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Experimental Analysis and Mathematical Modelling of Rolling Force

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This paper deals with experimental determination, mathematical modelling, analytical calculation and verification of the rolling force. The results of performed research indicate that mathematical-experimental modelling can be successfully used to define the rolling force and technological parameters of the rolling process. In this paper a mathematical model of the rolling force $F = f(\Delta h, \varepsilon, \delta, k)$ has been developed. Main achievements are: original experimental identification of the rolling force, original measuring sensor for rolling force measurement and a mathematical model for defining the rolling force.

Eksperimentalna analiza i matematičko modeliranje sile valjanja

Izvornoznanstveni članak

U ovom rada je prikazano eksperimentalno određivanje sile valjanja, matematičko modeliranje, proračun i verifikacija sile valjanja. Rezultati provedenog istraživanja pokazuju da se matematičko-eksperimentalno modeliranje može uspješno primijeniti za definiranje sile valjanja i tehnoloških parametara procesa valjanja. Osim toga, u radu je definiran matematički model sile valjanja $F = f(\Delta h, \varepsilon, \delta, k)$. Glavna postignuća su: originalna eksperimentalna identifikacija sile valjanja, originalni mjerni senzor za mjerenje sile valjanja i matematički model za definiranje sile valjanja.

1. Introduction

Roll forming is a metal forming process in which sheet metal is progressively shaped through a series of bending operations. The process is performed on a roll forming line in which the sheet metal stock is fed through a series of roll stations. Each station has a roller, referred to as a roller die, positioned on both sides of the sheet. The shape and size of the roller die may be unique to that station, or several identical roller dies may be used in different positions. The roller dies may be above and below the sheet, along the sides, at an angle, etc. As the sheet is forced through the roller dies in each roll station, it plastically deforms and bends. Each roll station performs one stage in the complete bending of the sheet to form the desired part. The roll forming process can be used to form a sheet into a wide variety of cross-section profiles.

The roll forming process has a wide application in many industrial fields. The reason for that is a list of advantages as follows:

- two distinct parts can be run together to form one assembly (Figure 1),
- roll forming is an energy efficient process usually requiring no process heat to be added,
- roll forming can produce superior surface finishes which often eliminates the need for additional finishing,
- producing parts with long lengths, and the only limitations are due to material handling equipment, space constraints, and shipping capabilities,
- with adequate equipment, tools, devices, and necessary process automation large quantities.

Symbols/Oznake

h_0	- initial thickness, m - početna debljina	X_i	- coded variable value - kodirana vrijednost varijable
b_0	- sheet width, m - širina trake	b_{imk}	- regression coefficient - regresijski koeficijent
D	- diameter of roller, m - promjer valjka		**Greek letters/Grčka slova**
F_{v}	- rolling force, N - sila valjanja	ε	- relative degree of deformation - relativni stupanj deformacije
Δh	- absolute deformation, m - apsolutna deformacija	δ	- coefficient - koeficijent
k	- yield stress, Nm^{-2} - granica tečenja materijala		**Subscripts/Indeksi**
x_i	- physical variable value - fizikalna vrijednost varijable	j	- trial - pokus

