THE IDENTIFICATION AND ASSESSMENT OF DEFICIENCIES MET DURING THE MANUFACTURE OF METALLIC ELEMENTS FOR SLIDING SUPPORTS OF UNDERGROUND EXCAVATIONS

*Valeriu PLEŞEA**, *Sorin Mihai RADU* **

Abstract: *In order to manufacture metallic supports for the execution of underground excavations, the laminated profile rods, either imported or bought from local suppliers, go through an ample processing operation, materialised by cutting it with an oxyacetylene torch and curbing the component parts through cold plastic deformation. Elements' cutting through welding generates the appearance of flaws at both ends, amplifying and developing them until they generate cracks and wedges on considerable lengths of the profile during the bending process. Nevertheless, the cold bending process determines the formation and exercise of a complex state of residual stress which generates the enhancement and manifestation of deficiencies while installing and using the metallic support in the underground. The paper brings forward the result of an analysis of the quality of the manufacture of metallic elements of supports, insisting on the results obtained following the graphical-analytical and numerical calculation for the assessment of the residual stress state observed during the cold bending process of the profiles.*

Key words: *Laminated profiles, welding cutting, cold bending, underground excavation, residual stress.*

1. Introduction

Having various usage possibilities, the sliding metallic support is made of u-shaped laminated profiles, obtained through lamination from carbon-manganese type steel (C-Mg) or low alloyed steel the chemical composition of which foresee reduced alloying additions, respectively below 0.19% vanadium, niobium, aluminium or titanium which in our country was used until 1980 in rolling mills for SG-18 and SG-23 type laminates, and until 1988 for the SG-29 type laminates.

From economical reasons, the lamination of the profiles was at that time made from OPM1 and 31Mn4 steel, characterised by the lack of alloying elements which were replaced by increased content of C, i.e. up to 70% maintaining therefore the mechanical resistance characteristics at superior limit values based although on the reduction of its deformation and exploitation properties below the minimum admissible limits of efficiency, respectively of elongation, contraction and resilience. The reduction of the deformation properties of non-alloy and non thermally treated steels, respectively the reduction of its tenacity, is due to an increased proportion of iron carbide (cementite) – Fe_3C in the ferito-pearlitic structure of steel, with the tendency of increasing together with the content of C, giving the steel increased toughness and fragility, having negative consequences regarding the processing deficiencies appearing during welding cutting and cold plastic deformation bending of profiles (cracks, wedges, and scrap material), including installation deficiencies of underground supports (resulting in openings at the ends of the girder connected to the supporting pillars, differentiated and uncontrolled torque while tightening the bridles, etc.). Abroad, compared to the situation in our country, maintaining the deformation and exploitation characteristics of non alloy steels is possible by mechanical cutting and hot plastic deformation of profiles. Even in the conditions of profile bending using cold plastic deformation (similar to our country), superior deformation properties are obtained while steel tenacity is based on the application by laminates suppliers of thermal enhancement treatments (normalising thermal treatment) necessary for the crystallisation and re-homogenisation of the structure, according to the specifications foreseen by the German norm DIN 21544-85, situation which unfortunately is quite different from the means of manufacture in our country.

2. Metallic support elements processing deficiencies assessment

2.1 Deficiencies recorded when cutting laminated profiles

Cutting and bending laminated profiles, as distinct phases composing the forming / processing process support metallic elements is presently self implemented by most of the beneficiaries of this type of supports, usually the mines the activity of

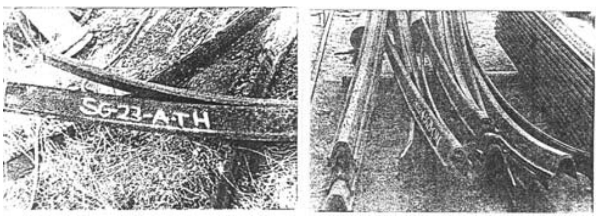
* *I[st] degree Scientific Researcher*, *Eng. Ph.D University „Constantin Brâncuşi” Tg-Jiu*
** *Prof. Eng., PhD., University of Petroşani*

which is represented by underground extraction of useful mineral substances [1], [2], [3].

Elements' cutting is made, exclusively with a oxyacetylene welding torch, while bending is made through cold plastic deformation using the three roller installations (presses) for bending SG-23 type profiles, as the only one type profiles which is made in Romania. The SG-29 type profile recorded a distinct case during bending, having therefore used a press specially built for this type of operation, but it's construction was stopped after 1990.

