordered to him. Within this context, the formulas previously presented are extremely useful, allowing for the evaluation of the usage performances of existent SMs, the definition of the technical parameters of SMs that must be purchased to be able to carry out a certain production programme or the selection of the technological regime for straightening that guarantees the minimum energy input and/or the maximum efficiency; the examples / case studies presented in the followings are suggestive / relevant justifications of the above statements.

A. The effects of knowing the local curvatures, $\rho_s = 1/r_s$ (with $r_s = k_c s$), of the steel plates which are to be straightened upon the magnitude of the required power, $P_{nec}$, to perform straightening on a selected SM, are highlighted by the diagrams presented in Figure 7, built after analysing the case of straightening some plate batches, with the thickness $s = 10$ mm and width $B = 2000$ mm, made of the steels S235 (with $R_y = 250$ MPa, $R_m = 400$ MPa, $A = 22$ %, $K = 527$ MPa and $m = 0.111$) and S355 (with $R_y = 400$ MPa, $R_m = 640$ MPa, $A = 20$ %, $K = 844$ MPa and $m = 0.120$), considering $k_3 = 0.01\ldots0.50$, chosen as a function of $k_c$ and the use of the SM with the technical parameters marked in Table 2. It can be noted that, if the steel plates subjected to straightening have local curvatures with great radii ($r_s > (150\ldots200)s$ and $k_3 > 0.15\ldots0.20$), $P_{nec}$ decreases considerably and the energy input for straightening decreases significantly.

B. The technological regimes for straightening plates (with different thicknesses $s$ and widths $B$, made of steels with different mechanical properties) can be selected using diagrams of the type presented in Figure 8, drawn considering the following conditions: a. the plates have thicknesses $s = 5...25$ mm and the width $B = 2000$ mm; b. the plates are manufactured from S355 steel (with $R_y = 400$ MPa, $R_m = 640$ MPa, $A = 20$ %, $K = 844$ MPa and $m = 0.120$); c. available SMs are JPG (with $v_{i,\max} = 10$ m/min and $P_m = 100$ kW) and W43G (with $v_{i,\max} = 16$ m/min and $P_m = 75$ kW). As it can be seen when examining the diagrams from Figure 8 (obtained considering $k_3$ = 0.06), when selecting the straightening regime, there are two options: a. if $P_{nec} \le P_m$, it will be used $v_s = v_{s,\max}$; b. if, considering $v_s = v_{s,\max}$, it results $P_{nec} > P_m$, one will adopt a $v_s < v_{s,\max}$, so that it results $P_{nec} = P_m$. It can also be noticed that the use of the JPG SM is more convenient, ensuring a greater efficiency when achieving the straightening (plates with thicknesses $s \le 12$ mm can be straightened using $v_{s,\max} = 10$ m/min).

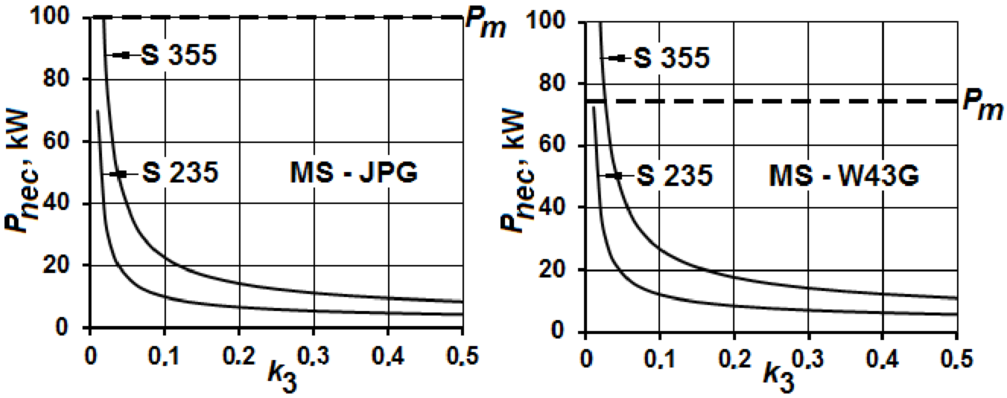

**Fig. 7.** Relationships between $P_{nec}$ and $k_3$, selected as a function of $r_s = k_c s$, when straightening steel plates

C. SM which has to be acquired or used can be selected based on the information synthetized in the diagrams from Figure 9, build considering that: a. the plates which must be straightened have the maximum thickness $s$ = 12 mm and the width $B$ = 2000 mm; b. The plates are made of S355 steel (with $R_y$ = 400 MPa, $R_m$ = 640 MPa, $A$ = 20 %, $K$ = 844 MPa and $m$ = 0.120); c. the available machines have $n$ = 5…13 rollers; $D_r$ = 100…350 mm, $d_r = 0.80D_r$, $t = 1.05D_r$, $v_s$ = 3...10 m/min, $\eta$ = 0.8 and $P_m$ = 100 kW. It can be noted that the most convenient alternatives are the ones with $n$ = 5…9 rollers and $D_r$ = 175…225 mm, for which $P_{nec} \le P_m$, when using the maximum straightening speed, $v_s$ = 10 m/min.

