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ROBUST DESIGN OPTIMIZATION OF ENERGY EFFICIENCY: COLD ROLL FORMING PROCESS

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ABSTRACT

Cold roll forming is an important sheet metal forming process for the mass production of a variety of complex profiles, coming from a wide spectrum of materials and thicknesses. Energy efficiency is a major trend nowadays, towards the reduction of energy consumption and the better utilization of manufacturing resources. The current paper has proposed a methodology for the robust design optimization of energy efficiency of the cold roll forming process. The energy efficiency indicator is calculated through an analytical model, and the quality characteristic constraints are checked through a model of finites elements. The robust design optimization of the process parameters algorithm is implemented, utilizing the analytical model of energy efficiency, so as to provide a practical approach for determining the optimum set of process parameters, taking into account the variability of noise factors. The current approach is applied to a U-section profile and is practical since it reduces the computational costs and takes into account any uncertainties in a real manufacturing environment.

KEYWORDS

Cold roll forming process, energy efficiency, optimization, robust design, noise factors

1. INTRODUCTION

Complex structural profiles from a wide spectrum of material and thicknesses can be mass produced by the cold roll forming process. Such a process demonstrates a high material utilization and productivity rates. With the introduction of high strength materials, several challenges have emerged, such as the requirement of increased deformation work and consequently energy consumption. Optimizing productivity and reducing energy consumption, including real manufacturing environment variability, can provide significant advantages against other sheet metal forming processes. Applying robust design techniques to the cold roll forming process, enables the finding of the optimum process variables that fulfil the objective and quality constraints' requirements, as these remain stable when exposed to uncertain conditions of noise factors (Jurecka, 2007).

Several studies have been presented towards the robust design optimization of major sheet metal forming processes, such as stamping and deep drawing. Mathematical meta-modeling techniques, such as Surface Respond Methodology (RSM), Dual RSM and Adaptive RSM, were applied with a stochastic analysis as calculating the estimation of the mean and the variance of the response for sheet metal forming processes (Hou et al, 2010) (Hu et al, 2008) (Donglai et al, 2008). The stochastic variation of noise factors affecting the sheet metal forming quality was studied, so as to minimize the impact of variations and achieve reliable process parameters (Tang and Chen, 2009). RSM was also applied with the Pareto-based multi-objective generic algorithm (MOGA) for optimization of the sheet metal stamping process (Wei and Yuying, 2008). Regarding the cold roll forming process, RSM was applied so as to study the effects of the main process parameters, namely the bending angle increment, toll radius, springback angle, and maximum edge membrane longitudinal strains (Zeng et al, 2009). Moreover, a semi-empirical approach, utilizing the Taguchi methods was also developed for the optimization of main roll forming parameters (Paralikas et al, 2010a).

In the current paper, a methodology for robust design optimization, utilizing orthogonal arrays, of energy efficiency of the cold roll forming process is proposed. Such methodology utilizes an analytical model for the calculation of the energy efficiency, and a finite elements model for the monitoring of the quality characteristic constraints of the most energy efficient solution. This hybrid optimization solution provides a significant reduction in the computational cost, as a finite elements model is used only for checking the quality characteristic constraints.

2. ENERGY EFFICIENCY OF COLD ROLL FORMING PROCESS

Energy efficiency in a manufacturing process is a generic term and mainly refers to less energy being used for the production of the same amount or more useful output, as products (Patterson, 1996). In the manufacturing sector, the energy efficiency can be defined as the energy required for producing an amount of products per unit time. Hence, the energy efficiency indicator for the cold roll forming process can be defined by the ratio of the production rate per hour to the energy required for a production of a product's meter:

$$\eta_{RF} = \frac{Useful\ output\ of\ process}{Energy\ input\ into\ process} = \frac{PRH}{E_{motor,in}} \quad (1)$$

, where:

- η_{RF} is the energy efficiency indicator of the roll forming process $\left(m^2 / Joules * hr\right)$
- PRH is the production rate of the roll forming mill per hour (products of one meter per hour, or meters of products per hour)
- $E_{motor,in}$ is the total specific input energy to the electric motor of the mill from the grid (Joules/m)

The total energy motor input is calculated by an analytical model, based on power distribution from grid to the material's deformation (Figure 1).

