UNIVERSITY OF PATRAS

SCHOOL OF ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING & AERONAUTICS

LABORATORY FOR MANUFACTURING SYSTEMS & AUTOMATION

DIRECTOR: Professor G. CHRYSSOLOURIS

PhD DISSERTATION

**COLD ROLL FORMING PROCESS ENERGY EFFICIENCY
OPTIMIZATION**

IOANNIS N. PARALIKAS

Mechanical & Aeronautical Engineer

PATRAS 2012

UNIVERSITY OF PATRAS

SCHOOL OF ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING & AERONAUTICS

LABORATORY FOR MANUFACTURING SYSTEMS & AUTOMATION

DIRECTOR: Professor G. CHRYSSOLOURIS

PhD DISSERTATION

**COLD ROLL FORMING PROCESS ENERGY EFFICIENCY
OPTIMIZATION**

IOANNIS N. PARALIKAS

Mechanical & Aeronautical Engineer

PATRAS 2012

Η παρούσα Διδακτορική Διατριβή εγκρίθηκε ομόφωνα με βαθμό Άριστα (10/10), από την Επταμελή Εξεταστική Επιτροπή η οποία ορίστηκε από την Γενική Συνέλευση με Ειδική Σύνοψη του Τμήματος Μηχανολόγων και Αεροναυπηγών Μηχανικών της Πολυτεχνικής Σχολής του Πανεπιστημίου Πατρών, στην υπ' αριθμόν 2/24-01-2012 συνεδρίασή της, σύμφωνα με το άρθρο 36 Ν. 1268/82 και το άρθρο 13 Ν. 2083/92, μετά από σχετική εισήγηση της Τριμελούς Συμβουλευτικής Επιτροπής.

Μέλη της Επταμελούς Εξεταστικής Επιτροπής αποτέλεσαν οι:

1. **ΧΡΥΣΟΛΟΥΡΗΣ ΓΕΩΡΓΙΟΣ** (Επιβλέπων)
Καθηγητής του Τμήματος Μηχανολόγων και Αεροναυπηγών Μηχανικών του Πανεπιστημίου Πατρών
2. **ΑΝΥΦΑΝΤΗΣ ΝΙΚΟΛΑΟΣ** (Μέλος της Τριμελούς Επιτροπής)
Καθηγητής του Τμήματος Μηχανολόγων και Αεροναυπηγών Μηχανικών του Πανεπιστημίου Πατρών
3. **ΠΑΝΤΕΛΑΚΗΣ ΣΠΥΡΙΔΩΝ** (Μέλος της Τριμελούς Επιτροπής)
Καθηγητής του Τμήματος Μηχανολόγων και Αεροναυπηγών Μηχανικών του Πανεπιστημίου Πατρών
4. **ΠΑΠΑΔΟΠΟΥΛΟΣ ΧΡΗΣΤΟΣ**
Καθηγητή του Τμήματος Μηχανολόγων και Αεροναυπηγών Μηχανικών του Πανεπιστημίου Πατρών
5. **ΜΟΥΡΤΖΗΣ ΔΗΜΗΤΡΙΟΣ**
Επίκουρο Καθηγητή του Τμήματος Μηχανολόγων και Αεροναυπηγών Μηχανικών του Πανεπιστημίου Πατρών
6. **ΔΕΝΤΣΟΡΑΣ ΑΡΓΥΡΙΟΣ**
Αναπληρωτή Καθηγητή του Τμήματος Μηχανολόγων και Αεροναυπηγών Μηχανικών του Πανεπιστημίου Πατρών
7. **ΜΑΝΩΛΑΚΟΣ ΔΗΜΗΤΡΙΟΣ**
Καθηγητή του Τμήματος Μηχανολόγων Μηχανικών του Εθνικού Μετσόβιου Πολυτεχνείου

*To my parents,
Nick and Eleni*

ACKNOWLEDGMENTS

Being member for more than 8 years to the Laboratory for Manufacturing Systems and Automation, initially as undergraduate and afterwards as postgraduate student, I had the chance to get involved with real engineering problems. During my postgraduate studies, I had the opportunity to work as research engineer and then as project manager in five European projects. I participated to more than 5 international conferences; I traveled for these reasons more than 40 times and visited 13 countries. Therefore, I would like express my gratitude to Prof. *George Chryssolouris*, Professor in the Department of Mechanical Engineering and Aeronautics and Director of the laboratory, for all these opportunities as well as the precious guidance and education he offered me.

Additionally, I would like to thank the two other members of the three-member advisory committee, Prof. *Pandelaki Spyridon* and Prof. *Anifanti Nikolao* for their valuable and useful advices and guidance for the finalization of my PhD dissertation.

I would like to give a special thank to the Assistant Prof. *Dimitri Mourtzi* as well as to the secretaries *Mrs. Angela Sbarouni* and *Mrs. Vaso Velaora* for their support. Moreover, I would like to deeply thank my friends and colleagues *Dr. John Pandremenos*, *Dr. Konstantinos Salonitis*, *Dr. Panagiotis Stavropoulos*, *Dr. Aristeidis Stournaras*, *Dr. George Michalos*, *Mr. George Dimitrakopoulos*, *Mr. Apostolos Fysikopoulos* and *Mr. Chris Doukas*.

I would like also to thank the technicians of the Machine Shop of the Department of Mechanical Engineering and Aeronautics of the University of Patras *Mr. Nikos Pavlou*, *Mr. Giannis Spyratos* and *Mr. Nikos Spyropoulos* for the hands-on knowledge and advices they offered me all over these years.

Last but not least, I would like to say a big “thank you” to my father *Nikolao* and my mother *Eleni* for their unreserved support, help and understanding all these years.

Ioannis N. Paralikas
Patras, February 2012

COLD ROLL FORMING PROCESS ENERGY EFFICIENCY OPTIMIZATION

SUMMARY

The objective of the current study is the development of an optimization methodology for the energy efficiency of the cold roll forming process. Towards that target, a hybrid modeling approach, utilizing analytical and computational models, is proposed and developed.

The energy efficiency indicator for the cold roll forming process is defined, as taking into account the cold roll forming process as a system with energy inputs and outputs. An analytical model was proposed and analyzed for the calculation of such energy efficiency indicator. Internal deformation work for longitudinal and bending strains and pulling frictional work were taking into account. Validation of the analytical model with experimental data and a sensitivity analysis for cold roll forming process variables are then presented. Furthermore a computational model for the cold roll forming process was proposed and analyzed. Simulation methods and modeling approach are analyzed for both forming and springback analysis. The computational model sections and variables are analyzed and results for longitudinal strains are validated with experimental data.

The aforementioned modeling approaches were integrated within an optimization methodology, which consist of a robust design algorithm and a closed loop checking for quality constraints. A robust design algorithm implementation was proposed utilizing the analytical model, as taking into account the uncertainty of noise factors within computer experiments. Closed loop checking of quality constraints is implemented using computational model and specified process guidelines.

The main outcome of this work is the complete method that was proposed and realized through analytical and computational models. The evaluation of the case study revealed the efficiency and practicality of the suggested approach towards energy efficiency optimization of the cold roll forming process.

ΒΕΛΤΙΣΤΟΠΟΙΗΣΗ ΤΗΣ ΕΝΕΡΓΕΙΑΚΗΣ ΑΠΟΔΟΤΙΚΟΤΗΤΑΣ ΤΗΣ ΔΙΕΡΓΑΣΙΑΣ ΔΙΑΜΟΡΦΩΣΗΣ ΜΕ ΠΕΡΙΣΤΡΕΦΟΜΕΝΟΥΣ ΚΥΛΙΝΔΡΟΥΣ

ΠΕΡΙΛΗΨΗ

Το αντικείμενο αυτής της διατριβής είναι η ανάπτυξη μιας μεθοδολογίας βελτιστοποίησης της ενεργειακής αποδοτικότητας της διεργασίας διαμόρφωσης με περιστρεφόμενους κυλίνδρους. Προς αυτόν τον στόχο, μια υβριδική προσέγγιση μοντελοποίησης, χρησιμοποιώντας αναλυτικό και υπολογιστικό μοντέλο, προτείνεται και αναπτύσσεται.

Ο δείκτης ενεργειακής αποδοτικότητας για την διεργασία διαμόρφωσης με περιστρεφόμενους κυλίνδρους ορίζεται, λαμβάνοντας υπόψη τη διεργασία ως ένα σύστημα με ενεργειακές εισροές και εκροές. Ένα αναλυτικό μοντέλο προτείνεται και αναλύεται για τον υπολογισμό του δείκτη ενεργειακής αποδοτικότητας. Υπολογίζονται το εσωτερικό έργο παραμόρφωσης για διαμήκεις και κάμψης παραμορφώσεις, και έργο τριβής μέσω έλξης του υλικού. Το αναλυτικό μοντέλο επαληθεύεται με πειραματικές παρατηρήσεις και στην συνέχεια πραγματοποιείται μία ανάλυση ευαισθησίας για τις μεταβλητές της διεργασίας διαμόρφωσης με περιστρεφόμενους κυλίνδρους. Επιπροσθέτως, ένα υπολογιστικό μοντέλο για την διεργασία διαμόρφωσης με περιστρεφόμενους κυλίνδρους προτείνεται και αναλύεται. Οι μέθοδοι προσομοίωσης και η προσέγγιση μοντελοποίησης αναλύονται για τις αναλύσεις διαμόρφωσης και επαναφοράς. Τα τμήματα του υπολογιστικού μοντέλου και οι μεταβλητές του αναλύονται καθώς και τα αποτελέσματα για τις διαμήκεις παραμορφώσεις επαληθεύονται με πειραματικά δεδομένα.

Οι εν λόγω προσεγγίσεις μοντελοποίησης ενσωματώνονται σε μία μεθοδολογία βελτιστοποίησης, η οποία αποτελείται από έναν αλγόριθμο εύρωστου σχεδιασμού και έναν κλειστό βρόγχο για τον έλεγχο των ποιοτικών περιορισμών. Η υλοποίηση του αλγόριθμου εύρωστου σχεδιασμού προτείνεται με χρήση του αναλυτικού μοντέλου, παίρνοντας υπόψη την αβεβαιότητα των μεταβλητών θορύβου σε πειράματα με H/Y . Ο κλειστός βρόγχος για τον έλεγχο των ποιοτικών περιορισμών χρησιμοποιεί το υπολογιστικό μοντέλο και συγκεκριμένες οδηγίες διεργασίας.

