Metal rolling – Asymmetrical rolling process

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Abstract. The development of theory and practice related to the asymmetric longitudinal rolling process is based on the general theory of metalworking by pressure and symmetric rolling theory, to which a large number of scientists brought their contribution. The rolling of metal materials was a serious problem throughout history, either economically or technically, because the plating technologies enabled the consumption of raw materials (scarce and expensive) to be reduced, while improving the mechanical properties. Knowing the force parameters related to asymmetric rolling leads to the optimization of energy and raw material consumption. This paper presents data on symmetric rolling process, in order to comparatively highlight the particularities of the asymmetric process.

1. Introduction
The modern rolling theory itself is an attempt to provide a scientific method for calculating the pressure developed by the metal materials on the rolls. It does not introduce any empirical coefficients, and, for performing the calculations for a given passing, in addition to the dimensions of the semi-finished product and rolls, we need two experimentally determined values, which incorporate a deep physical sense [1-3]:

- value of the coefficient of external friction;
- value of the yield point of the metal material, for the passage in question.

Besides these simplifying hypotheses that formed the basis of the classical theory, the following assumptions can be accepted in the modern theory:

- the influence of the areas located in the vicinity of the deformation outbreak is neglected, which makes the theory to be valid only for the cases where \( \frac{1}{h_m} > 1 \);
- the clamping angles are assumed to be not too large, but, seeing the calculations, it seems that this condition does not introduce great errors even in case of hot rolling, when the clamping angles can reach 22-24%;
- we adopt the assumption that the yield point \( \sigma_c \) is constant along the arc of contact; this hypothesis means that we do not take into account, at cold rolling, the influence of cold hardening during the passing of material and, at hot rolling, the influence of speed and deformation degree, i.e. we adopt the assumption that the yield point does not depend on the compression speed and the relative reduction per pass, which actually are not changing along the arc of contact following a complicated dependence;
- we introduce mathematical simplifications.
Usually, the content issues of the modern theory are given in a complicated mathematical form, which is sometimes hard to understand, although the key points are pretty simple. Therefore, the experimental researches on pressure distribution are important either for the theory or for the practice of rolling processes.

They can serve directly for the experimental confirmation of the correctness of theoretical conclusions regarding the general law of pressure distribution along the arc of contact, or for the influence on pressure of the main rolling factors, i.e. the coefficient of external friction, initial thickness of the metal material, degree of reduction, and temperature.

Depending on the assumptions mentioned above, in the modern rolling theory appeared several solutions for determining the rolling pressure. We are going to analyse some of them, which are more or less consistent with the experimental data or with those recorded in the operational practice.

Next, we present the main theories approached in the symmetric and asymmetric rolling theory, i.e. the mathematical apparatus they are based on:

### 1.1. Karman’s theory

Hereinafter, the following simplifications are allowed [1]:

- the vertical sections of the metal material are analysed as they are separated from each other, without any sliding friction between them, and the displacement strains in these edges are neglected;
- the vertical speed of the metal material particles is constant, so a uniform pressure distribution on the two vertical sides of the elementary section is accepted.

\[
\begin{align*}
\text{For the delay area, we obtain:} \\
p_x = \frac{k}{\delta} \left[ \zeta \delta - 1 \right] \left( \frac{h_0}{R} \right)^\delta + 1 \\
\text{For the advance area:} \\
p_x = \frac{k}{\delta} \left[ \zeta \delta + 1 \right] \left( \frac{h}{R} \right)^\delta - 1
\end{align*}
\]

where: \( \delta = \frac{2 \cdot \mu \cdot l}{\Delta h} \);

\( l \) - length of the contact arc, equal to \( \sqrt{R \cdot \Delta h} \)
1.2. Analysis of Siebel’s solution
The solution proposed by Siebel to solve more conveniently the Karman’s equation accepts two assumptions [1]:

- the frictional force over the length of the contact arc $\tau_x = \text{const} = \mu \cdot k$;
- the deformed contact arc has a parabola shape.