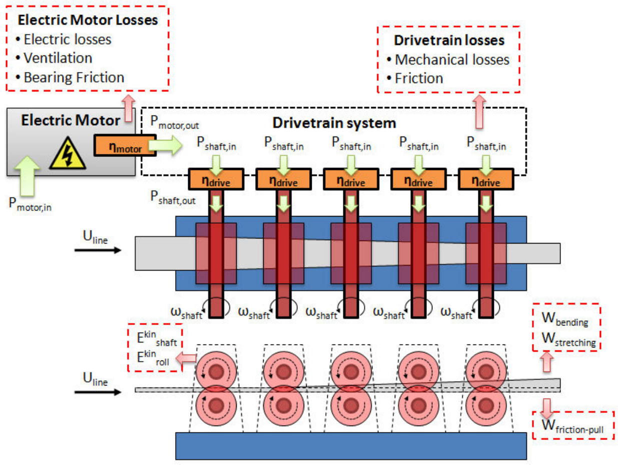

Figure 1 – Cold roll forming process layout for energy motor input calculation

The electric motor and drivetrain efficiencies are taken into account for power distribution to the roll forming mill shafts. An analytical model calculates the deformation work, the longitudinal stretching work at flange and the frictional pulling work.

3. ROBUST DESIGN METHODOLOGY

In a robust design optimization problem, the variables can be identified as: **i)** control factors as design/operational parameters that can be easily controlled, **ii)** noise factors that are hard or expensive to be controlled and provide uncertainty, **iii)** fixed parameters that provide the boundary conditions, **iv)** objective responses to be optimized and **v)** quality constrains. The main objective of the robust design optimization of a manufacturing process is that the control factors be calculated so as to achieve objectively the best process performance within quality constraints, being also insensitive to the uncertainty of noise factors.

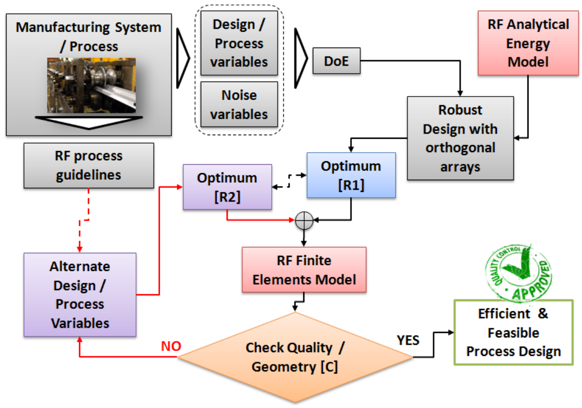

Figure 2 – Process robust design optimization using hybrid modeling approach

The proposed hybrid robust design optimization methodology is presented in Figure 2. An analytical energy model is used in the DoE/robust design algorithm (Figure 3) for the determination of the optimum mean value of energy efficiency with the minimization of variance. This leads to (16x9) 144 runs, which is rather impractical to be applied experimentally or for a computational expensive finite elements model to be used. Such an optimum energy efficient solution is investigated through a finite elements model for the fulfillment of quality constraints. In case those quality constraints are not met, then the control variables are alternated based on process guidelines and a new optimum solution is checked again.