Το κύριο αποτέλεσμα αυτής της εργασίας είναι η πλήρης μεθοδολογία που προτείνεται και πραγματοποιείται μέσω αναλυτικού και υπολογιστικού μοντέλων. Η αξιολόγηση της εφαρμογής της μεθοδολογίας σε βιομηχανικό προϊόν αποκάλυψε την αποτελεσματικότητα και την πρακτικότητα της προτεινόμενης προσέγγισης για την βελτιστοποίηση της ενεργειακής αποδοτικότητας της διεργασίας διαμόρφωσης με περιστρεφόμενους κυλίνδρους.

TABLE OF CONTENTS

ACKNOWLEDGMENTS.....	V
SUMMARY.....	VII
ΠΕΡΙΛΗΨΗ.....	VIII
TABLE OF CONTENTS.....	XI
1 INTRODUCTION	1
1.1 COLD ROLL FORMING PROCESS ATTRIBUTES	1
1.2 COMPETITIVENESS OF COLD ROLL FORMING PROCESS	4
1.3 ADVANCED MATERIALS AND APPLICATIONS OF COLD ROLL FORMING PROCESS	7
1.4 PROBLEM DEFINITION	13
1.5 SUGGESTED SOLUTION – SCIENTIFIC CONTRIBUTION	15
1.6 DISSERTATION’S ROADMAP.....	18
2 LITERATURE REVIEW	21
2.1 SHEET METAL FORMING PROCESSES OPTIMIZATION APPROACHES	21
2.2 COLD ROLL FORMING PROCESS MODELING APPROACHES	27
2.3 DISCUSSION	29
3 COLD ROLL FORMING PROCESS ENERGY EFFICIENCY	31
3.1 ENERGY EFFICIENCY INDICATOR OF COLD ROLL FORMING PROCESS.....	31
3.2 ANALYTICAL MODEL FOR INTERNAL DEFORMATION WORK.....	34
3.2.1 <i>Bending strain rate</i>	34
3.2.2 <i>Bending work</i>	39
3.2.3 <i>Longitudinal stretching work</i>	39
3.3 ANALYTICAL MODEL FOR PULLING-FRICTIONAL WORK.....	41
3.4 VALIDATION AND SENSITIVITY ANALYSIS OF ANALYTICAL MODEL FOR ENERGY EFFICIENCY INDICATOR OF COLD ROLL FORMING PROCESS	45
4 COLD ROLL FORMING PROCESS MODELING.....	53
4.1 COMPARISON OF SIMULATION METHODS AND MODELING APPROACH.....	53
4.2 COLD ROLL FORMING SIMULATION MODEL	57
4.2.1 <i>Element type</i>	57
4.2.2 <i>Material models for deformable strip and tooling</i>	57
4.2.3 <i>Contact, boundary and loading conditions</i>	59
4.2.4 <i>Meshing convergence</i>	60
4.3 COLD ROLL FORMING SIMULATION MODEL VALIDATION	62
5 COLD ROLL FORMING PROCESS ENERGY EFFICIENCY OPTIMIZATION.....	65

5.1	ROBUST DESIGN METHODOLOGY THROUGH HYBRID MODELING APPROACH	65
5.2	QUALITY CHARACTERISTICS CONSTRAINTS AND PROCESS GUIDELINES / COUNTERMEASURES	68
6	CASE STUDY	75
6.1	U-CHANNEL PROFILE – IDENTIFICATION OF VARIABLES AND BENCHMARK.....	75
6.2	ROBUST DESIGN SIMULATION AND DATA ANALYSIS FOR ENERGY EFFICIENCY INDICATOR	80
6.3	VERIFICATION OF THE QUALITY CHARACTERISTIC CONSTRAINTS	83
6.4	BENCHMARK ANALYSIS FOR THE U-CHANNEL PROFILE	90
7	CONCLUSIONS	93
7.1	FURTHER WORK.....	95
REFERENCES		97
APPENDIX A	NOMENCLATURE	103
APPENDIX B	LIST OF FIGURES	107
APPENDIX C	LIST OF TABLES.....	111
APPENDIX D	- ORTHOGONAL ARRAYS FOR CONTROL AND NOISE FACTORS AND S/N RATIOS	113
BRIEF BIOGRAPHICAL NOTE – PUBLICATIONS		119

1 INTRODUCTION

Objective of the present PhD dissertation is the development of the robust design optimization methodology for the energy efficiency of the cold roll forming process, utilizing a hybrid modeling approach. In this chapter, the description of the cold roll forming process, its competitiveness and advanced materials applicability are provided. Furthermore the problem being solved and the suggested approach and solution followed are presented. The scientific contribution of the dissertation is also discussed. The chapter closes by presenting the dissertation's roadmap.

1.1 Cold roll forming process attributes

Cold roll forming is a major sheet metal forming process for the mass production of a variety of complex profiles from a wide spectrum of materials and thicknesses. According to Chryssolouris (2005) and Lange (1985) roll forming process is classified into the category of sheet metal forming by bending with rotary tool motion. The plastic deformation of a solid body is achieved by means of a bending load. The metal strip enters into the roll forming mill, in a precut or coil form, and it is gradually formed through consecutive contoured rolls into complex shapes (Figure 1). Three dimensional deformations of the material include transversal bending and other additive redundant deformations. Panton et al. (1996) calculated analytically the development of longitudinal and shear strains during the roll

forming process. Also Panton et al. (1996) stated that longitudinal stains are produced at the flange, as the outer edge travels a greater distance than the web does through successive rollers (Figure 2).

Figure 1: Roll forming process (schematics)

Figure 2: Outer edge travels greater distance than web through successive rollers

Panton et al. (1996) have also discussed that both the longitudinal and the shear strains cannot be simultaneously minimized, but instead, a compromise between them should be made. Defects on products such as bow, twisting, edge waviness (buckling) and edge cracking are caused mainly on these redundant deformations, namely the longitudinal bending and elongation, the transversal elongation and the shear in strip's plane and thickness direction (Halmos, 2006).

Rolls are the tools that form the strip into the desired shape and turn it into roll-formed products. The design of the forming steps is called flower pattern and shows the subsequent bending of profile from one roll station to the other (Figure 3).

Figure 3: Typical flower pattern for a roll formed profile

Several factors have to be taken under consideration when designing the rolls that would form a particular product. These include the number of passes required, the material width, the flower pattern design, the roll design parameters and the roll material (Wick et al. 1984). The number of passes required is estimated, based on material properties, thickness of the strip and complexity of the profile to be produced (Halmos, 2006), (Wick et al. 1984). The strip width can be calculated from the profile drawing, based on the bend allowances calculated, the arc lengths of the curved elements and the straight lengths of the shape (Alvarez, 2006). The flower pattern design and orientation comprise the initial step of the roll tooling design and represent the designated flow of material into the mill, based on the number of passes required. The roll design parameters include the design of the rolls around each overlay of the flower pattern, and the considerations for the diameter of the rolls as well as the desired tolerances (Halmos, 2006).

Cold roll forming process shows several key characteristics that make it rather competitive for the mass production of straight profiles. It has low investment cost compared with other profiling processes, such as deep drawing. Its production speed can reach 30-60 m/min of produced profile, which makes it suitable for mass production. Tooling has low maintenance cost and provides very good dimensional stability of complex profiles. Roll forming mills shows flexibility in tooling changes and tooling adjustability with no cost and low setup times (Figure 4). Moreover profiles at any length can be produced with no additional cost (cut-at-length). On the other hand, only straight profiles can be produced with open ends, and experienced specialized engineers and designers are required for the production of very complex profiles.

Figure 4: Cold roll forming flexibility in tooling changes, tooling adjustability with no cost and low setup times

1.2 Competitiveness of cold roll forming process

Although cold roll forming process is an old process, which has a long history over a half of century, it is still in extensive usage due to its equipment simplicity, low cost and significant potential advantages against other processes. The development and the introduction of new high-strength and advanced high-strength materials into roll forming process, has increased the interest and spread the usage of cold roll forming process.

The competitiveness of cold roll forming against other profiling process, such as press brake bending, extrusion and deep drawing processes is discussed within current section. Several performance measures were listed for the evaluation of such profiling processes. These measures are: **i)** material utilization rate, **ii)** ability of the process to produce complex straight profiles, **iii)** materials applicability range and thicknesses, **iv)** production line speed, **v)** cost effectiveness of the process based on investment and tooling cost, **vi)** ability of the process to produce variable cross sectional profiles, and **vii)** the flexibility of the process in configuration changes for production of different profiles and setup. Evaluation has been implemented with utilization of a ranking system from “5 to 1” as indicating “Excellent” to “Not Good” rating to performance measures respectively (Figure 5).

Performance measures	Cold Roll Forming	Press Brake Bending	Extrusion	Deep Drawing
Material Utilization rate	4	2	5	2
Complex profiles	4	1	5	4
Materials range	5	5	4	5
Production speed	5	1	4	2
Cost effectiveness	4	5	3	2
Variable profiles	1	1	1	5
Flexibility	4	5	2	2
TOTAL	27	20	24	22

5 : Excellent 4 : Very Good 3 : Good 2 : Average 1 : Not good

Figure 5: Comparison of profiling process within ranking system (1 to 5) for different performance measures

Material utilization rate is a measure of material and resources effectiveness of the profiling process, and measures the ratio of the used material to the scrap material. Cold roll forming has “Very good: 4” material utilization rate with about 90-95%, as producing profiles directly to coils. Press brake bending has “Average: 2” material utilization rate due to the need to blanking of the required material with about 70%. Extrusion process has “Excellent: 5” material utilization rate of material due to the usage of billet and pushing all the material through the die with above 95%. Deep drawing shows “Average: 2” material utilization rate as blanking takes place before pressing and trimming also after pressing, that leads to about 60-70% utilization rate.

Complex profiles production is a main aspect in profiling processes, as providing applicability and integrated design with reduced number of parts. Cold roll forming has “Very Good: 4” ability of producing complex profiles, but with some limitation within inner features and open ends. Press brake bending has “Not Good: 1” ability of producing complex profiles, as many bending steps are required with many geometrical limitations in tooling positioning. Extrusion process has “Excellent: 5” ability of producing complex profiles, as almost profile cross section can be produced but with open ends. Deep drawing has “Very Good: 4” ability of producing complex profiles with closed ends, but shows some limitation to inner features.