At any type profile analysed, through the oxyacetylene welding torch cutting procedure, the overheating of the material favours the change of the internal structure of steel (alloy and non alloy) at its ends, resulting therefore in self "controlled" burning of profiles. Moreover, considering the case of non alloy steels, un-killed and untreated thermally, the overheating of the ends of the profiles generates the softening annealing of the material resulting in an accentuated reduction of the plasticity and tenacity of these areas, as increased carbon content steels (over 0.25% C) become irreversible considering their fragility and toughness. As a direct consequence, considering the case of alloy steels, welding torch cutting of profiles generates a visible wedge at their ends, especially in cold weather, favouring therefore the appearance of other cracks and material scraps during the bending process.

On the other hand, in the conditions of cold bending of profiles, the increased the deformation degree is and the increased the fragility conditions of the steel are, the larger the counter-resistance of its structure gets, resulting, as in the case of reduced heating temperatures of the semi-fabricates (below solidus point temperature) and high speeds for cold deformation (up to 3 cm/s), in an increased cold hardening degree favouring the increase and extension of micro-wedges at the ends of the profiles with the appearance of material cracks amplified at the base of the profile and extend almost on the entire length of the element (figure 1, a and b).



a **b**

Fig. 1 *Cracks appeared in the SG-23 (a) and SG-29 (b) type laminated profiles following the cold bending process*

2.2 Deficiencies recorded during profiles bending [2], [3]

Besides the aspect with cracks and wedges of the profile, the cold bending process determines as well the formation and exercise of a complex residual stress both in the case of alloy steel elements as in the case non-alloy steels which were not thermally treated. The analysis of the residual stress revealed that the more increased the deformation degree is, namely the bending radii of the support elements are reduced, the higher the deformation speed is, respectively the more reduced the number of rollers on the bending installation is, the more pronounced the degree of the residual stress is recorded.

3. The assessment of the residual stress recorded at the base of the profiles

3.1 Analytical assessment of the stress state [3]

The analytical calculation made for the three types of laminated profiles and the two delivery states of profiles, namely improved and unimproved states, reveals, as also presented in figure 2, the values of the limit bending momentum and of the residual stresses in the plastic domain presented in table 1.

From the analysis of the obtained data it is observed that for both delivery states of the profiles the loading degree is increased, the measure of the residual stress state being superior when obtaining OPB type steel, a consequence of its increase together with the flowing limit ($Rp_{0,2}$) of the material.

Analysed considering the deficiencies it generates, the cold bending process of profiles allows a minimum bending radius which needs to correspond to the plastic properties of the material, excluding therefore the possibility of creating increased residual stress and breaking the material. Therefore the results of the analytical calculation for the establishment of the minimum admissible bending radius (Rc_{min}), carried out according to the measure of the maximum admissible deformation for extreme fibbers, highlight that the non alloy steels, thermally un-killed and untreated allow for the support elements to be bent at higher radii compared to those of alloy steel (Table 2), resulting that the minimum value of the radii of the breaking point of extreme fibbers increases in direct proportion to the height of the height of the profile and decreases together with the increase in elongation of the material used for the execution of the work.

Compared to the bending radii applied for the execution of metal reinforcements used to realise different profile typo-dimensions for underground excavations, the minimum admissible radii obtained through calculation limit the applicability field breaking the utility of the SG-29 type laminated profiles for works with a free section (in light) of 12 m^2, of the SG-23 type laminated profiles for sections of minimum 10 m^2 and of SG-18 type laminated profiles for sections of minimum 8 m^2.

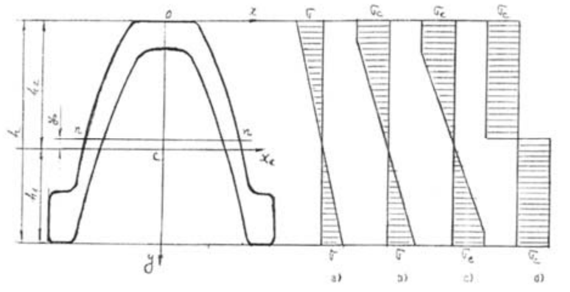


Fig. 2 *The state of residual stress forming inside support elements through cold plastic deformation: **a** – purely elastic stress state; **b** – unilateral plastic-elastic stress state; **c** – bilateral plastic-elastic stress state; **d** – Purely elastic stress state*

Table 1 *The results of the graphical-analytical calculation of the residual stress state in the case of cold bending of profiles*

