Aspects concerning the geometric elements of the rolling deformation area

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Abstract. The paper presents an experimental and practical study of aluminium strips lamination, calculating the conformations that define plastic deformation by lamination. A sample from aluminium alloy in the shape of a band was rolled and we calculated the logarithmic deformations in lamination. We started the lamination process from a semi-finished product, with a surface for the cross-section section ($S_0$) and it was carried out in three drawings up to a final section ($S_3$). The deformation assessment and measurement tool, the logarithmic degree of deformation gives the extent of the plastic deformation at each drawing, and the calculated total deformation degree is useful to quantify the deformation preformed for the entire lamination process over the three drawings. If analysed in this way, the plastic deformation process, the material undergoes a higher reduction at the last drawing and an encrustation of the band at its margin also. The preliminary usage of the coefficients defining lamination has a particular importance for practical objectives, in the carrying out of another lamination process.

1. Introduction
In the process of lamination, plastic deformation is achieved by continuously drawing the metallic material between the cylinders, by changing the dimensions of the material (decreasing the thickness, increasing the length and increasing the width), through the continuous modification of the lamination area.

The presentation and verification of calculation formulas for technological operations in the lamination of metallic materials implies the establishment of kinematic relations (evolution of geometric shape and deformation degrees) between the undistorted part and the deformed part, namely the prediction of the metal flow in the successive conduct of rolling operations. With the help of certain experiments of deformation through lamination performed in the laboratory, a large variety of improved properties through lamination are highlighted [1]. There is an increase in the resistance of the laminated materials and their structure is composed of fine grains. For a good progress of the lamination process, in order to obtain the desired shape and properties, it is necessary to understand and control the metal flowing mechanism in the deformation zone. The flowing direction of the metal, the size of the deformation and the temperatures, largely determine the properties of the products processed by lamination. Being influenced by the process variables, the metal flow in lamination determines the mechanic properties associated with the deformation in the deformation zone and to the undesired formation or generation of flaws (no-filling, cracks or creases, at the surface or within the
adjacent layers). In order to investigate the progress of the metal layers in lamination, bands covered with modelling clay were laminated [2].

![Figure 1. The idealised structure of the deformation zone [6].](image)

During the lamination process, friction between the cylinders and the deformed material in the deformation zone is inevitable and it determines the quality of the products’ surface, the value of the lamination force, the energy consumed within the process etc. [3]

By analysing the relative distribution of the deformations in the deformation zone, answers are searched for to the immediate distribution of the deformation in the lamination process in an equilibrium state.

Various researchers determined the reason for the formation of flaws by analysing the plastic deformation in the plates’ lamination zone [4]. To solve the problems related to the quality of the margins or the flaws of the margins they have built a thermo-mechanical model with finite elements (FEM) to simulate the warm lamination process of plates. Depending on the relation between the Lode parameter and the types of plastic deformation and the distribution of the values obtained in the post-manufacturing for the Lode parameters, they determined the types of flaws in lamination and they analysed the state of tensions at the exit from the deformation zone in lamination.

The lamination process is one of the most popular processes in the industry for processing materials where almost 80% of the metallic equipment have been exposed to lamination, at least once during the manufacturing process. As a result, many scientists have tried to adjust the quality and quantity of products by optimising this process and identifying the parameters which influence them in obtaining the highest quality products. In the paper written by the researcher [5] the lamination process was analysed through different analytical and numerical methods, such as the snow plate method, the gliding field method, the higher limit method, the border element method and the finite element method. In comparison with other analysis methods of the lamination process, the finite element is the most practical and the most precise [5].

2. Expression of deformation in the rolling of bands
Changing the size of the material, depends on the state of tension [6] and the deformation, induced in the material, by the deformation zone. The evolution of the deformation is quantified on the idealized structure of the deformation zone (figure 1) associated with the shape of the working cylinders and the laminate. The cross-section section of the work cylinder is considered to be a perfect circle. The line that unholds the centre of the cylinders is considered to be perpendicular to the direction of lamination and remains so during lamination [6]. The distance between the cylinder centres is considered to remain unchanged, ignoring the elastic deformation of the cajan. The rotation speed of the working cylinders is constant and after the mechanical load on them increases and the slowing occurs under high torsion loads. The laminate material is rectilinear, its sides make straight angles, the thickness and width are uniform, as well as the roughness of the surface is the uniform.
During lamination, the metallic material is not subjected to the simultaneous plastic deformation on its entire length, but only on a certain, relatively small portion, which is in the space between the cylinders. The lamination process is characterized by a shrinking of the height of the laminate before entering between the cylinders \( h_0 \) at a height value \( h_1 \) after the output between the cylinders. This transformation is associated with increasing the width (from \( b_0 \) the \( b_1 \)) and the length of the laminate (from \( l_0 \) the \( l_1 \)). This change of form has been evaluated \cite{6,8} by size, with the significance of some coefficients that define the plastic deformation suffered by the material:

- Reduction coefficient \( \eta = h_0 / h_1 \)
- Coefficient of width \( \beta = b_1 / b_0 \)
- Coefficient of length \( \lambda = l_1 / l_0 \)

In this case, I intended to laminate a band sample, aluminum alloy, 2000 series Al-Cu-Mg, on the lab mill with duo rolling and I will follow the geometric elements of the lamination zone and the entire lamination process and thus conclusions can be drawn on the lamination process.