Materials range applicable to process is an important issue for industrial applications as well as allowable wall thicknesses. Cold roll forming, press brake bending and deep drawing show “Excellent: 5” materials range usage, as any ferrous and non-ferrous metals can be used in a wide range of thicknesses. Extrusion shows “Very good: 4” materials range applicability due to some limitations in material thicknesses and material types.

Production speed affects process productivity as a critical performance measure of profiling processes in mass production. Cold roll forming process has “Excellent: 5” production speed with achievable high continuous production speeds up to 60m/min. Press brake bending has “Not good: 1” production speed as for complex profiles several bending steps are required. Extrusion process has “Very good: 4” production speed, very close to cold roll forming, but some limitations with die maintenance, die cleaning and setup timing. Deep drawing process has “Average: 2” production speed as a non continuous pressing process with multiple pressing stations for complex profiles and springback compensation.

Cost effectiveness measures the investment cost and the operational cost of each process. Cold roll forming shows “Very Good: 4” cost effectiveness, as has low investment cost for machine and tooling and low maintenance and operational cost due to integration of automations. Press brake bending has “Excellent: 5” cost effectiveness as showing a minimal investment cost with little operational cost. Extrusion process has a “Good: 3” cost effectiveness as increased investment costs and high energy demands for extrusion of steel and aluminum. Deep drawing process has “Average: 2” cost effectiveness with high investment and tooling costs.

Variability in cross section along longitudinal axis of profiles can provide evitable advantages in applications with increased stiffness and reduced weight. Cold roll forming, press brake bending and extrusion can produce only straight cross sectional profiles with “Not good: 1” ability for variability. Deep drawing process shows “Excellent: 5” ability to produce variable cross sectional profiles at any geometry with closed ends.

Flexibility in tooling changes, line setup and adaptability for producing different profiles is one of the main aspects for the competitiveness of profiling processes. Cold roll forming process shows “Very good: 4” flexibility in tooling changing and adjustability with low cost and setup times. Press brake bending shows “Excellent: 5” flexibility as it can produce any profile with same tooling in different steps and fully adjustable. Extrusion and deep drawing processes show “Average: 2” flexibility in tooling changes, as longer setup times required and low adjustability of tooling to different profiles geometries production.

Within current general evaluation cold roll forming is considered as the most effective and suitable profiling process. Such an evaluation is considered to be general and may differ for each application characteristics, based on the production volume, material type and customer demands.

1.3 Advanced materials and applications of cold roll forming process

Cold roll forming process can process almost any ferrous and non ferrous metallic sheet and alloys, such as steel, stainless, aluminum, copper, etc. Most common materials to be roll formed are steel and aluminum, as being also widely used in automotive industry for the manufacturing of structural profiles.

Figure 6: Overview of materials used in cold roll forming process in automotive industry (blue boxes) (Futura IP, 2008)

The introduction of Advanced High Strength Steels (AHSS), such as DP-series, has emerged several challenges and accentuated plenty of existing processing limitations. Main challenges using AHSS cover increased the springback effect and the cracking on the bending edge, due to lower formability and higher strength of such materials. Processing limitations accentuated such a development of longitudinal strains along the roll forming line and shear strains along the strips plane. These challenges and limitations can result in the magnification of defects, such as edge waviness, cracking and cross sectional deviation, due to buckling of the material within successive roll stations and the accumulation of residual strains. Moreover, the cost of such materials is higher than that of the traditional mild steels or HSLA steels, but their interest in application has been increased due to their potential for lightweight design and crashworthiness.

The overview of the materials used in automotive industry (blue color into Figure 6) is presented, as steel from mild to ultra high strength and aluminum 5000 and 6000 alloys are used. Such materials are distributed among the structural parts of an automotive Body-in-White based on the desired characteristics for strength, stiffness; crash and lightweight (Figure 7).

Figure 7: Evaluation matrix of different materials and application fields into automotive BiW (Futura IP, 2008)

This increase of interest and usage from automotive makers for such advanced materials is depicted within Figure 8. The usage of mild steels has been reduced and replaced from more advanced materials with higher strength, such as AHSS, UHSS and HSS. This is done for achieving increased strength, stiffness, crash performance and lightweight of the automotive Body-in-White (BiW).

Figure 8: Evolution of materials concepts for evolution of Mercedes-Benz C-Class (BR203 to BR204) (AHSS: Advanced High Strength Steels, HSS: High Strength Steels, UHSS: Ultra High Strength Steels) (Futura IP, 2008)

Cold roll forming process can produce structural parts from AHSS with (World Auto Steel, 2011):

- Steels with all levels of mechanical properties and different microstructures
- Springback compensation without particularly complex tools
- Small radii depending on the thickness and mechanical properties of the steel
- Reduced number of forming stations compared with lower strength steel (tooling cost reduction)

Moreover the forces onto rollers and frame are higher, due to the increased yield point of such materials. A rule of thumb says that the force is linear with the strength but square with the thickness (World Auto Steel, 2011), (Halmos, 2006). The AHSS is a class of steel material with tensile strength into range of 500-800 MPa, as shown with yellow and green color into Figure 9. AHSS shows same and higher strength with High Strength Low Alloy steel (HSLA) but higher formability. This is due to the microstructure of AHSS, such as Dual Phase steel (DP-series), which consists of different phases. Work hardening rate and excellent elongation creates DP steels with much higher ultimate tensile strengths than conventional steels or similar yield strength (HSLA).

Figure 9: Schematic of AHSS steels (shown in color) compared to low strength steels (dark grey) and traditional HSS (light grey) (World Auto Steel, 2011)

AHSS are distinguished into different types, such as Dual phase (DP), Transition Induced Plasticity (TRIP), and Partial Martensitic (PM) (Figure 10).

	Micro Alloyed Steel	Dualphase Steel	Transition Induced Plasticity Steel	Partiell Martensitic Steel	Partiell Martensitic Steel
	H320LA (ZE340)	HCT600X (DP600)	HCT700T (TRIP700)	HCT800C (PM800)	HCT1000C (PM1000)
Yield Strength $R_{p0.2}$ min	340 MPa	340 MPa	430 MPa	ca. 650-750 MPa	ca. 850-900 MPa
Tensile Strength R_m min	410 MPa	600 MPa	700 MPa	800 MPa	1000 MPa
Elongation A_{80}	30 %	23 %	28 %	10 %	8 %
Micro structure	Ferrit + Precipitation	Ferrit + Martensite(<20%)	Ferrit + Bainite + Austenite	Ferrit + Bainite + Martensite	Ferrit + Bainite + Martensite
<div style="display: flex; justify-content: space-around;"> Ferrit Martensite </div> <div style="display: flex; justify-content: space-around;"> Bainite Austenite </div>					

Figure 10: Properties and microstructure of the AHSS categories (World Auto Steel, 2011)

The most promising, in terms of applications and interest, currently is the DP steels. DP steels consist of a ferritic matrix containing a hard martensitic second phase in the form of

islands. The soft ferrite phase is generally continuous that gives to DP steel great ductility. Increasing the volume fraction of the hard second phases generally increases the strength, and different grades can be produced as shown from the properties of Table 1. DP steels exhibits higher initial work hardening rate, higher ultimate tensile strength, and lower YS/TS ratio than the similar yield strength HSLA. Moreover they have a bake hardening effect, which is the increase of the yield strength resulting from elevated temperature after pre-straining. The extend of bake hardening effect depends on the specific chemistry and thermal histories of the steel.

Table 1: Mechanical and forming properties of DP steels series (DP450-DP980) (Futura IP, 2008)

Property	Units	DP-450	DP-500	DP-600	DP-780	DP-980
Elastic modulus	Mpa	1.8844 e5	1.8844 e5	1.8844 e5	1.8844 e5	1.8844 e5
Density	kgr/mm ³	7.87E-06	7.87E-06	7.87E-06	7.87E-06	7.87E-06
Poison ratio	-	0.295	0.295	0.295	0.295	0.295
Yield stress (YS)	MPa	300	351.61	391.778	495.33	636.7
Tangent modulus	MPa	962.2460	1263.369	1929.6897	2260.7293	3582.04
		77				
Strain rate C	s ⁻¹	37146.5	58488.059	1041549.4	196815.04	238930
Strain rate P	-	3.2319	3.24461	3.63399	4.09168	3.45426
Total elongation (TE)	-	0.2846	0.2734	0.214	0.1808	0.1543
Strength Coef. - K	-	788.2	956.65	1120	1260	1566.59
Hardening Coef. - n	-	0.1916	0.19	0.171	0.15	0.14
Initial YP strain (EYP)	-	0.001463	0.0017152	0.0019111	0.0024162	0.00308
R ₀₀	-	1.26	1.374	1.24	0.881	1.12
R ₄₅	-	1.16	0.92	0.873	0.953	1.27
R ₉₀	-	0.96	1.11	1.08	0.711	1.05
Ultimate Tensile Stress (UTS)	Mpa	466.6	570.28	671.33	807.5	1003.48
Ultimate Elongation (UE)	-	0.1746	0.1748	0.14678	0.1405	0.1055

Roll forming, as a metal fabricating process, is used in many diverse industries to produce a variety of shapes and products. Roll forming is a desirable process since it adds both strength and rigidity to lightweight materials. Some industries that frequently use roll-formed

products include: aerospace, automotive, appliances, building/construction, infrastructure and further applications (Figure 11).

Figure 11: Cold roll forming process applications

An efficient and flexible application of cold roll forming of AHSS within automotive industry is the application of modularity and scalability of profiles within BiW sills. From a common cold roll forming mill, two different sills can be produced at two different lengths with no extra cost or extra tooling (Figure 12). This “cut-at-length” concept can provide great flexibility and lowering cost within automotive industry.

