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An experimental and modelling approach for improving utilization rate of the cold roll forming production line

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A B S T R A C T

This paper presents theoretical approach and complex experimental research which was conducted within the real production conditions of cold roll forming channel sections. The experimental investigation was focused on forming forces measuring on the rolls and the deflections of roll stands due to the forming loads. The comparison and analysis of the obtained experimental results was performed for the majority roll stands. Based on the experimental results mathematical modelling of the forming a force-roll load was performed by response surface methodology for different values of the input parameters of the process: material properties, sheet thickness, and sheet width. The defined force model and experimental research show insufficient energetic and technological utilization of the existing production line. After the conducted research in the production process a sheet thickness of up to 1.40 mm is used instead of 0.70 mm, and the utilization of the installed energy has increased from 20 % to 75 %. This is confirmed by the measured deformations of the roll stands and the energy consumption of the powered electric motor. Through realized modernization of the cold roll forming production line, 30 % higher productivity is achieved, which is a result of optimal number planning of roll forming stations and approximately the same load of all roll stands, as well as the higher flow rate of the profile sheet.

A R T I C L E   I N F O

Keywords:
Cold roll forming;
Modelling;
Experimental investigation;
Response surface methodology;
Force-roll load;
Roll stand deflection

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1. Introduction

1.1 Cold roll forming process

Profiles can be produced, from strip or sheet metal in three possible ways of bending: press brake forming (e.g. die bending) – by linear tool motion (Fig. 1), using rotating rollers-roll forming (Fig. 2a), and draw roll forming (Fig. 2b) [1]. The cold roll forming, high volume production process, plays an important role in sheet metal forming processes used to create wide variety of product. It creates segments like automotive, aircraft, buildings, construction, agricultural, office furniture, consumer appliances and other sheet metal products according to customer's requirements for high quality and quantity, at the right time and for the right price [2]. The roll forming is a continuous bending operation in which sheet or strip metal is formed between successive pairs of rolls (rotating tools) that progressively bend and form until the desired cross-sectional configuration, known as profiles (C- and U-channel, L-, T-, V- and Z-sections, trapezoidal profiles, and many others), is obtained (Fig. 3) [3]. The advantage of roll forming in compari-

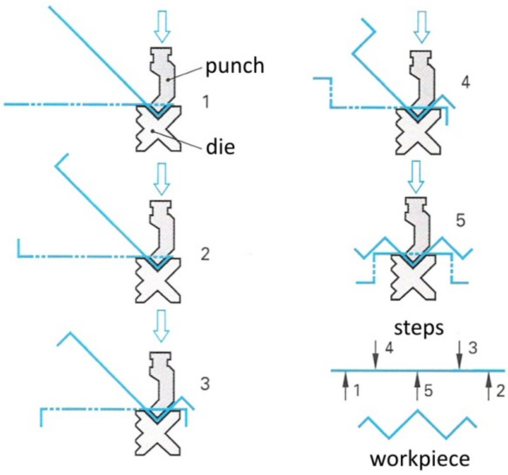


Fig. 1 The profile forming by die bending process

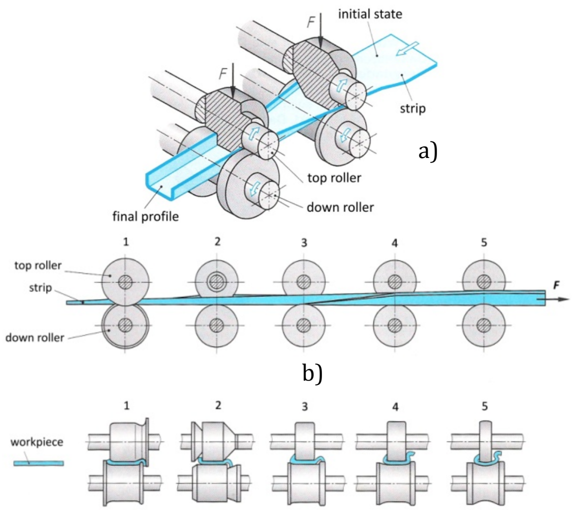
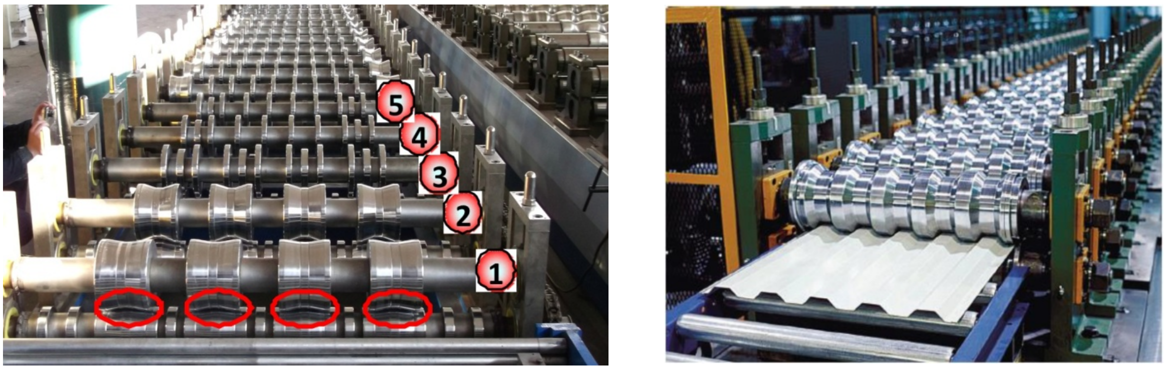