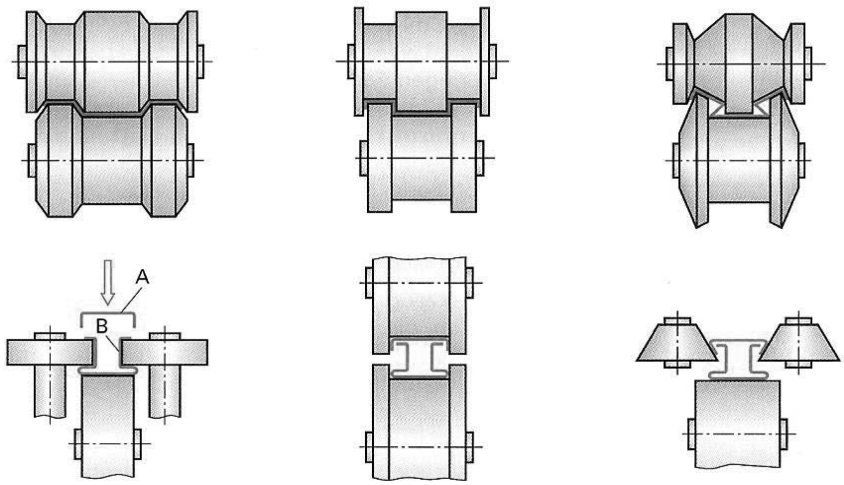
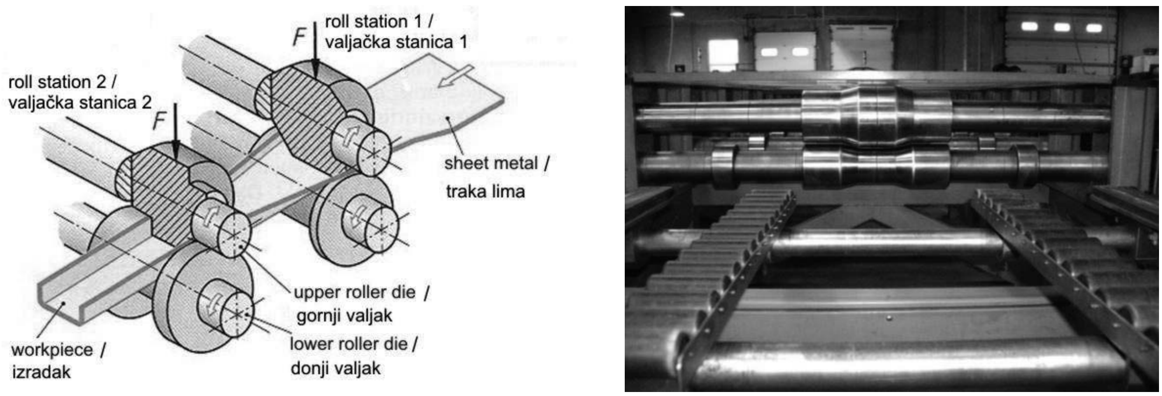


Figure 1. Show of complex profiles using a simple form of two profiles

Slika 1. Prikaz izrade složenih profila uporabom dvaju profila jednostavnijeg oblika



a.) b.)

Figure 2. Scheme of process (a.) and line for roll forming (b.)

Slika 2. Shema procesa (a.) i linija za profiliranje lima (b.)

The process of sheet metal roll forming is characterized by adjustable upper rolls ensuring a constant sheet thickness ($s_0 = s_1 = s_2 = ... = s_n$), as well as a cross-section area ($A_0 = A_1 = A_2 = ... = A_n$) and according to this, material flow is:

$$A_0 v_0 = A_1 v_1 = A_2 v_2 = ... = A_n v_n = const \tag{1}$$

or sheet velocity:

$$v_0 = v_1 = v_2 = ... = v_n = const \tag{2}$$

2. Experimental research of rolling force

The objective of this paper is to develop mathematical model of the rolling force in dependence on basic influential parameters. This paper is based on experimental results for the rolling force on the line for rolling with three forming modules (stations), where the measuring equipment and measurement system are used for rolling force measuring. The initial data are: cold rolling strip material DIN St 14 (Table 1), initial thickness h_0 = 2,5 mm and width sheet b_0 = 350 mm. The diameters of rolls on each machinig modules are: D_1 = 207,9 mm; D_2 = 175,7 mm and D_3 = 157,9 mm. Parameters of the rolling process are: absolute deformation Δh, relative degree of deformation ε, coefficient δ and yield stress of materials k.