In this case, the solutions for solving the equation for the delay area are:

$$p_x = k \left[ \zeta_0 - \log \frac{z_0^2 + 1}{z^2 + 1} \right] + 2\tau_x \sqrt{\frac{R}{h_0}} \arctg \frac{z_0 - z}{1 + z_0 z}$$ (3)

and for the advance area:

$$p_x = k \left[ \zeta_i + \log \left( z^2 + 1 \right) \right] + 2\tau_x \sqrt{\frac{R}{h_l}} \arctg z$$ (4)

where: $z = \frac{l}{l} \sqrt{\frac{\Delta h}{h_l}} x$; $z_0 = \sqrt{\frac{\Delta h}{h_l}}$

1.3. Analysis of Nadai’s solution
The solution proposed by Nadai is also based on two assumptions:

- acknowledging the existence of viscous friction, $\tau_x = \eta \cdot \frac{dh}{dh}$, where $\eta$ represents the dynamic viscosity;
- the deformed contact arc has a parabola shape.

The solution of this equation proposed by Nadai is:

$$p_x = k \left[ \zeta_i + \log \left( z^2 + 1 \right) \right] + \frac{A \cdot \tau_x}{2} \left[ \frac{z}{z^2 + 1} - B \cdot \arctg z \right]$$ (5)

where: $A = \frac{2 \cdot l}{\sqrt{h_l \cdot \Delta h}}$, $B = \frac{l - z_n^2}{l + z_n^2} = \frac{2 \cdot k}{A \cdot \tau_x} \cdot \frac{\left[ \zeta_i - \zeta_0 + \log \left( l + z_0^2 \right) \right] + \frac{z_0}{l + z_0^2}}{\arctg z_0}$

and $z = \frac{l}{l} \sqrt{\frac{\Delta h}{h_l}} x$; $z_0 = \sqrt{\frac{\Delta h}{h_l}}$

As can be seen in Figure 2, the maximum values of the ratio $\frac{P_x}{2k}$ differ widely from one solution to another.

The attempt to apply one of these solutions to hot rolling leads to considerable errors, mainly because the effect of temperature on the physical properties of the metal material and on the friction coefficient $\mu$ is not taken into account.

Secondly, the vertical speed of the metal material particles undergoing deformation in the rolling direction cannot be considered constant, this assumption being not be justifiable. In other words, the plane section assumption cannot be maintained.

![Figure 2. Graphical representation of solutions analyzed](image-url)
From the comparative analysis of the calculation solutions, we can draw the following conclusions:

- the normal pressure distribution over the contact arc length is depending on the hypothesis considered for the distribution of frictional forces between the metal material and rolls;
- all cases result in the presence of portions with sliding friction; therefore, the pressure distribution diagram highlights the existence of delay and advance areas. By using the Nadai’s equation, the separation by neutral plan of these areas is not highlighted;
- the analysed solutions are mostly applicable for cold strip rolling with contact angles less than 6…8°.

The theoretical and experimental research conducted, [4-7] have broadened the knowledge about the phenomena occurring in the rolling deformation area.

In general, when rolling relatively flat strips, \( \frac{l}{h_m} > 5 \), the geometric deformation area consists of two portions:

- the portion of metal sliding on the rolls, where the contact friction is subjected to Coulomb’s law, \( \tau_x = \mu \cdot P_x \); there are actually two portions included here, which are located in the immediate proximity of the geometric deformation area, i.e. at the metal material entry / exit between / from the rolls;
- the adherence area (where the material slides on the roll surface) is missing, i.e. the metal surface layer moves with a tangential speed equal to the peripheral speed of the rolls, as though the metal material particles stick to the surface of the rolls.

So, the general relation for calculation will be:

\[
p_m = 2k \left[ \frac{l - 2\mu \cdot h_m}{l} + \frac{l}{4h_l} - \eta \left( I + \frac{h_m}{l} \left( \frac{l}{\mu} - \eta \right) \right) \right] \tag{6}
\]

In this relation, the first term characterizes the composition of total average pressure determined by the sliding areas, and the second term – the adhesion area component.
2. The experimental plant and testing method

The research for this theme purpose have been made on a 170 mm reversing two-high rolling mill, created and installed in the no conventional technologies and plastic deformation laboratory of the Engineering Faculty from Hunedoara [4].