Fig. 2 The profile forming by, a) roll forming process, b) draw roll forming process

son with the other bending processes is that strips-sheets of any length (simple or complex cross sections) can be formed at a relatively high speed [4, 5].

1.2 Literature review

In general, forming process is characterized by various process parameters including geometrical data of tool and workpiece, material properties, contact conditions and different technological parameters. Therefore, the determination of the optimal forming parameters by using optimization techniques is a continuous engineering task with the main aim to reduce the production cost and achieve desired product quality [6]. Therefore, several authors with different aspects of roll forming process were studied from theoretical point of view to application through experimental research and mathematical modelling to numerical simulation. This was always with only one aim-to upgrade the process efficiency and for controlling of the process to be more predictable. Bhattacharyya *et al*. developed semi-empirical method for calculation of roll load in the cold roll forming process and obtained theoretical results which were verified with the experimental ones [7]. Paralikas *et al*. presented an optimization approach of the roll forming process parameters, for U-channel, based on semi-empirical method [8]. The optimal values of the process parameters for each roll station resulted in with reducing longitudinal and shear strains, and lastly with better product quality. Also, introduced by Paralikas *et al*. was used modelling for prediction deformation, as a function of the main roll forming process parameters and its impact on the V-section profile quality [9]. The study of Traub *et al*. presented a numerical modelling approach combining global and submodels enabling a high resolution of the strain distribution in the bending zone at acceptable computational costs [10]. The simulation concept was proofed by experimental results. Numerical simulation of the cold roll forming process of the U-channel was done by Bui *et al*. [11] and it was also studied by Lindgren [12, 13] with emphasis on change in the longitudinal peak membrane strain and deformation length of strip when yield strength increase. This was used to determine the number of forming steps and a distance between the roll stand. The proposed FE-method was shown to be an appropriate approach to research cold roll forming process. Paralikas *et al*. introduced energy efficiency indicator and presented on application a U-channel profile and analyzed influence of process parameters on energy efficiency indicator [14]. Ferreira [15] studied both experimentally and numerically, a deflection of roll stands during the forming process with a main aim to better predict defects. In the paper by Jurkovic *et al*. [16] an experimental investigation was presented of force and torque during the sheet roll forming in order to achieve improvement of the process. The application on response surface method and FE simulation in paper Zeng *et al*. [17] was studied on the optimization design of the cold roll forming process of a channel section. Liu *et al*. [18] developed mathematical model to analyze the deformation in roll forming a channel section.



a) b)

Fig. 3 The cold roll forming production line, a) beginning, b) ending of line

In paper [19] Wang *et al*. investigate the fracture mechanism on roll formed part. This paper has been presented experimental work of measuring elastic deformation of the roll forming stands under forming forces (also measured) occurring when strip is being bent in desired trapezoidal profile. The experimental research was carried out on the real production system in which the computerized, measuring and sensory equipment was installed. Based on the obtained experimental results mathematical modelling of the roll forming force was performed for different values of the input parameters of the process: material properties (R_m), sheet thickness (s), and sheet width (b). That is of a high importance to bring the roll forming force under control to achieve closer tolerances of profiles, which was crucial in the leading process in stable ones.

2. Materials and methods

The experiment was carried out in real production conditions on the roll forming production line. The production line was specially prepared with the equipment for forming forces measuring on the rolls and the roll stands deformation on forming stations. It was also prepared with other necessary resources for implementation of the design of experiment.

2.1 Roll forming production line – basic facility data

The production line has 20 forming stations (length 10.20 m and width 2.0 m). The experimental research was carried out on it in the real production process (Fig. 4). Each station had two rollers: upper and lower one. The electric motor power is 11 kW, the output speed of the gearbox is 41 min^{-1}, the transmission drives from electric motors to the shafts is a chain, the maximum sheet width is 1250 mm and the sheet thickness is between 0.4-1.0 mm. Further, the production system consists of decoiler with a coil weight of 10000 kg, in feed unit, straightening machine, roll forming machine, and shear cutting of the profiled sheet at a certain length [20, 21].