Table 1. Chemical composition and mechanical properties of sheet metal St 14 (DIN)

Tablica 1. Kemijski sastav i mehanička svojstva lima St 14 (DIN)

Chemical composition / Kemijski sastav (%)					
C	Mn	P	S	Al	N
0,07	0,22	< 0,03	< 0,03	0,01	0,006

Mechanical properties / Mehanička svojstva			
Tensile strength (N/mm^2) / Zatezna čvrstoća (N/mm^2)	Yield strength (N/mm^2) / Granica tečenja (N/mm^2)	Elongation (%) / Produljenje (%)	Flow stress curve (N/mm^2) / Krivulja očvršćivanja (N/mm^2)
330	214	36	$580 \cdot \varphi^{0,231}$

In this paper an experiment plan has been presented as well as its results for the rolling force, modelling procedure, model adequacy testing, analysis result of modelling and the experiment, comparison of the experimental and modelling force, and at the end simulation of the rolling force [1-9].

According to analytical loading calculation of roller dies carried out using large approximation, where continuous roller loading is replaced by concentrated forces in order to reduce the complexity of the calculation (Figure 2). Therefore, experimental research is to verify the analytical calculation of force and torque values of rollers and the forming system as a whole. The experimental analyses of rolling process are made with the aim of measuring the rolling forces which are used for modelling and simulation of the rolling process (Figure 3).

Original experiments have been carried out in the industrial conditions (plant "*Krajinametal*" Bihać) under macro project titled: *Research and development of flexible rolling machines* (Bosnia and Herzegovina) and project titled: *Modelling and simulation processes by using genetic and stochastic algorithm* (Croatia).

2.1. Measuring system

When testing rolling forces and elastic deformation of the closed frame the rolling process is performed in a technologically stable area, that means that when elastic deformation remains within allowed limits, the rolling machine will be utilized optimally.

By means of a special designing measuring element using strain gauge (Figure 4) an experimental test - mechanical load of the rolling machine in process of cold rolling with measuring the rolling forces (Figure 5) was carried out.

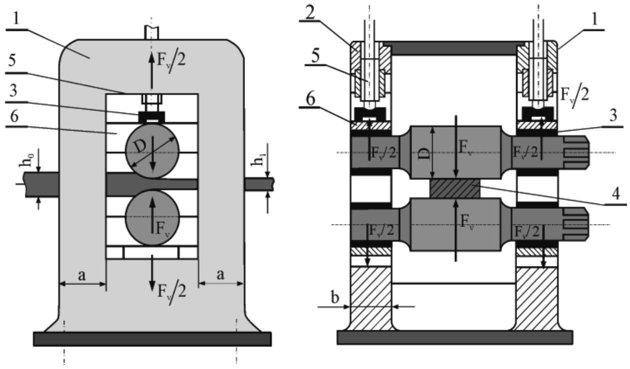


Figure 3. Closed rolling machine frame (1,2), sensor force (3), rolled section-sheet metal (4), thread spindle (5), roller cradle (6)

Slika 3. Zatvoreni okvir (1,2) valjačkog stana, senzor sile (3), valjani materijal (4), navojno vreteno (5), kolijevka valjka (6)

Measurement of the rolling force is done by producing the original measurement sensors that are placed between the threaded spindle (5) and roller cradle (6) as shown in Figure 3 and Figure 4. Dimensions of the elastic element are determined on the basis of the known criteria of the design and calculation of transducers where the mechanical values in the form of force (N) are transformed into electrical (mV). Figure 6 shows two diagrams of rolling forces measuring the deformation degree: $\varepsilon = 0.20$ and $\varepsilon = 0.35$.

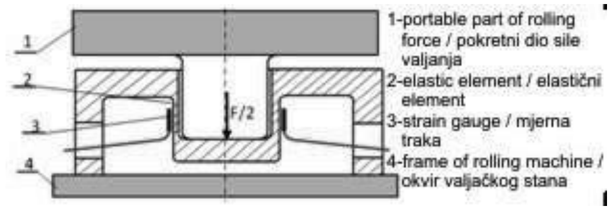


Figure 4. Strain gauge transducer - measuring element [8]

Slika 4. Mjerni pretvarač [8]

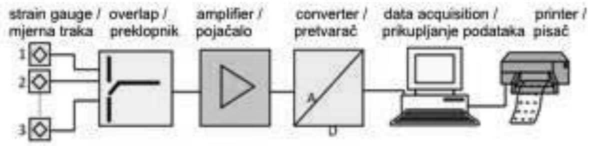


Figure 5. Measuring system

Slika 5. Mjerni sustav

The large number of measurements has been performed with the established relationship between the amplitude of the rolling force (mm) and values of the measured rolling force (kN). The outer wall of the measuring element is a set of 8 strain gauges (3/120 LA-11 HBM) joined in full Whestone's bridge (Figure 5).