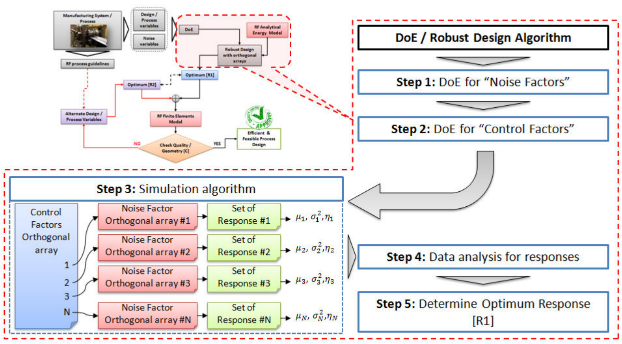

Figure 3 – DoE / robust design algorithm for calculation of optimum energy efficient solution

4. COLD ROLL FORMING PROCESS VARIABLES

The fixed parameters, control and noise factors need to be defined in order for the optimization problem to be formulated. The fixed parameters are mainly referred to the product geometrical characteristics that have been set by the product/customer as identified in Table 1 for the demonstration of the U-section.

Table 1 – Fixed parameters for a roll formed U-section

No	Fixed parameters	Units
1	Inside bending radii – (r_i)	mm
2	Length of the flange – (A)	mm
3	Length of the web – (w)	mm
4	Total strip width (calculated) – (L)	mm
5	Final bending angle – (A_{final})	Deg.
6	Material type	-
7	Strip thickness (nominal) -	mm

Control factors are parameters easy to be controlled from the design phase during processing (Table 2). Such parameters do not affect the fixed ones, but influence an objective response and the quality characteristics that need to be optimized. The bending angle concept refers to the bending sequence of the roll formed profile, as the leading and final angle increments should be 5-10 degrees (Halmos, 2006). The middle angle increment can range from 5 to 20 degrees, affecting the bending sequence and consequently the number of roll stations required. The bending concepts C5, C10, C15 and C20 lead to 18, 10, 7 and 6 roll stations respectively.

Table 2 – Control factors for cold roll forming process

No	Control Factors	Units	Range
1	Bending Angle Concept – (BAC)	degrees	C5 - C20
2	Roller diameter – (D_L)	mm	100 - 220
3	Line velocity – (V)	mm/sec	100 – 310
4	Rolls stations inter-distance – (L_R)	mm	480 - 540
5	Rolls gap (clearance) – (G)	Thickness % (2.0 mm)	1% - 3% (0.02-0.06 mm)

Noise factors are parameters that are expensive or practically impossible to be controlled during processing (Table 3). As tooling wears, the rolling friction coefficient will be alternated randomly and will not be easily determined online. Moreover, there is a practical variation in the material thickness and material parameters from coil-to-coil of the material supplier.

Table 3 – Noise factors for cold roll forming process (AHSS DP-600 material parameters)

No	Noise Factors	Units	Mean target
1	Rolling friction coefficient – (Crr)	-	0.01196
2	Material parameter: Strength coefficient – (K)	MPa	956.65
3	Material parameter: Hardening coefficient – (n)	-	0.171
4	Thickness of material – (t)	mm	2.0

Thus, there is a variation in such noise parameters that cannot be easily controlled (Table 4). A range can be set from statistical values (Kunitsyn et al, 2011) and material supplier data (Arcelormittal, 2011), as it leads to a standard deviation of noise factors.

Table 4 – Stochastic variation of noise factors

No	Noise Factor	Mean (μ_i)	Range	Standard deviation (σ_i)
1	Crr	0.01196	0.01072	0.00268
2	K	956.65	191.33	47.8325
3	N	0.171	0.0342	0.00855
4	t	2.0	0.16	0.05

5. QUALITY CHARACTERISTICS CONSTRAINS

Quality characteristic constraints are based on specific failure modes (defects), such as warping, twist, edge waviness and bending edge cracking, during the cold roll forming process (Figure 4). Such failure modes are driven from specific redundant deformations (Halmos, 2006).