Figure 12: Roll formed automotive BiW sills and scalability for different floor lengths

1.4 Problem definition

Natural resources, such as raw materials and fossil fuels, are of limited capacity. Climate change is already happening and one major factor is extensive usage of fossil fuels for producing energy as powering manufacturing industry and other sectors. Globalization of manufacturing has become more and more profound during last decade as developing economies, such as China and India, are “taking over” manufacturing. Impact of manufacturing on environment is increased as more goods are needed to be produced; more energy and natural resources are needed to be consumed. Global energy demand in total has increased by 36% over the last 40 years (International Energy Agency, 2010), and projections are expected to be increased more until 2020 (Figure 13).

Cold roll forming process is an old process and its history started with the first cold roll forming mill on the end of 1910s, and until mid 1960s developments were based only on empirical knowledge and experience. At mid 1960s the first fundamental research on cold roll forming process started, until 1980s when the first CAD/CAE tool for cold roll forming process was introduced. From mid 1980s the scientific knowledge started as the initial finite elements model (FEM) introduced at start of 2000s with also cold roll forming process total management tools. Cold roll forming process still has not an insight research and lack of optimization methods applied existing. Main issue nowadays is the study of process mechanics and redundant deformation of such a complex 3D bending process, utilizing mainly computational technology.

Figure 13: Historical evolution of the cold roll forming process and energy consumption by sector

It is profound that there is a need of further scientific development and optimization of cold roll forming process towards the global needs and trends of manufacturing sector. Cold roll forming optimization methods need to be oriented towards energy reduction and better utilization of resources. Thus it is important to consider not only energy consumption reduction, but an overall process energy efficiency.

Figure 14: Cold roll forming process energy efficiency pylons and optimization targets

There is a need of optimizing manufacturing processes towards energy efficiency for “Producing more with Less” (Chryssolouris, 2005) under the prism of four pylons: **i)** materials, **ii)** energy, **iii)** waste and **iv)** production. Cold roll forming process should be optimized for integration of advanced materials, such as AHSS, for lightweight profiles as maintaining quality standards. Energy consumption should be reduced as taking into account also energy losses in whole process level. Material utilization rate of cold roll forming process should be exploited with proper line configuration and design. Productivity, measured as production rate, should be also maximized, as increasing process flexibility with proper design. Therefore three main target are emerged for the cold roll forming process energy efficiency optimization as: **i)** lowering energy consumption and losses, **ii)** increasing production rates as lowering cycle time, and **iii)** maintain desired quality characteristics with advanced materials integration (Figure 14).

1.5 Suggested solution – Scientific contribution

Based on the afore-mentioned pylons and optimization targets, the energy efficiency indicator of cold roll forming process has been defined as the ratio of the production rate to the energy consumption of the roll forming mill. A hybrid modeling robust optimization methodology is suggested as solution to the afore-described problem, as shown into Figure 15. Such hybrid modeling robust optimization methodology is utilizing two models: **i)** an analytical energy model for the calculation of the energy efficiency indicator as implementing the robust design algorithm, and **ii)** a computational model (FEM) for checking quality constraints.

Figure 15: Energy efficiency optimization methodology for the cold roll forming process

Within such optimization approach control and noise variables of the manufacturing system / process are defined. Based on such variables, the Design of Experiments (DoE) is constructed and the robust design algorithm is implemented using the analytical model for the energy efficiency indicator calculation. Data analysis from the robust design algorithm provides the first optimum solution [R1]. The computational model (RF FEM#1) for such optimum solution [R1] is constructed and quality characteristic constraints are checked. If these quality characteristic constraints requirements are not met, the control variables (design and process variables) are alternated based on process guidelines / countermeasures. Then a second optimum solution is generated [R2]. Such second optimum solution [R2] is compared with the first optimum [R1] from the robust design algorithm. A second computational model (RF FEM#2) is constructed and checked again against quality characteristic constraints. If the quality characteristics are met, the closed loop is finalized and the feasible and energy efficient solution is provided.

This approach lies in the efficient, computational inexpensive, practical and integrated approach for energy efficiency optimization. Current approach for the optimization of a manufacturing system / process using computer experiments is shown within Figure 16. After setting the optimization problem setup, the analysis of DoE is implemented using

computational models. The DoE execution results are used for building and verifying a meta-model (mathematical approximation). Then an optimization algorithm is implemented as to calculate the optimum solution.

Figure 16: Current approach for optimization using computer experiments

Proposed approach for optimization using computer experiments, instead of building and verifying a meta-model, is using an analytical model for the implementation of the robust design algorithm. Within such robust design algorithm the optimum solution is calculated, taken into account the uncertainty of the noise factors. Using the proposed approach significant computational time savings could be achieved.

Figure 17: Proposed approach for optimization using computer experiments

The key innovations of the dissertation are listed hereafter:

- Introduction and definition of the “*Energy efficiency indicator*” for cold roll forming process
- Introduction and development **for the first time** of an analytical model for cold roll forming process “*Energy efficiency indicator*” calculation
- Development for **the first time** of:
 - ✓ Hybrid modeling optimization approach (analytical and computational) for the cold roll forming process towards the energy efficiency indicator
 - ✓ Identification of the most “energy efficient” control process parameters, under uncertainty of noise factors
 - ✓ Identification of the number of roll passes required for energy efficiency, as previously calculated using equations with empirical factors

1.6 Dissertation’s roadmap

The dissertation is structured as follows:

Into **Chapter 2** the literature, relative to the topics of the dissertation, is comprehensively reviewed. The review is divided into two sections. In the first section, the review optimization methods of manufacturing systems / process and especially in the field of sheet metal forming and cold roll forming, is presented. In the second section, the modeling approaches and methods of the cold roll forming process are discussed.

Into **Chapter 3** the “*energy efficiency indicator*” for the cold roll forming process is defined. The analytical model for the calculation of such “energy efficiency indicator” is analyzed. Analytical model attributes are discussed and analyzed for the calculation of kinetic energy, deformation internal energy and frictional-pulling energy sectors. Analytical model for the calculation of the energy consumption of cold roll forming process is validated with experimental measurements over literature.

Chapter 4 deals with the computational modeling of the cold roll forming process. Modeling approach is presented and compared with other methods from literature. Cold roll forming process computational model attributes are then described and analyzed for explicit dynamics model. Such a computational model is then studied for results convergence and validated with experimental results for longitudinal strains response output.

Into **Chapter 5** the cold roll forming process energy efficiency indicator optimization approach and methodology is described and analyzed. The optimization problem for energy efficiency is defined and the “p-diagram” is constructed. The robust design algorithm is then analyzed and the quality characteristic constraints are described. Process guidelines / countermeasures are then analyzed for the alternation of process parameters during the closed loop for meeting quality characteristic constraints.

Into **Chapter 6** the application and demonstration of the aforementioned optimization methodology within a U-channel case study is described. The optimization problem is set and described for the U-channel case study and DoE is analyzed. Results from the robust design algorithm are provided utilizing the analytical model for the “energy efficiency indicator” calculation. Then the quality characteristic constraints are checked, through computational model, for the optimum solution and revised based on the process guidelines. The two computational model results are then compared regarding the quality characteristic constraints.

Appendices A, B, C and D contain the nomenclature utilized in the dissertation, the list of figures and tables as well as orthogonal arrays for control and noise factor and S/N ratios results regarding the case study demonstration of the optimization methodology

2 LITERATURE REVIEW

In the present chapter, the available literature relative to optimization approaches for sheet metal forming processes with focus on profiling, and especially cold roll forming modeling approaches are reviewed in detail. The chapter consists of three sections. The first section deals with the review of the optimization approaches for sheet metal forming processes with focus of profiling. The outcome of such a review is presented within a qualitative manner for the main four optimization approaches. The second section deals with the review of the modeling approaches of the cold roll forming process and the outcome of such modeling approaches. Finally, the third section deals with the overall outcome of the literature review, as pointing out the main points of the current dissertation contribution against current literature status.

2.1 Sheet metal forming processes optimization approaches

Optimization of manufacturing processes, such as sheet metal forming processes, has been brought into attention as globalized competition is in full growth for reducing production cost; ensure and enhance product quality and meeting safety and environmental requirements. Into industrial situation, optimization procedure should handle complex systems in accurate and affordable way. Uncertainty of a model derives from trying to fit a simplified model to a more complex process system. Two main classes of optimization exist to handle uncertainty:

i) *robust optimization*, if there is lack of measurements as to guarantee feasibility for the entire range of expected variations, and ii) *real-time optimization*, if measurements are available and system can be adjusted to process changes and disturbances (Chachuata et al. 2009).

Experimental design and optimization of manufacturing processes is important into industrial practices as leading to i) improve process yield, ii) improve the quality of the products as reducing variability and increase reliability, iii) reduce development time and iv) reduce the overall costs. An efficient experimental design must reduce the number of experiments and acquire as much information as possible. This can be done only with *robust optimization*, as statistical analysis of acquired data is employed as to achieve predefined goals. Experiments can be classified as “Physical experiments” and “Computer experiments”.

Physical experiments are experiments to be implemented into a laboratory with specified boundary conditions. This kind of experiments has random error and different responses may be obtained even if the same conditions were applied. This adds complexity and difficulty in gathering and analyzing experimental data. For that reason, development time using physical experiments is rather high and reliability of the optimization can be reduced. Rather high costs are occurring due to hardware and measurement systems costs. Flexibility of physical experiments in changes of the system model is quite low, as any change may incur additional costs, and increase development time and random errors.

Computer experiments have been used extensively during the last decade and have represent physical experiments utilizing sophisticated computer codes. Characteristics of computer experiments against physical experiments are (Fang et al. 2006):

- Computer experiments can involve a larger number of variables compared to those of physical experiments
- Larger experiment domain or design space is employed as to explore complicated non-linear functions
- Computer experiments are deterministic and have always the same random error, as with the same inputs a determined output will be produced.

Optimization procedure using “computer experiments” can reduce significantly hardware and measurement costs, and increase flexibility in model change as any change of the computer model can be done explicitly. But computer experiments, and especially representing complex systems, may require high computational time and processing of data. Validation and verification of computational models may be required against physical experiments, as these costs and time are added to the optimization procedure. Thus computational time using computer experiments may be bigger than implementing physical experiments, especially using complex models.