3. Analysis of the input and output variables

The force modelling has been performed for the four variables of rolling process (Fig. 4.). The parameters of the rolling process are defined in the following way:

- input variables: absolute deformation Δh (mm), relative degree of deformation ε, coefficient $\delta = 2\mu l/\Delta h$, where $l=\sqrt{\Delta h R}$, $R=D/2$ and yield stress of material k (N/mm^2).
- output value – rolling force Fv (kN).

The function of the process state is: $Fv = f(\Delta h, \varepsilon, \delta, k)$. A graphic presentation of the input – output values is given in Figure 7.

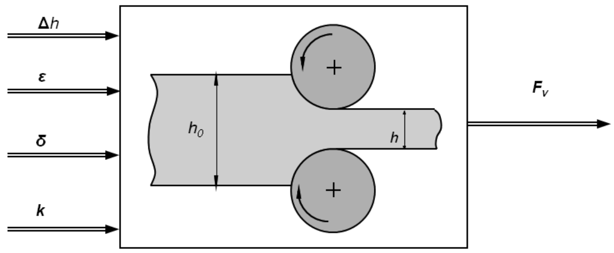


Figure 7. Scheme for rolling force modelling (input – output variables)

Slika 7. Shema modeliranja sile valjanja (ulazno-izlazne varijable)