2.2 Materials used in experiments

In this experimental research, different type of materials were used [16]:

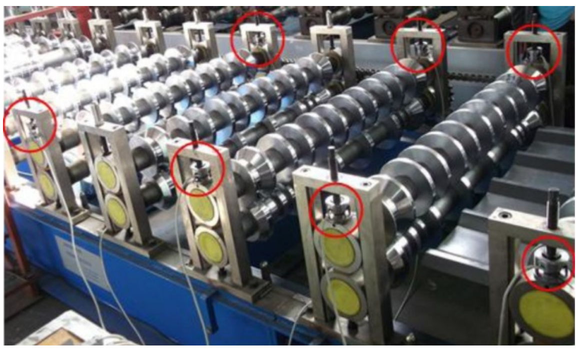


Fig. 4 Roll forming production line used in experiments

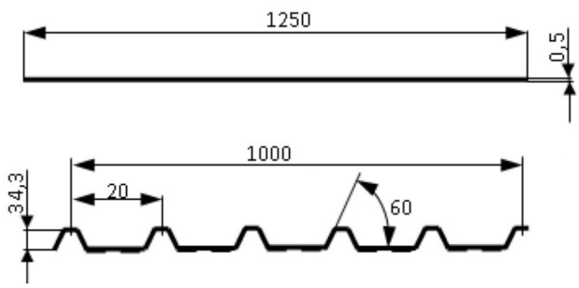


Fig. 5 Geometry of trapezoidal profiled sheet

Fig. 6 Force transducer location on roll stand, a) before, b) after setup

- steel sheet DX 51D (DIN 17162-1, EN 10327), mechanical properties: R_m = 383 MPa, R_e = 278 MPa, percentage elongation after fracture A_{10} = 31.3 %,
- steel sheet DX 53D (DIN 17162-1, EN 10327), mechanical properties: R_m = 270 MPa, R_e = 140 MPa and A_{10} = 30 %,
- aluminium sheet Al 99.5 (EN 1050), mechanical properties: R_m = 130 MPa, A_{10} = 5 %.

Sample sheets used in the experiment were: three types of sheet materials (130 MPa, 270 MPa, 383 MPa), three widths of the sheets (950 mm, 1100 mm, 1250 mm), and three thicknesses (0.50 mm, 0.60 mm, 0.70 mm) and a length of 2500 mm. The profiled geometry of sheet metal (Fig. 5) was obtained by continuous forming of the sheet between the rollers, through twenty of the forming stations. At each forming station, the bending occurred according to flower pattern and a geometrical shape of rollers.

2.3 Measurement devices setup

Measurement devices used in this experiment can be classified into two main groups [16]:

1) Measurement device used for measuring rollers load:

- force transducer with strain gauges, Fig. 6.
- multi-channel measuring amplifier HBM-QuantumX (MX840A), Fig. 7.
- multi-channel measuring amplifier HBM-SPIDER8 (8xSR55), Fig. 7.
- data acquisition software, Fig. 7.

Force transducer for measuring force-roller load during roll forming of sheet is located between the top shaft bearing housings and the top crossbar of roll stand (Fig. 6b).