During lamination, the metal volume prior to lamination \( V_0 \) equals the volume of metal after lamination \( V_1 \) it is known that \cite{7} \( \eta = \beta \cdot \lambda \). This means that the volume of metal deformed on the height of the laminate is equal to the deformed in the transverse direction (width) and longitudinal (lengthwise). Technologically, these coders give the extent of the plastic deformation capacity of the metallic material between the working cylinders, establish the connection with the size of the deformed metal door, making possible the constructive development of laminated products.

**Table 1.** Calculation of the coefficients which define the plastic deformation on lamination of the sample.

| Parameters                          | Undeformed, initial sample | First drawing | Second drawing | Third drawing |
|-------------------------------------|-----------------------------|---------------|----------------|---------------|
| Length, \( l \) [cm]               | 6.00                        | 7.10          | 8.20           | 11.50         |
| Width, \( b \) [cm]                | 1.25                        | 1.32          | 1.52           | 2.45          |
| Thickness, \( h \) [cm]            | 0.75                        | 0.60          | 0.45           | 0.20          |
| Surfaces of the cross-section, \( S \) [cm²] | 0.94                        | 0.79          | 0.69           | 0.49          |
| Reduction Coefficients \( \eta_1, \eta_2, \eta_3 \) | 1.25                        | 1.33          | 2.25           |
| Widening Coefficients \( \beta_1, \beta_2, \beta_3 \) | 1.06                        | 1.15          | 1.60           |
| Lenghtening Coefficients \( \lambda_1, \lambda_2, \lambda_3 \) | 1.18                        | 1.15          | 1.40           |
| Partial coefficient for lenghtening, \( \lambda_1, \lambda_2, \lambda_3 \) | 1.18                        | 1.15          | 1.40           |
| \( \lambda = \frac{S_0}{S_3} \)    | 1.92                        |               |                |
| \( \lambda = \frac{S_1}{S_2} \)    | 1.92                        |               |                |

In many lamination processes, as with the lamination of aluminium alloy strips, the evolution of the cross-sectional form of the laminate is more suggestive than the mere modification of each of the three dimensions, therefore the coefficient of lengthness is used not as a ratio of the length of the laminate, but of the surfaces of the cross-sectional, before lamination \( S_0 \) and after lamination \( S_1 \). Knowing that:

\[ S_0 = h_0 \cdot b_0 \]  \hspace{1cm} (1)
\[ S_1 = h_1 \cdot b_1 \]  \hspace{1cm} (2)

We calculated in the table 1 the partial coefficient of lengthing \( \lambda_1, \lambda_2, \lambda_3 \) Which give the measure of the plastic deformation at each passage:

\[ \lambda_1 = \frac{S_0}{S_1} \text{; } \lambda_2 = \frac{S_1}{S_2} \text{; } \lambda_3 = \frac{S_2}{S_3} \]  \hspace{1cm} (3)

And the total coefficient \( \lambda_t \) It is useful to quantify the deformation made on the whole process of lamination on the three drawings:

\[ \lambda_t = \frac{S_0}{S_3} = \frac{S_0}{S_1} \frac{S_1}{S_2} \frac{S_2}{S_3} = \lambda_1 \cdot \lambda_2 \cdot \lambda_3 \]  \hspace{1cm} (4)
In our case, the length coefficients are equal to the partial lengths of lengthing. In view of the evolution of the size of the laminate, the numerical values of the three coefficients are always higher than one, so they are super unitarian. In the practice of lamination, the maximum values of these coefficients, relative to a single drawing, do not exceed the value \((1.8 \div 2.0)\), limitation imposed by the plastic deformation capacity of the metallic material, the construction of the rolling line and the power of the engine drive. To these the following can be added: the presence of defects, an uneven metallographic structure, or even an uneven distortion of the various portions of the laminate [6].

3. Geometric elements of the deformation zone on lamination

The deformation zone is the part where lamination is carried out and is characterized by the following geometric elements:

- The height and width of the cross-section section, at the entrance and exit of the metal between the working cylinders \(h_0, b_0, h_1, b_1\), the grip angle \((\alpha)\) and the contact length at the metal cylinder interface \(l_c\) according to figure 2.

- The difference between the front and exit laminate height of the deformation zone, called absolute reduction in the case of aluminium alloy tape lamination [6] is:

\[
\Delta h = h_0 - h_1
\]

(5)

- The difference between the width of the laminate on the output and the entrance to the deformation zone, named absolute widening

\[
\Delta b = b_1 - b_0
\]

(6)

- AB circle arc, after which contact is made to the metal cylinder interface, called the contact arc.