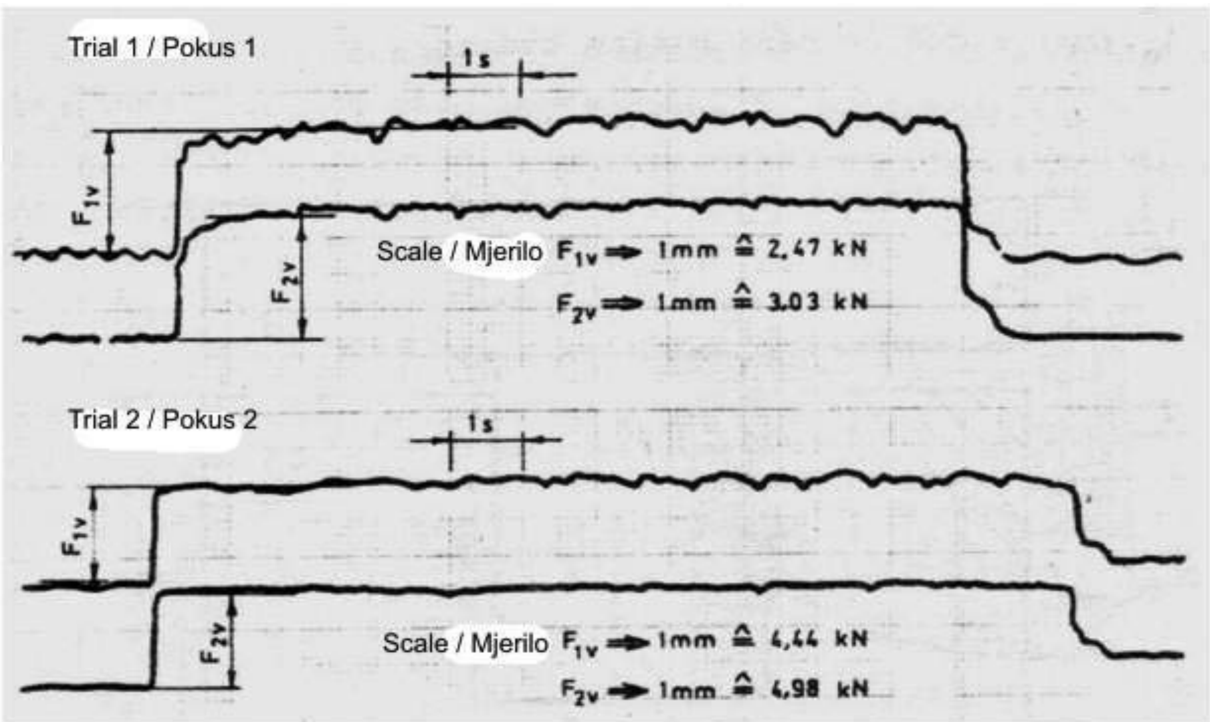


Figure 6. Diagram of rolling force intensity for relative deformation degree ε = 0,20 (trial 1) i ε = 0,35 (trial 2) [8]

Slika 6. Dijagram intenziteta sile valjanja za stupanj deformacije ε = 0,20 (pokus 1) i ε = 0,35 (pokus 2) [8]

The coded and physical values of influential parameters are presented in Table 2.

Table 2. Physical x_{ji} and coded X_{ji} values

Tablica 2. Fizikalne x_{ji} i kodirane X_{ji} vrijednosti

Influental factors / Utjecajni parametri		*Coded and physical input values / Kodirane i fizikalne ulazne vrijednosti*		
Physical input values / Fizikalne ulazne vrijednosti	$x_1 = \Delta h$ (mm)	*0,5*	*1,0*	*1,5*
	$x_2 = \varepsilon$	*0,20*	*0,40*	*0,60*
	$x_3 = \delta$	*2,0*	*3,5*	*5,0*
	$x_4 = k$ (N/mm^2)	*250*	*375*	*500*
Coded input values / Kodirane ulazne vrijednosti	X_i	*-1*	*0*	*1*

4. Experimental design and results

The experiments were performed by using experiments plan with $N = 2^k + n_0 = 2^4 + 4 = 20$ tests (Table 3). The design matrix meets the criteria of orthogonality, symmetry and normativity [1,10].

5. Mathematical modeling of the rolling force

When chosing a type of the mathematical model, there are no generally applicable rules, that means, that a model has to be chosen for each investigated process or system and its accuracy and adequacy in relation to the real process have to be examined. On the basis of performed experiment and regression analysis, the statistical model is determined by means of regression coefficients b_i, b_{ii} , b_{im} , b_{imk} so that the mathematical model obtains the form:

$$\hat{Y} = \sum_{i=0}^{k} b_i X_i + \sum_{1 \le i \le m}^{k} b_{im} X_i X_m + \sum_{1 \le i \le m \le k} b_i X_i X_m X_k \quad (3)$$

$$b_0 = \frac{1}{N} \sum_{j=1}^{N} X_{oj} Y_j , \qquad \mathrm{X_{oj}} = 1 \quad (4a)$$

$$b_i = \frac{1}{N - n_0} \sum_{j=1}^{N} X_{ij} Y_j , \quad \text{za } \mathrm{i} = 1,2,\ldots,\mathrm{k}$$

$$b_{im} = \frac{1}{N - n_0} \sum_{j=1}^{N} X_{ij} X_{mj} Y_j , \quad \text{za } 1 \le \mathrm{i} \langle \mathrm{m} \le \mathrm{k} \quad (4b)$$

The only significant coefficients of regression can be considered and the mathematical model of rolling force has the form:

$$Y = F = 5113{,}75 + 394{,}43\, X_1 + 406{,}81\, X_2 + 368{,}56\, X_3 + 600{,}43\, X_4 - 118{,}06\, X_1 X_4 - 193{,}81\, X_2 X_3 X_4 + 91{,}43\, X_1 X_2 X_3 X_4 \quad (5)$$