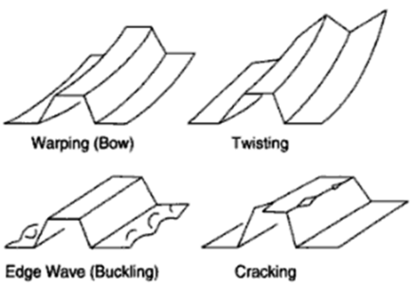

Figure 4 – Main defects of roll formed product (Halmos, 2006)

The material's Forming Limit Curve (FLC) can be used as a metric for monitoring major (ε_1) and minor (ε_2) strains of the profile. During the cold roll forming process; major strains (ε_1) can surpass the critical forming limit point (FLC_0). This can lead to excessive and unequal plane strain and result in warping and or cracking. Thus, the quality constraint can be formulated as:

$$FLC_0 > \varepsilon_1 \quad (2)$$

During cold roll forming the edge travels a greater length than the web does, resulting in the development of longitudinal strains at the edge. Such longitudinal strains are alternated from compressive, as the material reaches the lower roller, to stretching, as the material s passes the lower roller's centerline. Such longitudinal strains at edge, if surpassing the material's elastic limit in tensile (TYS) and buckling (CYS), are resulting in edge wave (buckling). Thus, the next quality constraint should meet:

$$TYS > \forall \varepsilon_{peak@edge} > CYS \quad (3)$$

Strains in the direction of thickness can provide a prediction to the thickness reduction along the profile's cross section and also cracking, is surpassing the ultimate elongation point strain (ε_{UEP}). Therefore, the quality constraint for cracking can be formulated as:

$$0 < \varepsilon_{TS3-peak} < \varepsilon_{UEP} \quad (4)$$

6. COLD ROLL FORMING PROCESS GUIDELINES

Several guidelines could be emerged from previous studies (Paralikas et al, 2010a) (Paralikas et al, 2010b) (Paralikas et al, 2009) so as to apply and alternate any undesired quality characteristic measures. Such guidelines can be divided into i) process and ii) rollers design guidelines.

Process guidelines involve the alternation of process parameters for the relief and correction of such quality characteristics. Increase in the rolls' station inter-distance can decrease the peaks of the elastic longitudinal strains at the edge. Decrease in the rolls' gap (% of nominal strip thickness) can decrease major-minor strains. Decrease in the bending angle increment between the roll stations can reduce dramatically the elastic longitudinal strains, but it will require an additional roll station in order for the desired final bending angel to be produced.

Design guidelines involve the alternation of the rollers' design and the roll forming line configuration. The downhill flow can be applied so as to provide reduction in strip thickness.

Increasing the rolls' diameter can yield a positive effect on the elastic longitudinal strains at buckling. Applying the variable bending radius along the roll forming line, can result in decreasing thickness, but can produce more elastic longitudinal strains.

7. CASE STUDY: U-SECTION PROFILE

A U-section profile (Figure 5) with a total bending angle of 90 degrees was selected for the application of the proposed robust design methodology. Such a profile is commonly used in many industrial sectors and applications.

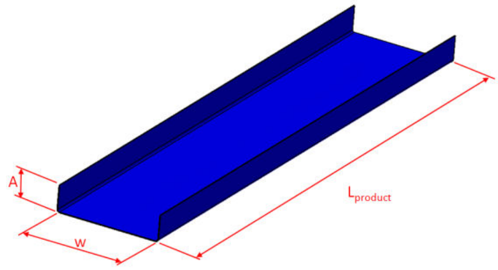

Figure 5 – U-Section roll formed profile (A=50mm, w=200mm, L=1000mm, r=4mm)

Based on the fixed parameters from the U-section profile design, the control and noise factors (as defined above) the robust design algorithm (Figure 3) was applied for the calculation of the optimum energy efficient solution, while the quality constraints were checked through finite elements modelling.