- The projection of the horizontal contact arc (on the rolling direction) \(e\) is the length of the geometric warp zone:

\[
l_c = \sqrt{R \Delta h}
\]

(7)

- The angle at the centre of the circle that is associated with the cylinder-metal contact, called \(\alpha\) contact angle, is determined from the relationship (8) or (9) for low angle values \(\alpha = (10-15)\)

\[
\cos \alpha = 1 - \frac{\Delta h}{D}
\]

(8)

\[
\alpha = \frac{\Delta h}{\sqrt{R}}
\]

(9)

Figure 2. The geometric elements of the deformation zone on lamination [6]
Table 2. The calculation of the logarithmic deformations on the lamination of an aluminium alloy sample.

| Parameters                  | Undeformed, initial sample | First drawing | Second drawing | Third drawing |
|-----------------------------|-----------------------------|---------------|----------------|---------------|
| Length, l [cm]              | 6.00                        | 7.10          | 8.20           | 11.50         |
| Width, b [cm]               | 1.25                        | 1.32          | 1.52           | 2.45          |
| Thickness, h [cm]           | 0.75                        | 0.60          | 0.45           | 0.20          |
| Logarithmic deformation for height \( \delta_h \) = \ln \frac{h_i}{h_0} | 0.22                        | 0.29          | 0.81           |               |
| Logarithmic deformation for width \( \delta_b \) = \ln \frac{b_i}{b_0} | 0.05                        | 0.14          | 0.47           |               |
| Logarithmic deformation for length \( \delta_l \) = \ln \frac{l_i}{l_0} | 0.17                        | 0.14          | 0.34           |               |
| \( \delta_t \) = \delta_1 + \delta_2 + \delta_3 | 0.65                        |               | 0.65           |               |
| \( \delta_t \) = \ln \frac{S_0}{S_3} | 0.65                        |               | 0.65           |               |

For larger plastic deformations (\( \varepsilon > 15\% \)) Laminate material has undergone appreciable dimensional changes and is more loopless to characterize the process of lamination by logarithmic deformations according to table 2. When the lamination process begins from a semi-manufactured with the surface of the cross section (\( S_0 \)) and runs in three drawings, up to a final section (\( S_3 \)) an evaluation tool and measure of deformation is the degree of logarithmic distortion, effective and total.

If we analyse the process of plastic deformation in this way, we can see that at the last drawing the material has undergone a higher reduction but also a belt gauge at its edge.

In the stable process of lamination, normal and friction forces act on the entire length of the contact arc at the cylinder-metal interface. The metal between the cylinders shall be deformed in the direction of minimal resistance, but the friction forces have opposite meanings at the entrance and exit of the deformation zone (figure 3). The vertical section where contact friction forces change meaning is called a neutral section, represented by the angle at the centre of the cylinder, called neutral angle (\( \gamma_n \)). In the absence of the action of the posterior and previous tension in the laminate, the neutral angle can be calculated with the expression [6], [8]:

\[
\sin \mu_n = \frac{1}{2} \sin \alpha_i - \frac{1 - \cos \alpha_i}{2 \mu_i}
\]  

where: \( \mu_i \) is the coefficient of friction at the cylinder-metal interface.

Figure 3. The action of the friction forces at the metal cylinder’s interface.
The deformation zone, in the longitudinal direction, is divided, relative to the position of the neutral section, in a delay zone (in the vicinity of the entrance plane, the friction forces are oriented in the direction of lamination) and another advance (in the vicinity of the plan output of the metal between the cylinders, the friction forces have the reverse direction of the rolling direction). The research and development of lamination processing involves a thorough understanding of manufacturing processes, the influence of variables, such as friction conditions, material properties and the geometry of the product to be processed.

4. Conclusions
The requirements for high quality products, as well as for reducing production and exploitation costs, led to a certain deformation on a passage of the material, taking into account the calculation of the coefficients which define the plastic deformation. We have calculated the coefficients that define the plastic deformation through lamination, and it can be seen that at higher deformation coefficients, at the third passage, the laminate material was unevenly deformed on the edges and defects occurred in the form of cracks. By introducing algorithms for the automatic calculation of deformation coefficients, the shape of passage, numerical modelling, physical and numerical simulation in the creation of optimal geometry, a strong representational framework of synthesis and analysis is provided. The calculation of logarithmic deformations when laminating an aluminium alloy sample makes it possible to present a lamination program to create an adequate flow of the deformed material in the drawing sequence. Following the calculations of the coefficients defining the plastic deformation presented above, it can be said that they represent, the most important contributions in the characterization of the transitions. In the evolution of the lamination process, as is observed, the outer shape of the processed product changes and suffers an increase in the longitudinal dimension (lengthening), a reduction in height and increase in width, which mainly depends on the reporting of the laminated product to the initial profile. This improves both the process state and the consistency of the products, minimizes costs and makes controlling the deformation easier. Starting from simple laboratory experiments, calculating the coefficients that define lamination, understanding the relations between the plastic deformation mechanism and chemical, mechanical, thermal, metallographic phenomena, modelling of the lamination process can be obtained.

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