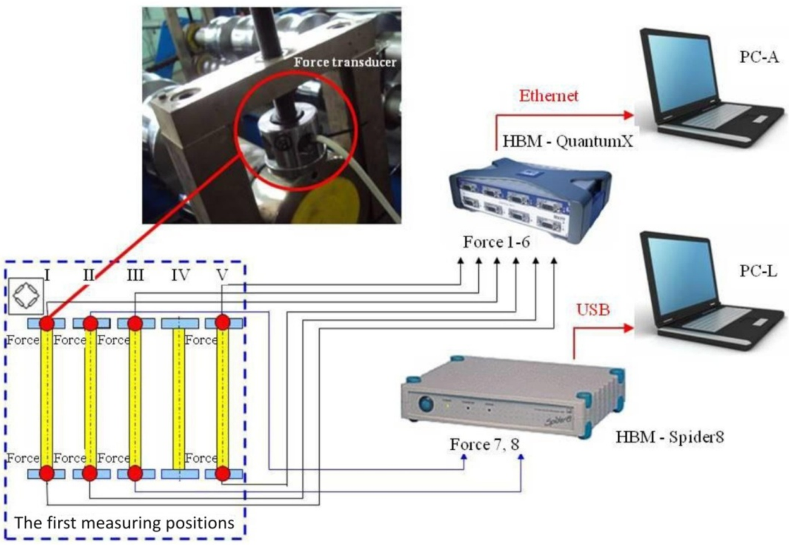


Fig. 7 Roll load – measurement device setup

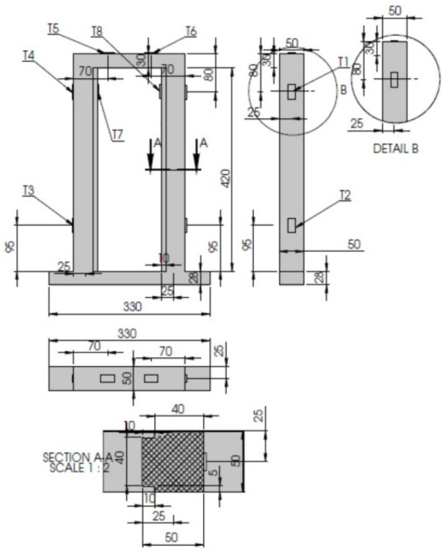


Fig. 8 The scheme of measurement points from T1 to T8

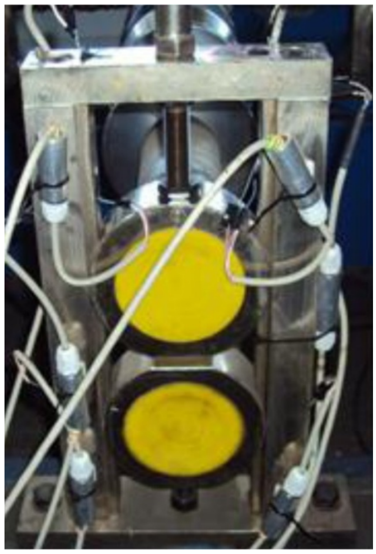


Fig. 9 Deflection measuring on roll stand – setup

2) Measurement device used for measuring the roll stand deflection:

For measuring of the roll stand deflection strain gauges were used with the following characteristics: resistance of 120 Ω ± 0.35 %, k = 2.05 ± 1.0 %, type 6/120LY4, temperature compensation α = 10.8 (10^{-6}/° C). The Fig. 8 present the roll stand with locations of strain gauges (T1-T8) [21, 22]. The roll stand prepared for the strain measuring is shown on Fig. 9.

In recording of the experimental data, three amplifiers were used (Fig. 10): the first one – DMCplus with eight channels for strain data acquisition from the eight position (T1-T8) of strain gauges placed on the roll stands. The second one QUANTUM X has also eight channels to forces data collect (F1-F6), while the two other channels collect torque data (M1-M2) from the rollers with the telemetry box. The last amplifier SPIDER 8 is connected by two channels for forces data collect (F7 and F8). Measurement setup was defined in a way to measured force, torque, and strain values in real time from the eighteen positions.

2.4 Design of experiment and experimental results

The measurement devices used in this experimental research enabled data acquisitions. Table 1 presents the measured values for the roll forces (Fig. 6b) and strains of the roll stand (Fig. 9) for the second forming station.

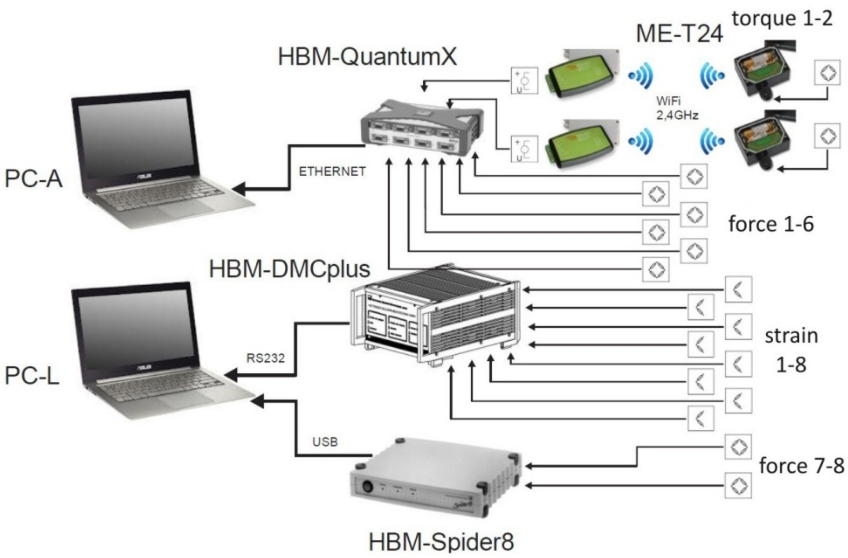


Fig. 10 Connecting scheme of amplifiers with measuring positions

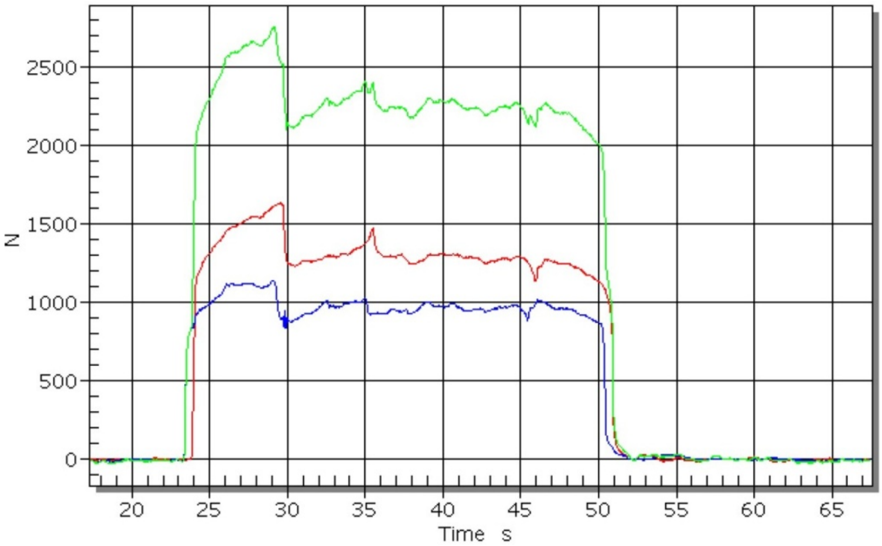


Fig. 11 Force diagram for the 3rd forming station, green curve – total force, red & blue forces on both side of a roller