It is mentioned the fact that, in order to perform the calculations required for solving the case studies previously presented, the software products CALCIND – 1...3 (in MathCad), conceived and developed by the authors [19], have been used.

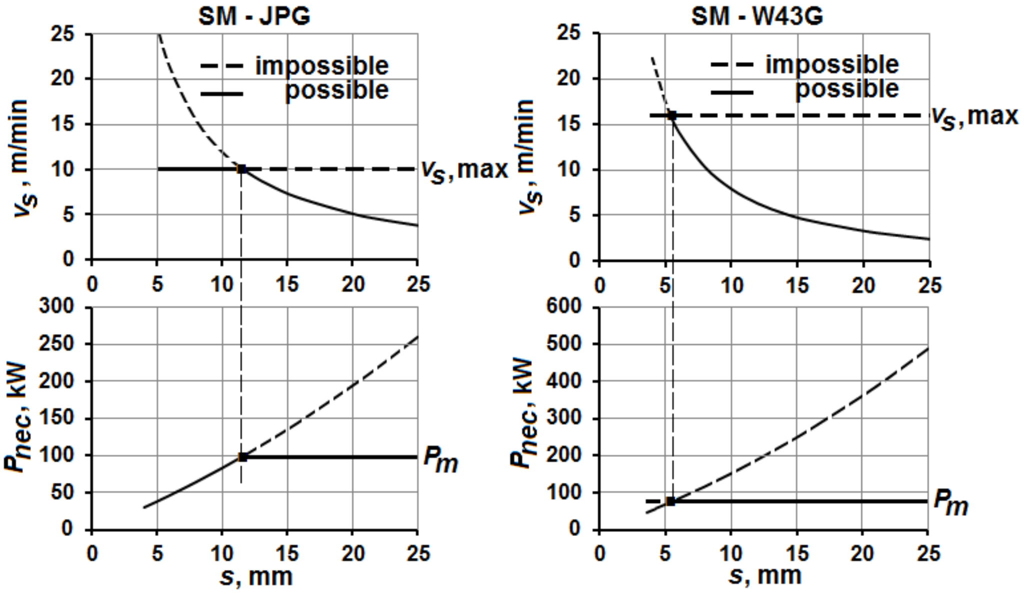

**Fig. 8.** Selection diagrams for the technological regimes for straightening steel plates

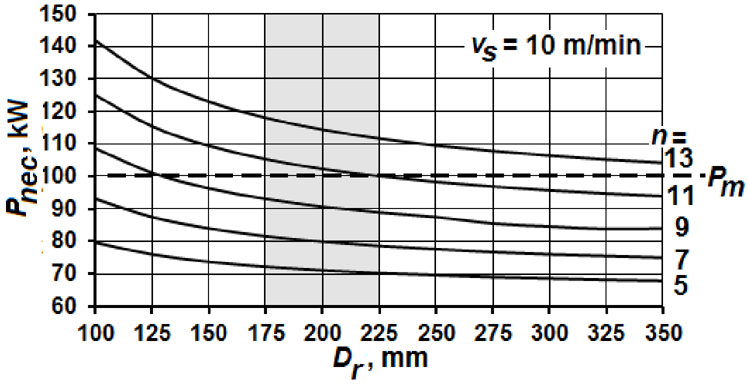

**Fig. 9.** SM selection diagrams for straightening steel plates

## Conclusions

The solutions proposed in the present paper are extremely useful and can constitute the technical support required for the adequate selection of the machines that achieve the straightening of the steel plates and rolled strips used for the manufacture of static equipment, of the type pressure vessels and storage tanks, for petroleum refineries and petrochemical plants. These technical solutions can also be used for the rational exploitation of the straightening machines, so that the technological operations of straightening the steel plates and strips are performed with a minimum energy input and their maximum efficiency is guaranteed.

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# Exploatarea raţională a mașinilor pentru îndreptarea tablelor și benzilor de oţel destinate fabricării echipamentelor statice din rafinăriile de petrol și instalaţiile petrochimice

## Rezumat

*Lucrarea analizează și soluţionează problematica deosebit de complexă a realizării operaţiei tehnologice de îndreptare a tablelor și benzilor de oţel destinate fabricării echipamentelor statice, de tipul recipientelor sub presiune și rezervoarelor de depozitare, pentru rafinăriile de petrol și instalaţiile petrochimice. Procedura și produsul informatic elaborate de autori pentru proiectarea operaţiei tehnologice de îndreptare a tablelor și benzilor de oţel pe mașni de îndreptat cu role multiple evidenţiază parametrii care descriu regimul operaţiei de îndreptare și modalitățile de alegere adecvată a valorilor acestora, precum și factorii care influenţează precizia formei semifabricatelor îndreptate și consumul energetic la efectuarea operaţiei de îndreptare. Informaţiile din prezenta lucrare sunt deosebit de utile pentru alegerea și exploatarea raţionale a mașinilor de îndreptat și pentru asigurarea calității corespunzătoare a semifabricatelor destinate realizării echipamentelor statice, cu caracteristici tehnice deosebite (gabarite și mase mari, presiuni de lucru ridicate, temperaturi de lucru ridicate sau scăzute, fluide de lucru agresive etc.), din instalaţiile de procesare a petrolului și gazelor.*