The coefficient of multiple regression R=0,982 shows a very good correlation between varying X_i and rolling force. By encoding the mathematical model (5) the physical mathematical model of the rolling force is obtained in the form of:

$$\begin{aligned} Y = F_v &= 992{,}35 + 2736{,}62\Delta h - 2890{,}73\varepsilon - 264{,}70\delta \\ &+ 3{,}15k - 1353{,}85\Delta h\varepsilon - 199{,}38\Delta h\delta - 3{,}40\Delta h\, k \\ &+ 2075{,}41\varepsilon\delta + 15{,}46\varepsilon k + 1{,}74\,\delta\, k - 6{,}25\varepsilon\delta k + 1{,}08\Delta h\varepsilon\delta k. \end{aligned} \quad (6)$$

6. Analysis of modeling and experiment results

6.1. Comparison of the experimental force and modeling force

Results obtained using developed the rolling force model, on the basis of performed experimental investigation and mathematical modelling were presented in Figure 8. Results comparisons have proved model (6) adequacy and its possible using in rolling force prediction. The obtained experimental results (Table 3) and results obtained by mathematical model (6) show a very good correlation between each other (Figure 8), also presented by multiple regression coefficient R = 0,982. Accordingly, the rolling force model (6) describes experimental results within domain of experiment accurately enough.

6.2. Simulation of rolling force

3D simulation model (6) was shown, in Figure 9, dependence on the rolling force in relation to relative degree of deformation ε and absolute deformation Δh. In the same time other input parameters coefficient δ and yield stress of material k were constant on coded level -1 shown in Table 2.

Table 3. Experimental results

Tablica 3. Eksperimentalni rezultati

trial N_j / pokus N_j	1	2	3	4	5	6	7	8	9	10
Experimental forces F_j (kN) / Sile dobivene eksperimentom F_j (kN)	3370	4460	3880	4900	3780	4825	5245	6190	4520	5440
trial N_j / pokus N_j	11	12	13	14	15	16	17	18	19	20
Experimental forces F_j (kN) / Sile dobivene eksperimentom F_j (kN)	5795	6140	5880	5924	5828	6730	4790	4868	4890	4820

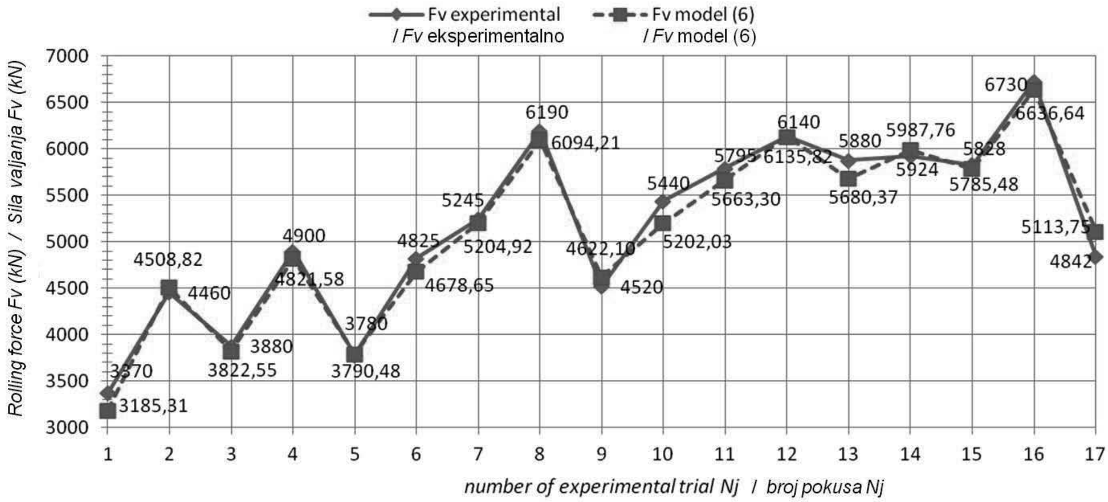


Figure 8. Comparison of the experimental and through model (6) obtained rolling force results

Slika 8. Usporedba eksperimentalnih i modelom (6) dobivenih rezultata sile valjanja