Table 1 Design of experiment with experimental results – second forming station

Trial No.	Input process parameters			Coded process parameters			Experimental results	
							Force	Strain $T_1/T_2/T_3/T_4$,
	R_m, MPa	s, mm	b, mm	X_1	X_2	X_3	F_R^E, N	Δl_i, μm/m
1	130	0.5	950	-1	-1	-1	372.3	1.019/1.609/-1.637/-0.418
2	383	0.5	950	1	-1	-1	908.0	1.867/2.333/-1.120/0.588
3	130	0.7	950	-1	1	-1	654.2	3.732/1.741/1.799/-1.877
4	383	0.7	950	1	1	-1	1543.7	2.085/2.646/-1.644/0.516
5	130	0.5	1250	-1	-1	1	425.3	3.822/1.386/0.843/-1.785
6	383	0.5	1250	1	-1	1	1458.6	4.507/2.499/2.536/-2.414
7	130	0.7	1250	-1	1	1	1373.6	4.190/2.798/2.159/-1.727
8	383	0.7	1250	1	1	1	2558.3	2.269/3.306/-1.724/-0.160
9	270	0.6	1100	0	0	0	1173.5	3.664/2.159/1.650/-1.855
10	270	0.6	1100	0	0	0	1100.1	2.470/3.592/1.944/1.431
11	270	0.6	1100	0	0	0	1011.4	2.066/1.438/-2.377/-0.584
12	270	0.6	1100	0	0	0	1142.8	2.024/1.547/-2.456/-0.649

The experiment was performed according to design of experiments with three input parameters of the roll forming process: material properties *(R_m)*, sheet thickness *(s)*, and sheet width *(b)*, resulting in with N = 2^3 + 4 = 12 experiments [23]. The force diagram for the third forming station (experiment No. 4) is shown in Fig. 11. According to Fig. 11, diagrams for other forming stations and for all the experiments also presented the change of forming force intensity (roll loads). The obtained data are necessary for a comprehensive analysis of the roll forming process, which consists of roll loads, optimal schedule of sheet strain through each station, the optimal flower pattern of sheet roll forming, optimal utilization rate of the energy consumption and the proposal for possible equally load on each forming stations of roll forming production line. The software for data acquisitions automatically processing the measurement results in real time.

2.5 Response surface methodology

Development and application of mathematical models in manufacturing processes is based on the application of knowledge, which is a prerequisite for the transformation of conventional and less productive processes in modern ones [23]. Therefore, mathematical modelling is based on the qualitative and quantitative relation between the input variables *(X_i)* and the output effects of the process *(Y_j)* in the form $Y_j = Y(X_i)$, which is the result of technology and technological process, workpiece material, and manufacturing system. In general, the theoretical model can be presented in the form of:

$$y = f(x_1, x_2, \dots, x_k, \beta_1, \beta_2, \dots, \beta_k) \tag{1}$$

where are:

- x_i – variable parameters of process i = 0, 1, 2,...,k,
- β_i – theoretical coefficients of regression model.

When mechanism of process is unknown, mathematical model can be shown in polynomial form:

$$Y = \sum_{i=0}^{k} \beta_i X_i + \sum_{1 \le i < m}^{k} \beta_{im} X_i X_m + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{1 \le i < m \le k} \beta_{imk} X_i X_m X_k \tag{2}$$

which insures optimal approximation of change of value x by means of function $f(x)$.
Based on the conducted experimental and regression analysis, the statistical model is determined by real regression coefficients b_i, b_{ii}, b_{im}, b_{imk} so that the mathematical model can get form:

$$Y = \sum_{i=0}^{k} b_i X_i + \sum_{1 \le i < m}^{k} b_{im} X_i X_m + \sum_{i=1}^{k} b_{ii} X_i^2 + \sum_{1 \le i < m \le k} b_{imk} X_i X_m X_k \tag{3}$$

3. Results and discussion

3.1 Modelling

Through application of the experiment, it is possible to define the accurate mathematical model with a minimal number of experimental data. In order to do so, the input variables of the process need to be determined first. In the experiment, constant parameters of the sheet roll forming are: forming machine, rollers geometry, lubrication, radius of rollers, bending angle, and stiffness of the rolls (Fig. 12).