Steel brand	Flow limit, Rp 0,2 (daN/cm^2)	Laminate type	Bending plastic limit momentum, M_{LP} (daN·cm)	Limited force in the plastic field, F_{LP} (daN)	Discharging stress (daN/cm^2)	Residual stress (daN/cm^2) Calculation point			
						1	2	3	4
OPM Alloy steel	4200	SG-18	246.960	9.878	5254,5	1055	-3600	4200	-1055
		SG-23	359.730	14.389	5369,1	1169	-3700	4200	-1169
		SG-29	489.050	39.480	5149,5	949	-3400	3500	-949
OPM 1 and 31 Mn 4 non alloy steels	3500	SG-18	205.800	8.232	4328,7	879	-3100	3500	-879
		SG-23	299.775	11.991	4474,3	974	-3100	3500	-974
		SG-29	404.600	16.184	4304,3	804	-2900	3500	-804

Table 2 *The results regarding the calculation for the determination of the minimum admissible bending radii of laminated profiles*

Steel Brand	Laminate type	Laminate height, h (cm)	The minimum distance between the neutral axes of the profiles (cm)	The minimum admissible bending radius, Rc_{min} (cm)
OPM (alloy)	SG-18	9.8	2.1	105
	SG-23	11.0	2.6	130
	SG-29	12.4	3.1	155
OPM 1, 31 Mn 4 (non alloy)	SG-18	9.8	2.1	126
	SG-23	11.0	2.6	156
	SG-29	12.4	3.1	186

3.2 Numerical assessment of the residual stress state [3], [4], [5]

Compared to the graphical-analytical procedure, which analyses the problem of stress considering a linear elastic context of the material, in the case of an assessment using the Finite Element Method (FEM), the hypothesis of the non-linearity of the material is therefore considered in order to solve the problem of the incremental model, namely the "step by step" model which considers that in the following relation:

$$\{R\} = |k| \cdot \{U\} \qquad (1)$$

the non-linearity between force {R} and displacements {U} results from the matrix of rigidity $|k|$ which is a non-linear property of the material, defined by the elasticity $|D(\sigma)|$. In correspondence to the situation existent in current practices, the model considers that during the cold bending of profiles cracks appear at the ends of the "a" and "b" type laminated profiles, which spread and increase in intensity when putting the profile through the two supporting rollers and the pressure roller of the bending installation (figure 3)

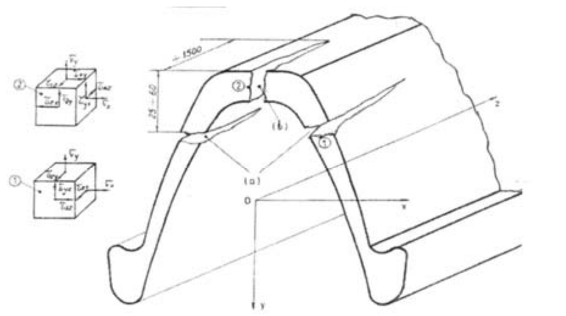


Fig. 3 *The appearance of type "a" and "b" cracks recorded at the ends of the profile during cold bending*

The form of the substructures of the three laminated profiles SG (18, 23 and 29) for which the calculation model was made up, is presented in figure 4, each being discretised through knots spatial networks, on which three-dimensional isoperimetric finite elements were defined, respectively 288 knots and 275 finite elements in the case of SG-18 type laminated profiles, 246 knots and 220 finite elements the SG-23 type one and 600 knots, with 655 finite elements in the case of the SG-29 type laminated profiles.

In the case of the 3 analysed types of laminates, the calculation of stress was made for two distinct situations, namely:

a) on the section where the maximum pressing force was applied (F), considering the distance between supports l = 510 m, namely the equivalent distance between the axels of the rollers of the bending installation;

b) on the bearing section of the profiles, respectively the areas where type "a" and "b" cracks appear (figure 5).

The first scenario brought forward the determination of the forces necessary to record the residual 6 mm, 12 mm, and respectively 18 mm deformations (arrows), namely while successively passing the profiles through the rollers of the pressing installations (bending installations).

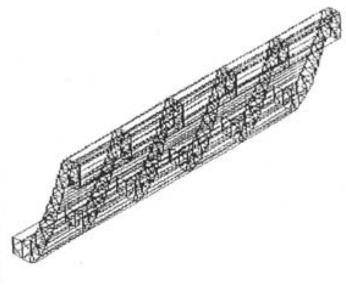


Fig. 4 *The substructure of the discretisation and calculation model of stress and deformations in SG (18, 23, and 29) laminated profiles*

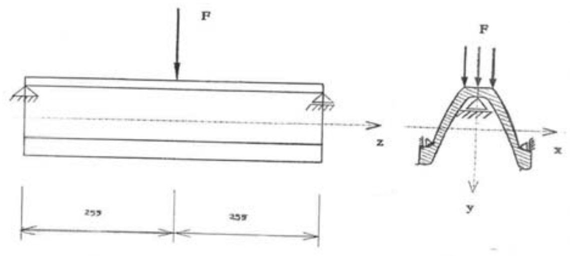


Fig. 5 *The load and calculation diagram of stress in SG laminated profiles:* ***a*** *– the section where the pressing force was applied;* ***b*** *– the bearing section of the profiles*

Following the run of the finite element program for the maximum deformation of 19 mm the maximum values of the stress forces (F_{max}) resulted and presented in table 3. The same table presents the values of the of the maximum forces of stress ($\sigma^{V.M.}_{max}$), determined according to the Huber – Von Mises plasticity criterion for the entire model chosen, including the maximum stress value σ_z obtained in the section where the maximum force was applied.