7.1. ROBUST DESIGN OPTIMIZATION FOR ENERGY EFFICIENCY

Within the robust design algorithm, the analytical model for the calculation of the energy efficiency indicator is used. For control factors, the $L_{16}(4^5)$ orthogonal array was selected as there are five factors with four levels each, yielding 16 runs. Regarding noise factors, the $L_9(3^4)$ orthogonal array was selected as there are four factors with three levels each, which yield 9 runs each (Phadke, 1989). As each row of the control factors orthogonal array is considered as input to each noise factors orthogonal array, then the total number of required runs is 144 (16x9). From each of the 16 sets of 9 runs each, the mean value and the variance can be calculated. For the S/N ratio of the mean and variance values (Table 5), the larger-the-better type problem was selected, as the quality characteristic is continuous and non-negative and the goal to be maximized (Phadke, 1989), can be calculated as:

$$S/N = -10\log_{10}\left[\left(\frac{1}{\mu^2}\right)*\left(1+3\left(\frac{\sigma^2}{\mu^2}\right)\right)\right] \qquad (5)$$

Table 5 – Mean, variance and S/N ration for energy efficiency indicator

Row No.	Mean (μ)	Variance (σ^2)	S/N ratio
1	17.22%	0.00008484	-15.314
2	13.95%	0.00014558	-17.203
3	8.40%	0.00007021	-21.640
4	5.00%	0.00002480	-26.150
5	13.56%	0.00022106	-17.506
6	9.69%	0.00007665	-20.377
7	21.12%	0.00005534	-13.523
8	18.53%	0.00003214	-14.655
9	22.78%	0.00011877	-12.878
10	25.94%	0.00011143	-11.742
11	7.05%	0.00002520	-23.103
12	11.88%	0.00003294	-18.532
13	13.75%	0.00003407	-17.257
14	9.12%	0.00001559	-20.825
15	9.48%	0.00001811	-20.493
16	5.06%	0.00000499	-25.936

Based on the calculated S/N ratios the analysis of means (ANOM) has been implemented (Table 6). The plot of means for control factors was also depicted within Figure 6.

Table 6 – Analysis of Means for the energy efficiency S/N ratio response

Control Factors	Levels			
	1	2	3	4
A - Bending angle concept	-20.0	-16.5	-16.5	-21.1
B - Roller radius	-15.7	-17.5	-19.6	-21.3
C – Line velocity	-21.1	-18.4	-17.5	-17.1
D - Rolls inter-distance	-17.0	-18.0	-19.2	-19.9
E - Rolls gap	-15.5	-17.3	-19.4	-21.8

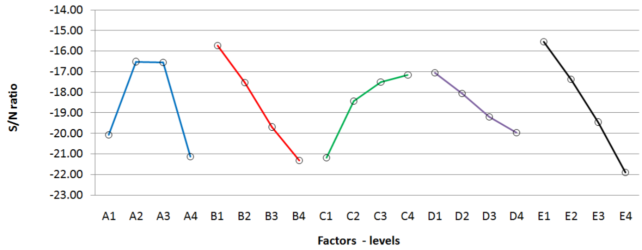

Figure 6 – Plot of means for control factors for the S/N ratio of the energy efficiency response

Based on the plot of the factor effects, the level with the maximum value is the optimum level for each factor and the level with the minimum value is the worst level for each factor. The optimum and worst set of the factors' levels are calculated (Table 7) and response characteristics (production rate, total power input, energy efficiency and number of roll stations) have been calculated.

Table 7 - Optimum and worst levels based on summary statistic of mean for power response

Control Factors	Levels	
	Optimum	**Worst**
A -Bending angle concept	A2 – C10	A4 – C20
B - Roller radius (R)	B1 – 0.1	B4 – 0.22
C – Line velocity (U)	C1 – 0.31	C4 – 0.1
D - Rolls inter-distance	D1 – 0.48	D4 – 0.54
E - Rolls gap (% of t)	E1 - 1	E4 – 3.1
Production rate (parts/min)	192.41	84.9
Total power input (W/m)	29.75	43.53
Energy efficiency indicator (%)	34.56	4.6
No. of RS	10	6

Moreover, the Analysis of Variance (ANOVA) was implemented for the control factors, and the responsibility of each control factor on energy efficiency indicator was calculated (Figure 7). The main factors affecting the energy efficiency of the cold roll forming process are rolls gap, roller radius and bending angle increment with 30.96%, 24.77% and 23.62% responsibility respectively. The roll forming line velocity and rolls inter-distance have an effect on the energy efficiency by 13.79% and 6.86% respectively.