Force model

Based on the experimental results by applying the response surface methodology, a force model in coded form was obtained (4) for the force profiling sheet metal by rollers:

$$\begin{aligned} y = 1143.483 + 455.4 \cdot X_1 + 370.7 \cdot X_2 + 292.2 \cdot X_3 + 63.15 \cdot X_1 \cdot X_2 + 99.1 \cdot X_1 \cdot X_3 \\ + 141.3 \cdot X_2 \cdot X_3 - 25.3 \cdot X_1 \cdot X_2 \cdot X_3 \end{aligned} \tag{4}$$

After decoding model (4), the mathematical model in physical form was:

$$\begin{aligned} F = 6560.701 - 13.969 \cdot R_m - 11697.472 \cdot s - 7.095 \cdot b + 19.658 \cdot R_m \cdot s + 0.013 \cdot R_m \cdot b \\ + 12.84 \cdot s \cdot b - 0.013 \cdot R_m \cdot s \cdot b \end{aligned} \tag{5}$$

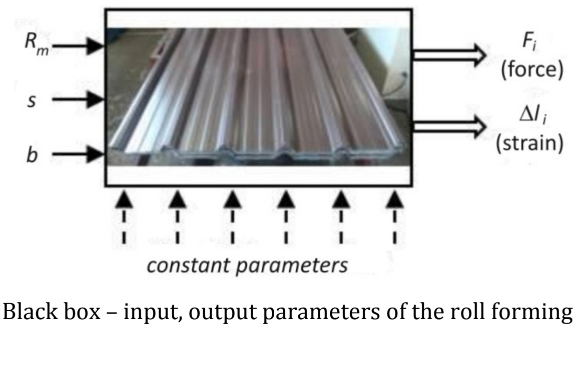


Fig. 12 Black box – input, output parameters of the roll forming process

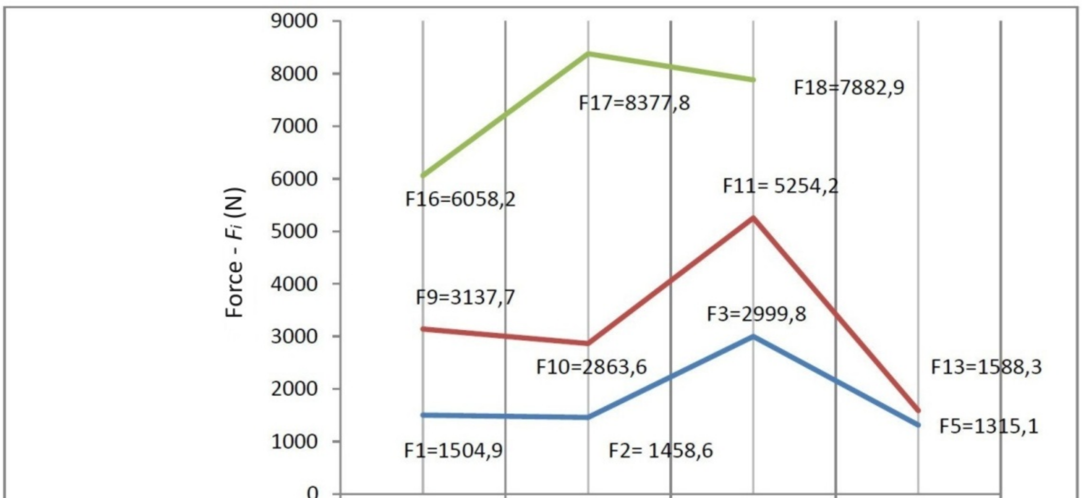
The obtained force model (5) adequately describes the force dependence of the roll forming parameters $F = F\ (R_m, s, b)$. Multiple regression coefficient is $R = 0.99$, which confirms the obtained mathematical model´s adequacy.

3.2 The roll load analysis at forming stations

In Fig. 13, measured intensities of the roll forming force on a roller of forming stations are shown: the first measuring positions (1, 2, 3 and 5), the second positions (9, 10, 11 and 13) and the third positions (16, 17 and 18) corresponding to a linear stations layout in the production line. The forming stations: 4, 6, 7, 8, 12, 14, 15, 19 and 20 don't have force transducer and there are not measurements. This is not a lack of research because the force was measured on 11 stations out of 20 stations. The results of measurements were shown on Fig. 13:

- load increase from first to third position of force transducer, so the station (1) – for a first position force has a value F_1 = 1504.9 N, station (9) – second position F_9 = 3137.7 N and the station (16) – third position F_{16} = 6058.2 N, four times compared to the first station or two times to the ninth station,
- the roll load increase by stations is not a constant although there is a general trend of upward load, as shown by the fact form 1 > 2 <3 > 5 < 9 > 10 < 11 > 13 < 16 < 17 > 18, forming stations,
- optimal technological process should provide approximately the same roll load at each forming station,
- the maximum roll profile force is on the station 17 (F_{17} = 8377.8 N),
- in the experiment No. 6 sheets had the same dimensions and mechanical properties in all forming stations.