One goal of computer experiments may be to find an approximate model, as “meta-model” (model of the model), using empirical mathematical formulations and Design and Analysis of Computer Experiments (DACE). The fundamental idea of meta-modeling technique is to find an empirical approximation model, which can be used to describe the typically unknown relation between input variables and response values of a process or product (Jurecka, 2007). In other words a metamodel can provide continuous responses over the space domain, as computer models or physical experiments cannot provide. This can lead to reduction of optimization time, as providing also increased information level and a more robust optimization as using rational computational time (Felli, 2008). Cost of preparation of such metamodels relies on the expression of the problem, stating of the responses and inputs and verification of the metamodel against the computer or the physical model. In the optimization context, approximations either allow for the analytical determination of the approximate optimum or they replace the original functions within one or in the course of several iteration steps (Jurecka, 2007). Three types of approximations can be distinguished for the metamodels (Barthelemy and Haftka, 1993):

- *Local approximations*: valid only in the immediate vicinity of the observed point
- *Mid-range approximations*: trying to predict the original function response in a well-defined sub-region of the design space
- *Global approximations*: aim at predicting the characteristics of the responses over the entire design space

Several studies have been presented for major sheet metal forming processes optimization for profiles production, such as stamping, cold roll forming, hydroforming, etc. Hou et al. (2010) prepared a stochastic analysis and an optimization based on Response Surface Methodology

(RSM) metamodeling technique for the stamping process of a deck lid inner panel from steel. Zeng et al. (2009) carried out a study for the roll forming process optimization using also RSM. The effects of bending angle increment and roll radius on springback angle, and maximum edge membrane longitudinal strains were studied. Hu et al. (2008) applied the Adaptive Response Surface Methodology (ARSM) into practical problems of sheet metal forming process for mathematical meta-modeling of highly non-linear problems. Sun et al. (2010) used multi-objective robust optimization for the designing of the bead of stamping process. Metamodel techniques such as Dual Response Surface Methodology (DRSM) were used as to consider the estimation of the mean and the standard deviation of the responses of the model. Tang and Chen (2009) investigated how the stochastic variation of noise factors affects the stamping process quality. Robust design models were implemented with integrated adaptive response sampling and response surface method as to minimize the impact of variations and achieve reliable process parameters. Ingarao et al. (2009) managed to integrate numerical simulation, response surface methodology and Pareto optimal solution search techniques within the design of a complex Y shape tube profiling through hydro-forming process. Oh and Kim (2008) analyzed and optimized the roll forming of a slide rail, having set the pass with largest deformation as target pass and the position and shapes of the rolls as design variables. Cost function minimized for satisfaction of design constraints with the use of design of experiments and RSM. Wei and Yuying (2008) studied a Pareto-based multi-objective genetic algorithm as to optimize sheet metal stamping process. Process parameters, such as blank holder force and draw bead restraining force were optimized having as objective functions the fracture, wrinkle, insufficient stretching and thickness variation. Donglai et al. (2008) proposed a method, based on adaptive response surface model, for optimization of sheet metal forming process parameters and predict the performance tolerance including effects of variability of noise factors. A stochastic and an adaptive response surface model were established as to figure out the uncertainty of performance caused by the variation of noise factors. Bonte et al. (2008) proposed a generally applicable optimization strategy for industrial metal forming processes that makes use of FEM simulations. Li et al. (2007) developed a novel intelligent optimization approach that integrates machine learning and optimization techniques. A machine learning method based on the rough set theory is integrated with a gradient based algorithm and RSM under the scope of improving robustness and efficiency of optimization. Jakumeit et al. (2005) performed an optimization of process parameters in deep drawing process using a new optimization Kriging strategy. The parameterized time-dependent blank holder force was used as to control the deep drawing

process. Zhang et al. (2003) prepared a simulation model for the flat surface-straight edge hemming process, and numerical simulations were used based on DoE and Latin Hypercube Sampling.

Most studies for robust design optimization of sheet metal forming processes were implemented using mathematical meta-modeling and optimization algorithms in order to take into account the variation of noise factors. Such approach however, is impractical for industrial practice, since building, verifying of meta-models and developing optimization algorithms is rather complicated due to the need of extensive experimental or computational efforts. Thus, an alternative approach for the robust design optimization of processing should be proposed that should be practical and covering wide range of applications. Moreover, regarding the cold roll forming process it seems that there is not an existing approach for the robust optimization towards the energy efficiency.

Into the following Figure 18, a qualitative comparison over development time and computational cost (in qualitative form) and respective main characteristics are presented for optimization using physical, computer experiments, approximation meta-models, and proposed hybrid modeling approach.

Figure 18: Qualitative comparison of optimization methods - using physical experiments computer experiments, meta-models and hybrid modeling procedures - for development time and computational cost

Within physical experiments, although accurate results can be measured and there is lack of approximation errors, high preparation time and investment costs are required. For avoiding large measurement errors, development time is increasing for preparing physical experiments execution. Moreover, such approach provides very low flexibility in changes and model alternation and requires a low computational cost.

Computer experiments can reduce the investment cost significantly, as few hardware expenses are required. Such approach is quite flexible in changes and model alternations, as a computer model can be alternated virtually. Large and complex non-linear problems are requiring high computational time for simulated over computer experiments. Discrete results are provided with a certain approximation error. Moreover, as reducing and monitor such approximation error there is a need of verification and validation (V&V) of such models with respective physical experimental results.

Optimization approach using meta-modelling techniques (mathematical approximations) can provide quick and continuous response over the domain. There is a need to “build” and verify a meta-model for a specific computer experiment for specific variables and ranges. Verification of meta-model may require a computational expensive procedure with a large number of computer experiments, as assuring that approximation error is within acceptable limits over the optimization domain. Once such meta-model has been “built” and verified, it can provide continuous results over the variables ranges. An additional optimization algorithm should be developed as to solve the optimization problem over specific constraints.

Within proposed hybrid modelling optimization approach a prompt response can be calculated through the analytical model. Such analytical model once has been verified for a simple profile, can be adjusted to any geometrical requirements without further verification. Moreover, it can provide high degree of adjustability and flexibility in changes, as it provides very low computational cost. Approximation errors in analytical model may exist due to ignorance of complex physical phenomena, but verification of the model with respective experimental conditions can restrict the error within desired limits. Moreover, there is a need of computational model preparation and verification for checking only constraints for the calculated optimum response through the robust algorithm.

2.2 Cold roll forming process modeling approaches

Cold roll forming process modeling is a high non-linear problem (bending in three dimensions) and required quite large and computational expensive computer modeling approach. Several studies have been carried out for the simulation of the roll forming process. Over the last decade, the interest in simulating and accurately predicting the deformations during the roll forming and the geometrical characteristics on the final product has been increased. The introduction of new materials, such as the AHSS, into an “old” process has brought about new challenges and accentuated existing processing limitations. Paralikas et al. (2009) and Salonitis et al. (2008) prepared a simulation model for the roll forming process that can predict redundant deformations, such as transverse and longitudinal strains and distribution onto the cross section, as well as the final produced geometry. The LS-Dyna code was used along with the solid elements for the deformable strip. A V symmetrical section was simulated, as the strip was pulled through the rigid rolls. The main process parameters, such as line velocity, roll gap, rolls diameter, friction and distance between the passes, were investigated as to their effect on undesired deformations during roll forming. It was concluded that the inter-distance of the forming passes has a major influence on the magnitude of the main redundant deformations. Paralikas et al. (2010) prepared an optimization method of the roll forming process based on semi-empirical approach and the Taguchi method. The responsibility of main roll forming process parameters on main redundant deformations was calculated for a U-shaped profile. Jeong et al. (2007) has carried out a simulation analysis for the roll forming process so as to compare two different flower patterns for the upper member of a rail mechanism. The design of the two flower patterns was performed and then simulated with the use of the SHAPE-RF. This roll forming analysis program exploits the rigid-plastic finite element method. Prediction of longitudinal strains along the roll forming direction and the estimation of straightness were compared for the two flower designs leading to a conclusion for the prevention of defects on the roll-formed product. Bui et al. (2007) presented a three-dimension finite element analysis in order to simulate the roll forming process. The simulation results, for longitudinal strains at the edge of the strip, were compared with the experimental ones, and were found in good comparison. A U-shape section was studied by using a rigid-plastic model and Swift’s isotropic strain hardening law so as for the material’s behavior to be described. A parametric study was implemented where the yield limit and work-hardening exponent play a major role on the product’s quality. The forming speed and the friction were found to have less influence on

the product's quality. Lindgren (2007a) prepared a simulation model in order to investigate the change in the longitudinal peak membrane strain, at the flange edge, and the deformation length when the yield strength increased. This could provide the estimation of the passes and distance between them required for each material to be roll formed. The finite element program MARC/MENTAT was used with the material modeled as elasto-plastic, with the isotropic material hardening rule and the Von Misses yield surface as well as the associated flow rule. The simulation results predicted that the longitudinal peak membrane strain decreased and the deformation length increased when the yield strength was increased. Tehrani et al. (2006) used finite element simulation in order to predict localized edge buckling, as a limiting factor in the cold roll forming of a circular tube section. ABAQUS 6.4 was used for the simulation models built with S4R shell elements. The simulation results showed that if the profile angle, in the first station, exceeded a particular limit, the reverse bending applied by the rolls of the second station might induce local edge buckling. Boman et al. (2006) used the Arbitrary Lagrangian Eulerian formalism in order to compute the steady state of the U-shaped cold roll forming process. This method allowed for refining meshing near the tools, giving in that way an accurate contact prediction all along the simulation with a limited number of elements. During simulation, each time step is divided into two phases: the first one is purely Lagrangian and the second one the ALE phase. The ability of managing efficiently the free surfaces of the sheet has been proven. Han et al. (2005) presented a B_3 -spline finite strip method that can investigate the effects of the main roll forming process parameters, such as bend angle increment, strip thickness, material yield limit, flange length, web width, and the distance between the roll stations, on the longitudinal strain at the edge of the profile. The B_3 -spline finite strip method (B-FMS) divides the displacement function into two parts. The first is the transverse Hermitian cubic polynomials and the second is the longitudinal B_3 -spline function that describes the boundary conditions of the strip. The analytical results were in agreement with the practice of roll forming, as the longitudinal strain increased by increasing the bend angle increment, strip thickness, material yield limit, flange length, and the web width. Decreasing the distance between the rolls could bring a decrease in the longitudinal strains at the edge. Lindgren (2005) investigated the longitudinal strains at the flange and the prediction of the deformation length during the forming of a U-channel. Longitudinal strains in the flange of the profile can emerge since the material in the flange travels a greater distance during the roll forming, through successive rollers. These redundant deformations should not enter the plastic region in order for the plastic strains, in that direction, and the defects in the finished profile, such as camber, bow and twist to be