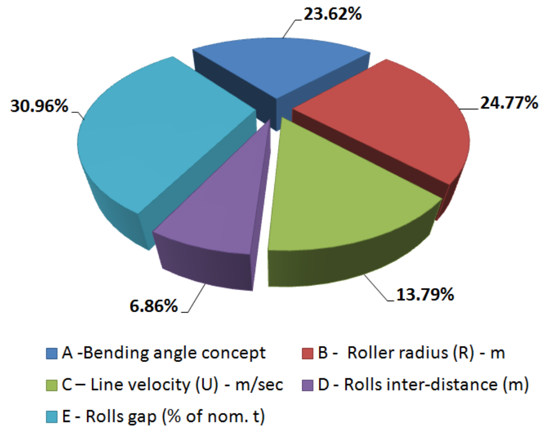

Figure 7 - Responsibility (%) of each factor on energy efficiency indicator response

7.2. COLD ROLL FORMING PROCESS QUALITY CONSTRAINS

Based on the optimum set of process parameters' levels, as calculated and shown in Table 7, the Finite Elements Model (FEM) was implemented and the cold roll forming process was simulated. An explicit dynamics finite element modelling was used for the cold roll forming process simulation as discussed in (Paralikas et al, 2010a) by utilizing shell elements for both a deformable strip and rigid rolls. Quality constraints were checked utilizing the FEM of the cold roll forming process with an optimum set of process parameters (control factors) and mean values of the noise factors. Such quality constraints cover the elastic longitudinal strains at the edge of the profile along the roll forming direction, mapping of major and minor strains on the material's FLD diagram of the roll formed strip and prediction of a thickness reduction through total strain in thickness direction.

Regarding the FLC and major-minor strains, the FEM results provided that the maximum major strain is below the critical forming limit point, as it was also shown in Figure 8.

$$FLC_0 = 0.235 \geq \varepsilon_1 = 0.2305 \qquad (6)$$

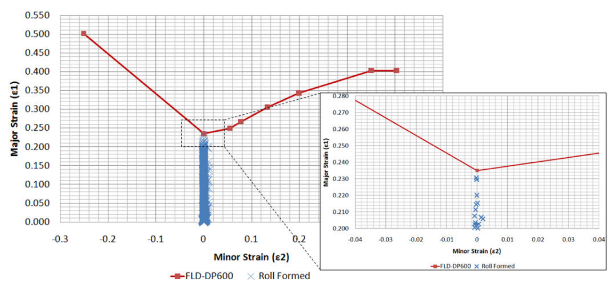

Figure 8 - Major and minor strains of strip after roll forming processing

Longitudinal strains at the edge of the profile were also plotted along the roll forming direction (Figure 9). All peaks of longitudinal strains, in compression and tension, are within the material's elastic limits as:

$$0.1715\% > \forall \varepsilon_{peak@edge} > 0.1715\% \quad (7)$$

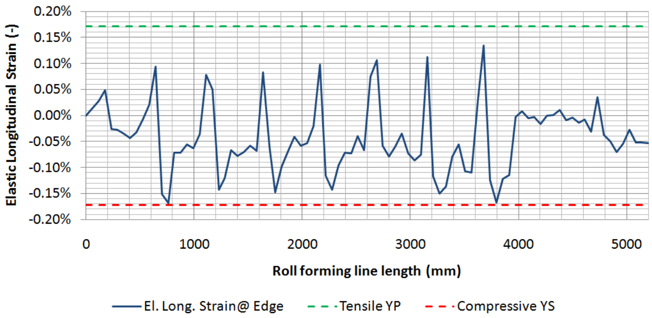

Figure 9 - Elastic longitudinal strains at the edge of the flange along roll forming direction