On the basis of experimental research, it can be concluded that the roll load increases with the number of stations (Fig. 13). Fig. 14 shows that the force intensity changes for forming stations 1, 2, 3 and 5, wherein the change of force is shown as a function of the number of experiments from 1 to 12. Thus, the force F_1 refers to the first station, the force F_2 to the second station, and so on. Also, Fig. 14 shows the maximum value of the roll profile force (F_i) for the four stations (1, 2, 3 and 5). The analysis by Fig. 14 shows the maximum force (F_3) to be on the third station. Also, this station has a maximum value of force in experiments No. 2, 4, 6 and 8, which was expected because the strength of the sheet was the largest, R_m = 383 MPa.



forming stations	1, 9 & 16	2, 10 & 17	3, 11 & 18	5 & 13
No. 6, first measuring positions	1504,9	1458,6	2999,8	1315,1
No. 6, second positions	3137,7	2863,6	5254,2	1588,3
No. 6, third positions	6058,2	8377,8	7882,9	

Fig. 13 The forces obtained in the experiment No. 6 on the forming stations: 1, 2, 3 & 5; 9, 10, 11 & 13; 16, 17 & 18

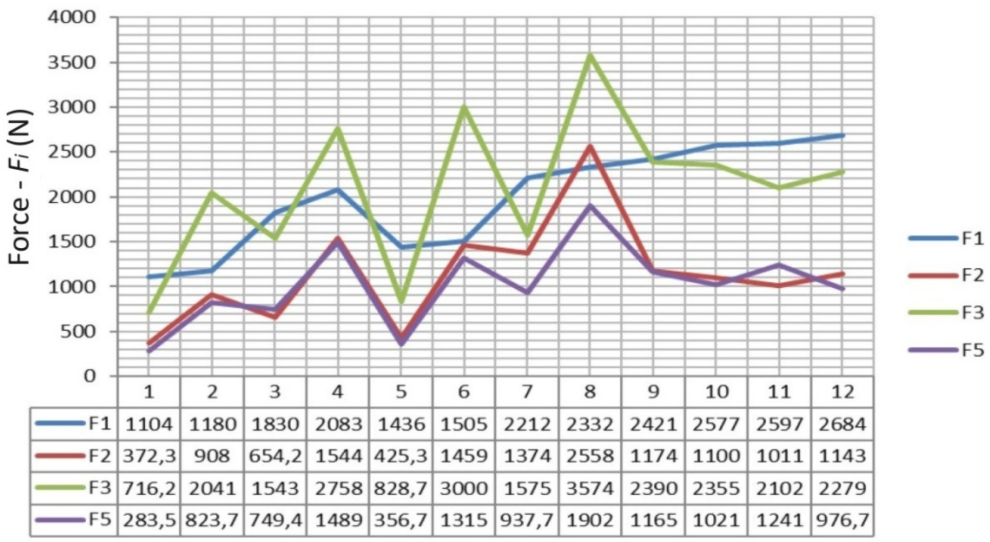
3.3 Roll stand deflection analysis

The results of the strain analysis obtained for measuring points (Table 1 and Fig. 9) 1, 2, 3 and 4, show that their absolute values, the largest values (Δl_1) at the measuring point 1 (T1), and the least values (Δl_4) at the measuring point 4 (T4). On the basis of that, it can be concluded:

- a strain is not classified by any logical sequence nor is the absolute value, nor is the sign of strain (+, -),
- on intensity and the sign of strain the profile tension between forming stations influences (due to a contact friction between the sheet and the roller). This is because there is no symmetry between the strain on the measuring points T1 and T4, T2 and T3, T1 and T2, and T3 and T4, although the profile velocity is equal between the stations, i.e. constant,
- the differences in the strength of the sheet material can be affected on the load change of roll stand,
- a contact between the sheet and the rollers with respect to friction is not constant, although the roll profile processes with a constant cross-sectional area because there is no change in the thickness of the sheet,
- on the measuring points T1 and T2 there is an obtained strain have + sign, while on the measuring points T3 and T4 have + and – sign, without being able to carry out a specific conclusion because there are more influential variables in such a result,
- the maximum strain generated in the experiment (8) and (6) wherein is the biggest strength and width of the sheet, while the least is expected in the experiment (1) and (2),
- the intensity of the deflection of the roll stand is very small and it meets the rigidity and accuracy of the roll profile. However, with the use of a thicker sheet, deflection will be increasingly significant.

3.4 The directions of modernization of the roll forming production line

The presented experimental research and modelling were carried out due to the modernization of the process and the roll forming production line for the profile sheet in order to achieve the optimal values of technological, energy consumption, and economical parameters. The roll load of the forming stations depends on: the material strength of the sheet (R_m), the thickness (s), and the sheet width (b). The model (2) obtained by modelling approach is in function of the mentioned parameters.