The distribution of stress according to the Huber-Von Mises criterion is presented in figure 6 while the distribution of stresses σ_z, for the transversal section of the profiles is presented in figure 7.

Table 3 *The results of the numerical calculations (FEM) of residual stress during cold bending of profiles*

Type of laminated profile	Maximum stress force, F_{max} (danN)	Maximum residual arrow, Y_{max} (cm)	Maximum residual stress			Extreme residual stress after discharge, $\sigma_{max\ des.}$ (daN/cm^2)	
			$\sigma^{V.M.}_{max}$ (daN/cm^2)	$\sigma_{z\ max}$, (daN/cm^2)			
				$\sigma_î$	σ_c	$\sigma_î$	σ_c
SG-18	45000	1,9	6260	4670	-4670	45000	1,9
SG-23	66000	1,9	6420	6340	-6340	66000	1,9
SG-29	74400	1,9	6220	6400	-6390	74400	1,9

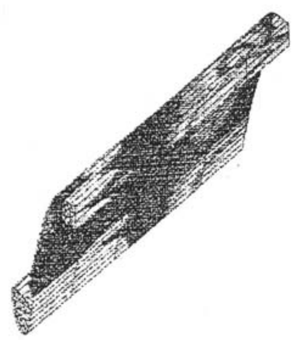


Fig. 6 *The distribution of stress in the area of where the maximum pressing force F_{max} is applied (stress according to the Huber-Von Mises criterion for the entire chosen model) – longitudinal section:* ■- *compression maximum residual stress;* ■- *hog maximum residual stress*

Fig. 7 *The distribution of stress σ_{zmax} on the section where the maximum force F_{max} is applied – transversalsection:* ■- *compression maximum residual stress;* ■- *hog maximum residual stress*

3.3 Conclusions regarding the assessment of residual stress

A conclusion which may be drawn from the analysis of the results is that there is a high degree of stress during the entire cold bending process, observing a reduced value of the $\sigma_{max}^{V.M.}$ stress for the SG-29 laminate compared to the one of the SG-23 type laminated profile and the SG-18 one, in the conditions of a charge larger with 11.3%, respectively 39.5 %. In comparison to the results obtained with the calculation using the graphic-analytical method, a relative deviation of the results obtained through the numerical finite element method is observed (approx. 10%).

Following the determination of the residual maximum stress in the area where type “a” and “b” cracks appear (figure 2), it has been demonstrated that for type “a” cracks the maximum stresses which may be produced in the connection area between the flanges (wings) and the sole of the laminated profiles ($\sigma_{x.max}$, $\sigma_{y.max}$, $\tau_{xz.max}$, $\tau_{yz.max}$, $\sigma_{1.max}$, $\sigma_{max}^{V.M.}$) occur on the interior surface, starting to convey from one point on the surface of the profile (figure 8).

For the area where type “b” cracks occur, the results obtained highlight that the normal maximum stretching stress is produced within the interior fibbers of the sole of the profiles (11, 14 and 16 mm thick fibbers, equivalent to the thickness of the base of the profile), while the maximum compression stress occurs in the exterior fibbers of the sole (0 thick fibbers). It resulted from the analysis that the dominant cracks are type “b” ones, for which the conveying stress takes part with the most increased proportion to the value of the main maximum stresses $\sigma_{1.max}$ and $\sigma_{max}^{V.M.}$.

Moreover, following the numerical analysis, it has been highlighted that in the case of the SG-29 laminated profile, due to its increased resistance at the base, type “b” cracks convey at stress values much higher than the SG-18 laminated profile, including with the SG-23 one.

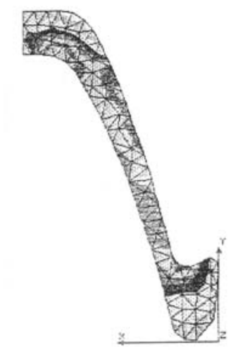


Fig. 8 *The distribution of stresses on the height of the bearing section of the laminated profiles:* ■- *compression maximum residual stress;* ■- *hog maximum residual stress*

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