avoided. The speed production of the profile is between 15-185m/min (250-3083 mm/sec), depending on the desired tolerances of the cross section, the material and the machine specifications. The thickness of the material that can be roll formed is 0.15-19mm. CAE systems for the tooling design use the “rules of thumb” for the cold roll forming process design. The FE analysis tools have been used for validating the design of the CAE tools. The disadvantage of the FE-analysis is the large demanding CPU time, as special profiles require up to 40 roll forming stations. Alsamhan et al. (2004) presented the development of a real time re-meshing technique that could be used for the running of the cold roll forming process simulation. This investigation aims at decreasing the computational time and predicting the final geometry of the roll formed product. The EPFEP3 code was used, which is an implicit elastic-plastic program. It was shown that the dual mesh FE model needed much less time than the conventional model did, and with the accuracy of the results being acceptable. Zhiwu et al. (2002) developed a finite strip method and an elastic-plastic large deformation spline finite strip method, based on the Update-Lagrange method in order to simulate the roll forming process of a channel section with the outer edge. It was concluded that the peak transverse elongation existed on the corner of the strip whilst the peak longitudinal elongation existed on the outer edge of the deformable strip. Hong et al. (2001) developed a simulation program in order to investigate the forming length of the strip during roll forming. This simulation program, utilizing finite element analysis of shape and roll forming analysis, is based on a kinematical steady state condition. The forming length was analyzed based on parameters, such as material properties, strip thickness, roll diameter and roll velocity. The results showed that the work-hardening exponent of the material’s properties had a stronger influence on the forming length during roll forming. Bhattacharyya et al. (1984) investigated the occurrence of the longitudinal strains when single or multiple roll stations were used. The results showed that the level of the peak strain was dependent on the bend angle increment, and the longitudinal strain increased almost linearly with the increase of this angle increment.

2.3 Discussion

Based on the critical review on optimization and modeling approaches of the roll forming process, the following outcomes are derived:

- Cold roll forming process is commonly modeled using explicit finite element method, and some trials have been introduced using implicit finite elements, ALE formalism and B₃-spline finite strip method.
- Over the last decade (2000-2010) cold roll forming modeling approach using computational models was introduced. The period before cold roll forming process was treated experimentally and using rules of thumb from experience and empirical equations.
- Specific products defects and failure modes were predicted through computational modeling of cold roll forming process, such as edge buckling, forming length, peak longitudinal strains at edge, etc.
- Optimization of the cold roll forming process has to deal only with dimensional errors of the products, and not with the whole manufacturing system responses, such as energy consumption, length of the roll forming line, productivity, etc.
- There is no previous attempt to calculate and optimize energy efficiency of the cold roll forming process. Mainly focus was given in quality and cycle time optimization of roll formed products.
- There is no previous method to calculate the number of required number of roll forming stands (and consequently line length and productivity) for a specific response. Number of roll forming stands is still calculated based on empirical equations and estimated from experience.

3 COLD ROLL FORMING PROCESS ENERGY EFFICIENCY

The present chapter focuses on the development of an analytical model for the calculation of the energy efficiency indicator of the cold roll forming process. The energy efficiency indicator is defined for the cold roll forming process. Afterwards, the sections that the analytical model consists of are analyzed, such as internal deformation work and pulling frictional work. The analytical model results for energy consumption are validated with experimental data from literature. Finally, a sensitivity analysis utilizing orthogonal arrays is implemented as analyzing responsibilities of main cold roll forming process parameters on energy efficiency indicator.

3.1 Energy efficiency indicator of cold roll forming process

Energy efficiency of a manufacturing process is a generic term and mainly refers to using less energy to produce at least the same amount and if possible even more useful output, as products (Patterson, 1996). Into 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 cold roll forming process can be defined as the ratio of production rate per hour to the energy required for the production of one meter of product:

$$\eta_{RF} = \frac{\text{Useful output of process}}{\text{Energy input into process}} = \frac{\text{Production Rate (PRH)}}{E_{motor,in}} \quad \text{Eq. (3.1)}$$

The useful output of the process in the energy efficiency indicator is not necessarily needed to be an energy output. Such productivity to energy ratio however contains information about the energy efficiency of the cold roll forming process. The efficiency ratio defined like this, can also lead to project economic (productivity) and environmental (energy) issues and provide useful insights for the overall process efficiency in industrial practice.

An alternative definition of the energy efficiency indicator could be introduced as the ratio of deformation work to the total energy input to the motor. However, for the case of roll forming process, it does not really make sense. This can be justified due to the fact that the total energy input and the mill dynamics are alternated by the change of the number of roll stations (different bending sequence concept as defined later on). Adding more roll stands, the “mill dynamics” is altered as more energy to rotate the additional rollers masses is consumed. As “mill dynamics” is referred as the sum of moments of inertia of rotational masses, such as shafts, rollers and drivetrain equipment of the mill. Thus the energy ratio cannot provide a useful output for the whole energy efficiency of the process. The productivity of the cold roll forming process can be characterized from the production rate, and thus measured in meters of roll formed products per hour as:

$$PRH = \frac{3600 * U_{line}}{N_{rolls} * L_{rolls} + 1} \quad \text{Eq. (3.2)}$$

The energy consumed per roll formed product is related with **i)** the kinetic energy required for rotating the rollers (tooling) with specific angular velocity, **ii)** the internal work required for the deformation of the strip to the desired shape, and **iii)** the overcoming of the rolling friction through pulling of the material inside the mill with specific line velocity. The internal work is the work required for the deformation of the material involving an applied torque over a designated angle. The kinetic energy is the capacity of energy required for the rotating of the shafts and rollers. Power required for the cold roll forming is the rate of doing the deformation and frictional work and the rate of using such a kinetic energy.

The total specific input energy to the electric motor of the mill ($E_{motor,in}$) can be calculated from input power of the motor ($P_{motor,in}$) (Figure 19) and the time required for the production of one meter of profile:

$$E_{motor,in} = P_{motor,in} * \left(\frac{3600 * U_{line}}{L_{rolls} * N_{rolls} + 1} \right) = \left(\frac{\sum P_{shaft,out}}{\eta_{motor} * \eta_{drive}} \right) * \left(\frac{3600 * U_{line}}{L_{rolls} * N_{rolls} + 1} \right) \quad \text{Eq. (3.3)}$$

Figure 19: Cold roll forming line schematic for power distribution

The required input power for the roll forming of one meter of product can be calculated as:

$$\sum P_{shaft,out} = \frac{E_{total} * U_{line}}{L_{rolls} * N_{rolls} + 1} \quad \text{Eq. (3.4)}$$

The total energy for the cold roll forming of one meter of product can be thus calculated as the sum of the rotating kinetic energy of the shaft and the rolls, the internal deformation energy and rolling friction energy through pulling of material inside the mill:

$$E_{total} = E_{kin} + E_{int}^{def} + E_{fr}^{pull} \quad \text{Eq. (3.5)}$$

As the velocity of the mill is steady during major part of the cold roll forming, the kinetic energy of the shaft and rolls can be calculated as:

$$E_{kin} = N_{rolls} * 2 * (E_{kin}^{shaft} + E_{kin}^{rolls}) = N_{rolls} * (I_{shaft} + I_{rolls}) * \omega_{roll}^2 \quad \text{Eq. (3.6)}$$

The internal deformation work can be calculated as the energy required for bending of the material and stretching of the flange along roll forming line, as:

$$E_{int}^{def} = E_{bending} + E_{stretching} \quad \text{Eq. (3.7)}$$

3.2 Analytical model for internal deformation work

Deformation energy is the energy required to deform the material within the desired shape, and plays a major role on the overall energy efficiency of the process. When metal sheet passes through two subsequent roll forming stations, bending in lateral and stretching in longitudinal direction of metal strip take place.

3.2.1 Bending strain rate

Strain rate is defined as the rate of change in deformation strain with respect to time. Within cold roll forming process, as a bending operation, this could be regarded as the change of bending strain with respect to time. Taking into account the bending of the sheet along cross sectional (plain bending), the difference of strain can be defined for small angles $\Delta\theta$ and arithmetically simplified as:

$$\varepsilon = \lim_{\Delta s \rightarrow 0} \frac{\Delta s' - \Delta s}{\Delta s} = \lim_{\Delta s \rightarrow 0} \frac{(\rho - y)\Delta\theta - \rho\Delta\theta}{\rho\Delta\theta} \approx -\frac{y}{\rho} = -\frac{y}{\Delta s} \Delta\theta \quad \text{Eq. (3.8)}$$

For small angle increments ($\Delta\theta \rightarrow 0$) the arc length Δs , as shown within Figure 20, can be calculated as:

$$\cos\left(\frac{\Delta\theta}{2}\right) = \frac{\frac{\Delta s}{2}}{R} = \frac{\frac{\Delta s}{2}}{r + \frac{t}{2}} \approx 1 \rightarrow \Delta s = 2r + t \quad \text{Eq. (3.9)}$$

Figure 20: Deformed elements during bending of the strip

Then the calculation of the bending strain can be defined as:

$$\varepsilon = -\frac{y}{2r + t} \Delta\theta \quad \text{Eq. (3.10)}$$

The maximum bending strain occurs at the outer fiber, where $y = -t/2$, then:

$$\varepsilon_{\max} = \frac{t}{2(2r + t)} \Delta\theta \quad \text{Eq. (3.11)}$$

Then the bending strain rate can be calculated as the derivation of the bending strain over time. Derivation of the bending angle increment can be further analyzed as the ratio of linear

vertical bending velocity of the edge of the flange (u_{bend}) to the length of the flange (A), as shown into Figure 21. Thus the bending strain rate can be denoted as:

$$\dot{\epsilon} = -\frac{y}{2r+t} \frac{d\theta}{dt} = -\frac{y}{2r+t} \omega_{bend} = -\frac{y}{2r+t} \frac{u_{bend}}{A} = -\frac{y}{2r+t} \frac{\omega_{roll} R_{roll}}{A} \left(\frac{L_1^{def} - L_{rolls}}{L_{rolls}} \right) \quad \text{Eq. (3.12)}$$

For the maximum strain at the outer fiber, the bending strain rate can be calculated as:

$$\dot{\epsilon}_{max} = \frac{t}{2(2r+t)} \frac{\omega_{roll} R_{roll}}{A} \left(\frac{L_1^{def} - L_{rolls}}{L_{rolls}} \right) \quad \text{Eq. (3.13)}$$

The schematic of the roll forming (Figure 21) of a strip is shown with flange length A, along a two roll forming stations (with inter-distance L) for an angle increment $d\theta$. Edge of the flange travels a greater length (L_1) than the web in the middle of the profile (L). L_1 is expressed as L_1^{geo} (Figure 21) as it is the geometrical length, and not the deformed (L_1^{def}) “real” length of the edge, as the edge during roll forming is following a helix route between successive rollers.