An experimental installation formed of: special construction rollers, bearings, punctiform captors for lamination pressure, lamination forces captors and lateral pressure captors it was created for research in condition of technological similitude symmetrical and asymmetrical process.

In Figure 1 it is presented in overview the mentioned installation, with the way force captors are assembled in order to determine the lateral efforts in the longitudinal asymmetrical lamination but also to show the author’s contribution regarding method of experimentation [1].

The bearing holders of the inferior roller were modified for recording the lateral efforts so that the respective captors could be installed incorporated perpendicularity on the bearing’s axis.

On the surface of captors were stuck tensiometric stamps bound in deck, stamps that modify their dimension under the action of the effort to be measured. These dimensional modifications of tensiometer stamps are generating variations of their electric resistance, that are proportional to the deformation efforts and the measuring of the forces is limited to the measuring of these resistance variations.

The research conducted on symmetric and asymmetric rolling process aimed the recording, along with other process parameters, of the rolling pressures and actual contact lengths of the arcs with the upper and lower roll.

This enabled us to know the distribution modality of the average pressure compared to the actual length of the contact arc, and to assess the influence of the distorted shape of the deformation area on the key process parameters.

The symmetric and asymmetric rolling process was carried out by equipping the work rolls with segments adjusted with various radii, which have led to the following ratios between the diameters of the upper \( (D_s) \) and lower \( (D_i) \) rolls:

\[
\frac{D_s}{D_i} = \frac{170 \cdot 160 \cdot 150 \cdot 140 [mm]}{170 \cdot 180 \cdot 190 \cdot 200}
\]

The modality to mount the segments on the rolls (of the rolling mill) for obtaining these combinations is shown in Figure 5 and 6, and schematically, for the symmetric and asymmetric process, the working variant is given in the Figures 5 and 6.

Usually, the tensiometer stamps of a forces captor are bound in deck. The deck has on a diagonal it is measured a electrical signal – proportional of the applied effort – and for recording of the measured values this signal is recorded by an oscillograph.

The oscillograph is a the type N-700, having 14 channels, the impulses on recorded are a scale of 120 mm width, heaving 4 cm/s moving speed of the paper band.
Figure 5. Research variant of the contact pressure on the symmetric longitudinal rolling

\[
\frac{D_i}{D_s} = \frac{170}{170} \text{[mm]}
\]

1-upper roller
2-lower roller

Figure 6. Research variant of the contact pressure on the asymmetric longitudinal rolling

\[
\frac{D_i}{D_s} = \frac{140}{170} \text{[mm]}
\]

3. The analysis of experimental data related to the rolling pressure in the symmetric and asymmetric processes

Since the intended purpose was to study the qualitative aspect of phenomena related to the asymmetric longitudinal rolling, for eliminating the inevitable influence of the iron oxides (scale) on the process, the tests were carried out on samples of aluminium and copper, with the following dimensions:

- \(h_0 = 12.6; 2 \text{ and } 1 \text{ mm}\)
- \(b_0 = 40 \text{ mm} \quad l_0 = 150 \text{ mm}\)

The mechanical properties of the materials used to carry out the experimental tests are given in Figure 7.

Figure 7. The mechanical properties of the materials used to carry out the experimental tests

The samples of aluminium and copper were cut from the same rolled strip.
To ensure the isotropy of the properties, before rolling, the aluminium samples were subjected to annealing for recrystallization at the temperature of 420°C, and the copper samples at 750°C, for two hours, and then carefully cleaned with a fine emery paper. Before rolling, each sample was washed with chemically clean acetone [1].

The segments of the rolls were also washed with acetone, before each sample was individually rolled.

In this paper, by analyses and calculations, we are going to use the experimentally obtained values for pressure, and the actual contact lengths of the arcs with the upper and lower roll.