Thickness reduction was checked through the mapping of strains, in a thickness direction along the cross section of the U-section profile (Figure 10). Strains in thickness direction are within the material's limits.

$$0 < \varepsilon_{TS3-peak} = -17.5\% < \varepsilon_{UEP} = -17.9\% \quad (8)$$

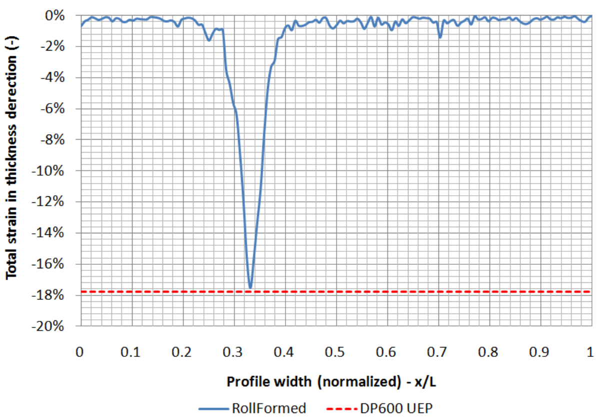

Figure 10 - Total strain in thickness direction along cross section of profile (half profile due to symmetry)

8. CONCLUSIONS

A robust design optimization methodology of the cold roll forming process energy efficiency, utilizing a hybrid scheme of analytical and finite elements models, is proposed. An analytical model is used within the robust design algorithm for the calculation of the energy efficiency indicator. The Analytical model results of the roll forming mill motor consumption are verified by an experimental investigation for energy consumption of the roll forming mill by (Lindgren, 2007). The optimum energy efficiency indicator was calculated based on the proper selection of control factors through the analysis of means. The analysis of variance was then implemented for the calculation of the responsibility of the control factors on the energy efficiency indicator. Based on the optimum solution for the energy efficiency, the Finite Elements Model was created and the quality characteristic constraints were checked. Through the final step, the profile's feasibility and quality were monitored.

A major innovation of the current study is the introduction of an analytical model of energy efficiency of the cold roll forming process calculation within the robust design optimization, through orthogonal arrays. The robust design simulation consists of a total 144 runs (16 x 9 runs). Using only the FEM, it is rather impractical, as an FEM run is computationally expensive and takes about 1.5 days in order to provide a run solution. Utilizing a computational efficient and non cost expensive analytical model for energy efficiency, only one FEM run is required for checking the feasibility of the optimum solution, under specific quality characteristic constraints. This implies that the current methodology is considered practical and provides a guide towards the application of the optimum energy efficient solution of the cold roll forming process.

A U-section profile was demonstrated for the calculation of a feasible solution to the optimum energy efficiency. The optimum energy efficient solution was calculated through the robust design algorithm and the control and noise factors orthogonal arrays. The production rate was 192.41 parts per minute, and the total power input to the electric motor was 29.75 Watts per meter of the produced profile, which yielded to an energy efficiency indicator of 34.56%. The number of roll stations, required for the optimum energy efficient solution, was ten rolls stations. The cold roll forming process parameters' (control factors) responsibility on energy efficiency was calculated, with major parameters to be the rolls gap, the rollers radius and the bending concept with a 30.96%, 24.77% and 23.62% responsibility respectively. The optimum energy efficient solution feasibility was checked through FEM, for showing that the parameters' levels provide a solution within specific quality constraints for the major-minor strains, the elastic longitudinal strains at edge along the roll forming direction and the thickness reduction.

9. ACKNOWLEDGMENTS

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