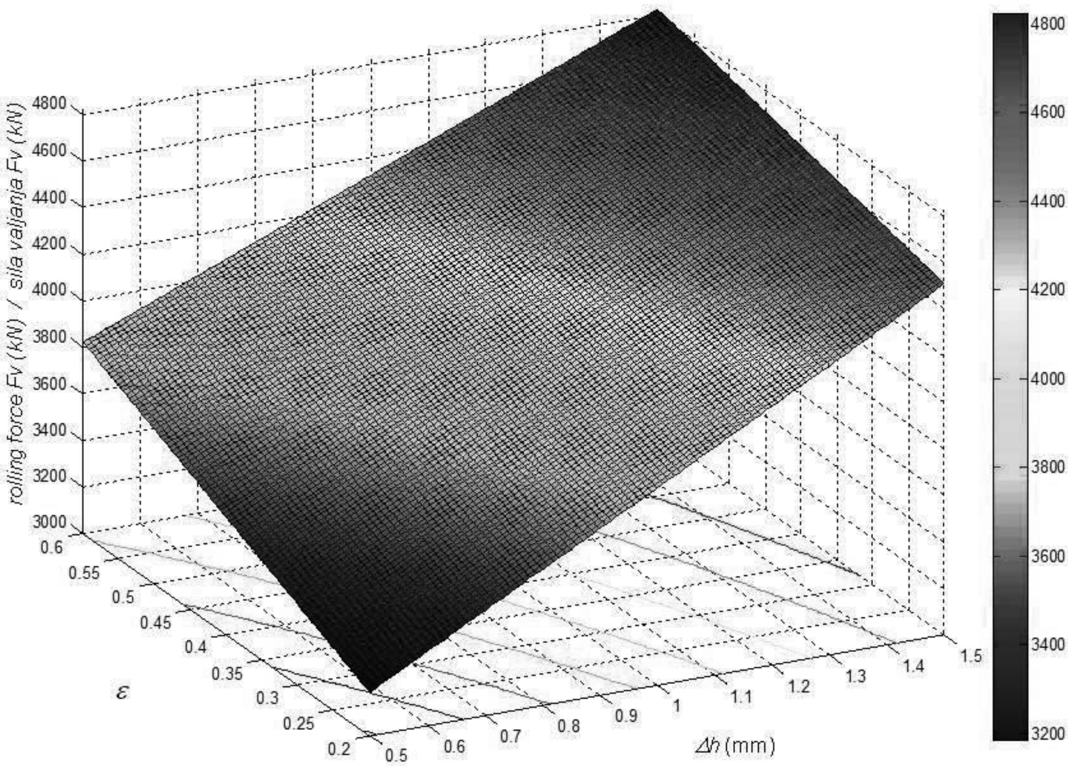


Figure 9. Response surface for rolling force model (6) depends on relative degree of deformation and absolute deformation with constant values of the coefficient $\delta = 2$ and yield stress of material $k = 250$ N/mm^2

Slika 9. Odzivna površina sile valjanja prema modelu (6) ovisna o relativnom stupnju deformacije i apsolutne deformacije s konstantnim vrijednostima koeficijenta $\delta = 2$ i granice tečenja materijala $k = 250$ N/mm^2

7. Conclusion

Analytical models known in literature are approximate solutions for calculation the rolling force. On the basis of authors experimental researches carried out over the many years with modern measurement (sensor) equipment and appropriate data acquisition and statistical software, in comparison with analytical rolling force models obtained results have been shown variations up to 50% compared to presented approach. Therefore, the mathematical model developed using stochastic modelling approach by means of experimental measurements of the rolling forces has provided accurate information of the forces intensity which is still in the phase of technology planning for the roll forming sheet, loading calculation of rollers and design of roll forming system in all. The developed model of the rolling force describes this roll forming force very correctly, which is to be confirmed with the confidence level P=0.95 and the coefficient of multiple regression R=0.982. With the model developed and presented in this way, the production cost can be reduced and desired product quality achieved.

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