In the first part of researches, we carried out the rolling by using rolls with equal diameters

$$\frac{D_d}{D_i} = \frac{170}{170}[\text{mm}]$$

![Figure 8. Variation of the pressure in the rolling contact arc length of copper, $h_0 = 12 \text{ mm}$ samples between same diameter cylinders $\frac{D_d}{D_i} = \frac{170}{170}[\text{mm}]$, applying various reductions](image)

1-oscillogram number 35, $\varepsilon=9.15\%$
2-oscillogram number 37, $\varepsilon=13.75\%$
3-oscillogram number 39, $\varepsilon=22.1\%$

Through a careful execution and adjustment of the transducers, as well as choosing the right power supply for the measuring strain gauge bridges, we succeeded to obtain at calibration absolutely identical features of the upper and lower transducers.

The asymmetric process, related to the roll diameters, was performed by changing the various- radii segments mounted in the lower and upper roll.
Figure 9. Variation of the pressure in the rolling contact arc length of aluminum, $h_0 = 12 \text{ mm}$ samples between same diameter cylinders $\frac{D_s}{D_i} = \frac{170}{170} [\text{ mm}]$, applying various reductions

1-oscillogram number 6, $\varepsilon=13,9\%$
2-oscillogram number 2, $\varepsilon=32,5\%$
3-oscillogram number 4, $\varepsilon=49,5\%$

Figure 10. Variation of the pressure in the rolling contact arc length of aluminum, $h_0 = 12 \text{ mm}$ samples between same diameter cylinders $\frac{D_s}{D_i} = \frac{140}{170} [\text{ mm}]$, applying various reductions, upper cylinder

1-oscillogram number 362, $\varepsilon=19,5\%$
2-oscillogram number 353, $\varepsilon=38,9\%$
3-oscillogram number 347, $\varepsilon=45,8\%$
Thus, instead of the segments made with radii corresponding to the diameters of 170/170 mm, which were used for the symmetric process, we mounted the segments afferent to the ratios:

\[
\frac{D_i}{D_s} = \frac{160}{180}; \frac{140}{200} \text{[mm]}
\]

![Figure 11](image)

**Figure 11.** Variation of the pressure in the rolling contact arc length of aluminum, \(h_0 = 12 \text{ mm}\) samples between same diameter cylinders \(\frac{D_i}{D_s} = \frac{140}{170} \text{[mm]}\), applying various reductions, lower cylinder

1-oscillogram number 362, \(\varepsilon=19.5\%\)
2-oscillogram number 353, \(\varepsilon=38.9\%\)
3-oscillogram number 347, \(\varepsilon=45.8\%\)

The data for the interim variant (160/180 [mm]) is not presented in this paper, because they just fully confirm the analysis made for the variant 140/200 [mm].

4. Results and conclusions

Through the conducted experiments, we obtained the laws of changing the average pressures, as well as the length of the contact arcs in the asymmetric process, which enabled us to eliminate the contradictions from the considered problem.

We have also clarified, by this research, the laws of qualitative transition from the symmetric to the asymmetric process, depending on the change in rolling conditions, thus confirming the Romanian researchers’ idea, in particular the idea of professor Ilca, who stated that the symmetric process is just a special case of the asymmetric process which is widespread in the rolling industry practice.

- by using the experimental plant, we studied the dependency on reduction of the pressure and the actual lengths of contact arcs, at asymmetric rolling between rolls with unequal diameters.
- we found the dependency between the average pressure variation modality and the actual lengths of the contact arcs at the asymmetric longitudinal rolling.
- the experimental plant and equipment will continue to be used either for research, to find correlations between the technological and force parameters of the rolling process, or for operation, to find the strain degree of the technological equipment.
- we have also established that, depending on the thickness of the rolled strips and reduction, for a given ratio between the diameters of the work rolls, at asymmetric rolling, there is a critical value of the deformation degree up to which the pressure exerted by the roll with the larger diameter is high, and for values higher than this critical value the situation is reversed. The contact arc lengths variation is reverse in nature, i.e. the small lengths correspond to the maximum pressure values, respecting the equality of forces on both rolls.
at the critical value of the deformation degree, for rolls with unequal diameters, the pressures become equal, as well as the lengths of the contact arcs. Therefore, the current opinions regarding the distribution of reductions between the rolls at asymmetric rolling are correct only for particular cases of rolling conditions.

- the locus of points corresponding to the value of critical reductions is a parabola that characterises the conditions of ideal symmetry (rolling pressure, length of the contact arcs) at rolling between rolls with unequal diameters.

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