Figure 21: Schematic for velocities and main geometrical dimensions for one roll forming between two roll stands

Based on trigonometry (within Figure 21) geometrical length of the flange can be calculated as:

$$L_1^{geo} = \sqrt{L_{rolls}^2 + A^2 \left[\sin^2 d\theta + (1 - \cos d\theta)^2 \right]} \quad \text{Eq. (3.14)}$$

To express the three dimensional deformed curve of the strip between two roll stands, a normalized function $S(X)$, so called as “shape function” is used (Halmos, 2006). Such a “shape function” is estimating the helix development (Figure 22) of the strip between successive roll stands and described by:

$$S(X) = \sin \left[\left(\frac{\pi}{2} \right) \left(\frac{X^*}{L} \right)^n \right] \quad \text{Eq. (3.15)}$$

, where:

- $X^* = X - X_1$
- $L = X_2 - X_1$

Figure 22: Calculated “shape function” for different values of factor “n”

The deformed length of the flange L_1 is calculated by the length of the normalized “shape function” and multiplying it with the geometrical length of the diagonal. Thus the length of the normalized “shape function” can be used as correction factor on the geometrical length of the flange edge and can be calculated by:

$$L_{S(X)} = \int_0^1 \sqrt{1 + \left(\frac{dS(X)}{dx} \right)^2} dx = \int_0^1 \sqrt{1 + \left[\sin \left[\left(\frac{\pi}{2} \right) \left(\frac{X - X_1}{L} \right)^n \right] \right]^2} dx \quad \text{Eq. (3.16)}$$

Different values for the shape function can be calculated for different inter-distance lengths and different values of factor n , as shown into Figure 23. The deformed length of the edge of the flange between two roll stands can be estimated by the following equation, as to fulfill the boundary conditions (for $\theta=0$, $L_1^{def} = L$):

$$L_1^{def} = \sqrt{L_{rolls}^2 + A^2 \left[\sin^2 d\theta + (1 - \cos d\theta)^2 \right] L_{S(X)}} \quad \text{Eq. (3.17)}$$

Figure 23: Calculated “Shape function” values across inter-distance lengths for different values of n

Based on predicted flange edge development, through computational model, the value of $n = 2.2$ was selected for the calculation of correction shape factor $L_{S(X)}$. Then the different bending strain rates are calculated for different inter-distances between roll stations (L) along cold roll forming line velocity range, as shown within Figure 24.

Figure 24: Bending strain rate for different inter-distances between roll stations along cold roll forming line velocity range

3.2.2 Bending work

For the calculation of the bending moment, a unit length of a continuous strip is assumed, in which a cylindrical bent region of radius of curvature ρ is flanked by a flat sheet (Marciniak et al., 2002). Bending moment per unit width M (in $Nt \cdot m/m$) and a force per unit width is applied T (Nt/m) at the middle surface of the sheet ($y=0$) are defined within Figure 25.

Figure 25: Stress distribution for a power-law-hardening sheet bent without tension (Marciniak et al. 2002)

$$M_{bending} = \int_{-t/2}^{t/2} \sigma_1 y dy = \left(1 + \left(\frac{\dot{\epsilon}}{C} \right)^{\frac{1}{P}} \right) K \left(\frac{1}{\rho} \right)^n \frac{t^{n+2}}{(n+2)2^{n+1}} \quad \text{Eq. (3.18)}$$

The bending work per unit length (Joules/m) of the strip can be calculated for the angle increment ($D\theta$ in radians) between two roll stands as:

$$E_{bending} = \int_{\theta_0}^{\theta} M_{bending} d\theta = M_{bending} \frac{D\theta^2}{2} \quad \text{Eq. (3.19)}$$

3.2.3 Longitudinal stretching work

Longitudinal stretching work is based on the fact that the flange is traveling into greater length than the web (Paralikas et al. 2009) (Paralikas et al. 2010a). Longitudinal membrane (middle layer) strain is induced and is influenced on the bending angle increment; roll stands inter-distance (L) and the flange length (A) (Figure 26).

Figure 26: Cold roll forming process schematic - outer edge travels greater distance than bending line through successive rollers

Longitudinal membrane (middle layer) strain along flange length is calculated by

$$\varepsilon_{long} = \ln\left(\frac{L_1^{def}}{L_{rolls}}\right) = \ln\left(\frac{\sqrt{L_{rolls}^2 + A^2 \left[\sin^2 d\theta + (1 - \cos d\theta)^2\right]} L_{S(X)}}{L_{rolls}}\right) \quad \text{Eq. (3.20)}$$

Longitudinal membrane strain is zero at the web, and increased into squared sine form across the flange width. Longitudinal membrane strain takes its maximum value at the flange edge, as the flange edge is traveling the greater length at the same time frame (Figure 27).

Figure 27: Total longitudinal membrane strain profile along flange length during roll forming between two roll stands

Longitudinal membrane strain is inducing longitudinal stresses along thickness of the strip and consequently stretching work during roll forming between two roll stands. Thus specific stretching work (Joules/m²) can be calculated as the area under the $f(\sigma, \varepsilon)$ curve:

$$w_{stretching}^i = \frac{W_{stretching}^i}{V_{flange}} = \int \sigma(\varepsilon) d\varepsilon \quad \text{Eq. (3.21)}$$

, where: $V_{flange} = A * t * L_{product}$ as the volume of flange that is under longitudinal deformation.

- For the elastic region of the material, $\varepsilon < \varepsilon_0$

$$\frac{w_{stretching}^{elastic}}{L_{product}} = A * t * \int E * \varepsilon d\varepsilon = A * t * E \frac{\varepsilon_{elastic}^2}{2} \quad \text{Eq. (3.22)}$$

- For the plastic region of the material, $\varepsilon \geq \varepsilon_0$

$$\frac{w_{stretching}^{plastic}}{L_{product}} = A * t \left[\left(1 + \left(\frac{\dot{\varepsilon}}{C} \right)^{\frac{1}{P}} \right) K \left(\frac{(\varepsilon_{YP} - \varepsilon_{plastic})^{n+1}}{n+1} \right) \right] \quad \text{Eq. (3.23)}$$

Thus the total stretching work can be calculated by the sum of the elastic and plastic regions stretching work, or alternatively the area under the $f(\sigma, \varepsilon)$ curve, as:

$$\frac{w_{stretching}}{L_{product}} = \frac{w_{stretching}^{elastic}}{L_{product}} + \frac{w_{stretching}^{plastic}}{L_{product}} = [Area \text{ under } f(\sigma, \varepsilon) \text{ curve}] * A * t \quad \text{Eq. (3.24)}$$

3.3 Analytical model for pulling-frictional work

Rollers are in contact with the strip and rolling friction is “pulling” the strip through the roll stands and is moving the material within the roll forming mill. Through strips longitudinal movement, the three-dimensional bending takes place and the profile is gradually roll formed.

Rolling friction takes place only on the web of the profile, as the design of the roll stands includes the “relief angle” on the upper roller into flange section (Figure 28). This “relief angle” aims at loosening contact of the upper surface of the strip with the rotating upper roll in order to avoid the generation of lateral moment during three-dimensional bending. Lateral moment could be generated as the rotating radius along the flange is alternated and the rotational velocity remains the same. Consequently, the longitudinal velocity will be alternated along the flange width and lateral moments along cross section of the profile will be applied. Without such a “relief angle”, profile could be distorted within the mill through additional redundant deformations.

Figure 28: Roll stands profile (half due to symmetry) and relief angle applied on the upper roller

As the strip is passing through the roll stand, rotating rollers are pulling the material utilizing the gap existing between the rollers. This gap is characterized as “rolls stand gap” and is expressing the distance between the contact lines of the rotating rollers with the strip. This gap can be alternated, as a process parameter, and consequently affects the contact forces and rolling friction. The rollers were assumed rigid and the strip deformable for the calculations. Thus, roller can deform elastically the surface of the strip, as the thickness of the strip remains the same on the web. The contact force can be then calculated into the elastic region (no plasticity as the thickness of the strip remains the same) through the contact stress and the contact area between roller and strip (Figure 29):

$$\sigma = \frac{F_{contact}}{A_{contact}} = E\varepsilon \rightarrow F_{contact} = E_{strip} * \varepsilon_{contact} * A_{contact} \quad \text{Eq. (3.25)}$$

Figure 29: Contact force profile on the contact area of roller web on the strip surface

For $x \in \left[0, \frac{a}{2}\right]$, the profile of the roll gap can be described as:

$$d_i(\theta) = d \sin\left(\frac{\theta_i}{2}\right) \quad \text{Eq. (3.26)}$$

The thickness of the strip along the contact area of the roller with the strip can be calculated as:

$$\frac{t_i}{2} = \frac{t}{2} - d_i(\theta) = \frac{t}{2} - d \sin\left(\frac{\theta_i}{2}\right) \quad \text{Eq. (3.27)}$$

The true strain (or logarithmic strain) can be calculated as:

$$\delta\varepsilon = \frac{\delta l}{l} \rightarrow \int \delta\varepsilon = \int_L \frac{\delta l}{l} \rightarrow \varepsilon = \ln\left(\frac{l}{L}\right) = \ln\left(\frac{\frac{t_i}{2}}{\frac{t}{2}}\right) = \ln\left(\frac{\frac{t}{2} - d \sin\left(\frac{\theta}{2}\right)}{\frac{t}{2}}\right) \quad \text{Eq. (3.28)}$$