	1	2	3	4	5	6	7	8	9	10	11	12
F1	1104	1180	1830	2083	1436	1505	2212	2332	2421	2577	2597	2684
F2	372,3	908	654,2	1544	425,3	1459	1374	2558	1174	1100	1011	1143
F3	716,2	2041	1543	2758	828,7	3000	1575	3574	2390	2355	2102	2279
F5	283,5	823,7	749,4	1489	356,7	1315	937,7	1902	1165	1021	1241	976,7

Fig. 14 The roll profile forces for experiments 1 to 12 and the forming stations 1, 2, 3 and 5

The basic parameters of modernization are from technological, energy and economical point of view:

- technological parameters should have the optimal values that are determined by minimizing force and taking into account the economic criterion-minimum costs,
- energy criterion is based on the minimum energy consumption, which implies: an optimized flower pattern of the sheet metal processing through the forming stations, less energy idle utilization, which requires optimum construction of the drive and transmission mechanism from the drive motor to the roller,
- also, an important indicator of the optimization of the process and the production system is the degree of energy utilization i.e.: $\eta_e = f(n, N, M_p, M_{ph})$, where: n – electric motor spindle rotation; N – number of forming stations; M_p – torque and M_{ph} – torque of idle.

Achievements and benefits of modernization

Modernization of the roll forming production line is carried out in order to obtain the highest achievements that will bring competitive advantage. Hence, to take advantage of that it was necessary to do the following steps:

- to design an optimal technological process of the sheet roll forming: a) approximately equalization of the roll load on each forming station, b) the increased production efficiency, and c) the increased part of the useful work of sheet roll forming in the total energy consumed,
- the redesign of flower pattern ensures: a) the optimal technological process (optimal flower pattern), b) greater bending angle per forming station (greater strain of bending sheet), c) larger sheet thicknesses with respect to the installed energy of the existing production system, and d) optimum flow rate of the production line depending on the complexity of the profile, type of material and product quality,

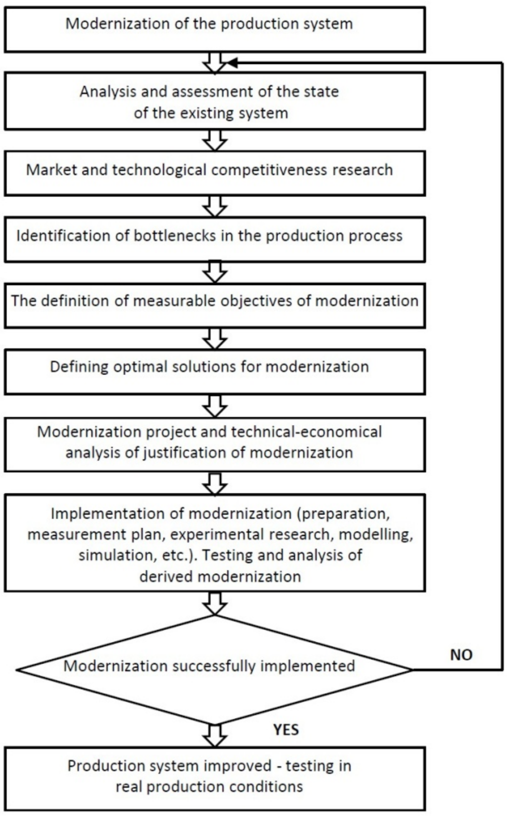


Fig. 15 Flow chart of complete modernization of the production system

- 30 % higher productivity of the production line after modernization as a result of the optimal flower pattern, higher utilization rate of the forming stations capacity, and the uniform roll loading on each roll stand,
- achieved high alignment of the production process and system by technological and energy point of view.

Flow chart modernization of the production system

The modernization of the production system beginning with the identification and analysis of the current state of the production system for that modernization is needed and the definition of the aims of modernization. The project of modernization and techno-economical analysis should show the validity of the modernization implementation (Fig. 15). Naturally, implementation of modernization needs to have measurable aims, experimental research, and relevant results to prove realized modernization. Previously mentioned things are fundamental of successful process and system modernization.

4. Conclusion

In this paper, the experimental research and modelling were carried out in order to test the roll forming process and system in real production conditions, with the aim of optimal process parameters of the sheet roll forming is increasing productivity of the production line. The obtained force model and deformation of the roll stand showed an insufficient utilization rate of the forming stations and consequently the production line. Therefore, in the process of the work, after modernization, the maximum sheet thickness of 1.40 mm was used instead of the thickness of up to 0.70 mm. The measured deformations of the roll stand were confirmed through this approach. The modernization of roll forming production line for sheet profile has been achieved with the following main objectives:

- technological process of the roll forming was optimized – forming stations are approximately equalization of a roll load, what resulted in the production line with a maximum efficiency and higher product quality,
- technological process of the sheet roll forming has been redesigned: the bending deformation for each forming station is greater, defining the optimal flower pattern, and an increased flow rate of the profiled sheet through the forming stations of the production line,
- and finally, productivity of modernized roll forming production line is higher for 30 %, what is the result of higher utilization rate of forming stations capacity and the balanced roll load on the forming stations.

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