And using the calculation of the thickness of the strip at the roller axial line:

$$\varepsilon = \ln \left(\frac{\frac{t}{2} - d \frac{\sqrt{R^2 - (R-d)^2}}{R}}{\frac{t}{2}} \right) \quad \text{Eq. (3.29)}$$

The angle of contact on the roller can be calculated as assuming for small contact angles approximation that $\sin(x) \approx x$. Thus:

$$\sin \frac{\theta}{2} \approx \frac{\theta}{2} = \frac{\alpha}{2R} = \frac{\sqrt{R^2 - (R-d)^2}}{R} \rightarrow \theta = \frac{2\sqrt{R^2 - (R-d)^2}}{R} \quad \text{Eq. (3.30)}$$

Thus the area of contact along the web of the roller can be calculated as:

$$A_{contact} = sw = R\theta w = 2w\sqrt{R^2 - (R-d)^2} \quad \text{Eq. (3.31)}$$

Assuming that the middle layer of the strip (at the half thickness) is fixed in lateral movement and only deformation is appearing on the surface of the strip, the contact force on the roller axle can be then calculated as:

$$F_{cont}^u = 2E_{strip}w\sqrt{R^2 - (R-d)^2} \left| \ln \left(\frac{\frac{t}{2} - d \frac{\sqrt{R^2 - (R-d)^2}}{R}}{\frac{t}{2}} \right) \right| \quad \text{Eq. (3.32)}$$

Pulling of the strip is made by the rottary frictional force generated by the normal contact force and the rolling friction coefficient. The coefficient of rolling friction for a slow rigid wheel, not adjusted for velocity, can be calculated by:

$$C_{rr} = \sqrt{\frac{d}{2R}} \quad \text{Eq. (3.33)}$$

The rolling friction coefficient, for steel roller with low rotational speeds, is influenced from the distance of intrusion (rolls gap, d) and the diameter of the roller ($2R$). The torque that the roller is applying for the “pulling” of the strip can be calculated as:

$$\tau = F_{pull} R = C_{rr} F_{cont} R = C_{rr} R^2 E_{strip} \epsilon_{cont} w \theta \quad \text{Eq. (3.34)}$$

The pulling friction work can be calculated as:

$$W_{frict}^{pull} = \int_0^\theta \tau d\theta = 2 \sqrt{\frac{d}{2R}} E_{strip} \epsilon_{cont} w \left[R^2 - (R-d)^2 \right] \quad \text{Eq. (3.35)}$$

3.4 Validation and sensitivity analysis of analytical model for energy efficiency indicator of cold roll forming process

Analytical model results for the calculation of the energy efficiency indicator of the cold roll forming process were validated. This was implemented with the validation of the energy consumption (in kW) of the cold roll forming mill with experimental data as described from Lindgren (2007b). For the U-section of 80 degrees (20-40-60-80 degrees bending angles) with a velocity of 40m/min, 1.46mm thickness, 0.5m rolls inter-distance, AHSS material (Docol 800DP) and 0.125mm rolls gap, the calculated power motor input is 1.57 kW/m. The experimental measured power input is 1.7kW/m and it is in good agreement within 10% (actual difference about 7.64%) with calculated input power from analytical model, as shown within Figure 30.

Figure 30: Experimental conditions and comparison of experimental results for energy consumption^{**} (Lindgren 2007b) with analytical model results

All main process parameters can affect the energy efficiency indicator of the cold roll forming process. A U-section profile was selected, as a common profile, for the calculation of the energy efficiency indicator and the estimation of the effects of the main process parameters. The critical dimensions of the U-section profile are shown into Figure 31, A is the flange length ($A = 50\text{mm}$), w is the web length ($w = 200\text{mm}$) and L_{product} is the length of the product ($L_{\text{product}} = 1\text{ m}$), and internal bending radius r ($r = 4\text{mm}$). Material of the profile was selected the AHSS DP-600 (Futura IP, 2008) with strip thickness of $t=2\text{mm}$. The efficiencies of the electric motor and mill drivetrain were assumed as 0.82 (Almeida and Greenberg, 2004).

Figure 31: U-section profile and main dimensions: $A=50\text{mm}$, $w=200\text{mm}$, $L_{\text{product}}=1\text{ m}$, $r=4\text{mm}$

Based on calculations for the energy efficiency of the cold roll forming process the main process parameters were identified as: **A)** roll forming line velocity (u_{line}), **B)** roll stands inter-distance (L), **C)** bending angle increment ($d\theta$) as bending concept, **D)** rollers radius (R), and

E) rolls gap (G) (Figure 32). The $L_{16}(4^5)$ matrix of experiments was selected, which consist of five factors with four levels each factor, resulting in sixteen runs (Phadke, 1989).

Figure 32: Cold roll forming of a U-channel (half geometry due to symmetry) main process parameters (inter-distance between roll stands – L , roll forming line velocity – U_{line} , roller radius – R , and bending angle - $d\theta$)

Factors and the selection of ranges and respective values of levels as shown into Table 3 are analyzed as:

- **Factor A - Roll forming line velocity:** Most common roll forming line velocities are 30-40 m/min (0.5-0.65 m/sec) (Lindgren, 2007b). 0.5 m/sec was selected as the initial level with a step of 0.05 m/sec for the subsequent three levels.
- **Factor B - Inter-distance between roll stands:** Within the roll forming mill, the inter-distance between roll forming stands can be alternated. The starting level of 0.4m was selected with a step of 0.05m.
- **Factor C – Bending concept:** The bending concept indicates, how the bending sequence within the roll forming mill takes place. Number of forming stands can be calculated, based on the bending concept, as shown within Table 2. The first and last angle is always 5 degrees, as the strip must have a smooth entrance and exit from the mill. The other angles were set as the main angles of the bending concept (5 deg – 20 deg, with a step of 5 deg). Starting level was the bending concept C5 (five degrees main angle), as increasing until a limit roll forming angle of twenty degrees.

Table 2: Analysis of the bending concepts within the roll forming mill (all in degrees)

ID/RS	1	2	3	4	5	6	7	8	9	10	11	...	18	Total	No.
-------	---	---	---	---	---	---	---	---	---	----	----	-----	----	-------	-----

														angle	RS
C5	5	5	5	5	5	5	5	5	5	5	5	...	5	90	18
C10	5	10	10	10	10	10	10	10	10	5				90	10
C15	5	15	15	15	15	15	10							90	7
C20	5	20	20	20	20	5							90	6	

- **Factor D – Roller radius:** Rollers radius is a design parameter, as the first contact of the strip is made on the surface of the lower roller. Thus, as the roller radius is changing, the contact point is also alternated. In sake of simplicity, the upper and lower radiuses were assumed the same. Starting level of 0.09m was selected, with a step of 0.01m.
- **Factor E – Rolls gap:** Rolls' gap estimates the “gripping” of the strip between the rollers as pulling it through the mill. This can affect frictional work and consequently energy efficiency. Starting level was set as 1% of the nominal strip thickness with a step of 0.5%.

Table 3: Factors for matrix experiments and respective levels values

ID	Factors	Units	Levels			
			Level#1	Level#2	Level#3	Level#4
A	Line velocity (u_{line})	m/sec	0.50	0.55	0.60	0.65
B	Inter-distance (L)	M	0.4	0.45	0.5	0.55
C	Bending concept ($d\theta$)	deg	C5	C10	C15	C20
D	Roller radius (R)	m	0.09	0.1	0.11	0.12
E	Rolls gap (G)	%	1.0	1.5	2.0	2.5

Based on the selected orthogonal array, factors and respective levels, the sixteen runs were conducted and the energy efficiency indicator response was calculated, as shown within Table 4. Total deformation and frictional work was also calculated, as also the statistical summary for the motor power input (Phadke, 1989).

Table 4: $L_{16}(4^5)$ orthogonal array with roll forming process factors and levels, response for each run and statistical summary for each run

Run no.	Factors					PRH (parts/hour)	Energy input to motor (Joules/m)	Energy efficiency indicator (m/Joule*Hr)	Statistical summary for Energy Efficiency Indicator
	A	B	C	D	E				
1	0.5	0.4	C5	0.09	1	219.51	771.80	0.2844	-10.92
2	0.5	0.45	C10	0.1	1.5	327.27	966.81	0.3385	-9.41
3	0.5	0.5	C15	0.11	2	400.00	1222.98	0.32.71	-9.71
4	0.5	0.55	C20	0.12	2.5	418.60	1871.99	0.22.36	-13.01
5	0.55	0.4	C10	0.11	2.5	396.00	1311.80	0.30.19	-10.40
6	0.55	0.45	C5	0.12	2	217.58	1446.06	0.15.05	-16.45
7	0.55	0.5	C20	0.09	1.5	495.00	2203.01	0.2247	-12.97
8	0.55	0.55	C15	0.1	1	408.25	1015.04	0.4022	-7.91
9	0.6	0.4	C15	0.12	1.5	568.42	4554.70	0.1248	-18.08
10	0.6	0.45	C20	0.11	1	583.78	4182.46	0.1396	-17.10
11	0.6	0.5	C5	0.1	2.5	216.00	1391.47	0.1552	-16.18
12	0.6	0.55	C10	0.09	2	332.31	878.07	0.3785	-8.44
13	0.65	0.4	C20	0.1	2	688.24	9452.88	0.728	-22.76
14	0.65	0.45	C15	0.09	2.5	563.86	2055.23	0.2744	-11.23
15	0.65	0.5	C10	0.12	1	390.00	1235.82	0.3156	-10.02
16	0.65	0.55	C5	0.11	1.5	214.68	1465.86	0.1465	-16.69

The average summary statistics by factor levels for S/N ratios of energy efficiency indicator were calculated (Table 5) and the plot of factors effects based on the analysis of means (ANOM) is shown within Figure 33.

Table 5: Average of summary statistic by factor levels for S/N ratio for energy efficiency indicator

ANOM S/N ratio $\eta = -10\log_{10}(\eta_{rf})$	Levels			
	1	2	3	4
A-Line velocity (u_{line})	-10.762	-11.934	-14.950	-15.174
B - Inter-distance (L)	-15.539	-13.549	-12.218	-11.512

C - Bending concept ($d\theta$)	-15.060	-9.567	-11.732	-16.460
D - Roller radius (R)	-10.891	-14.064	-13.475	-14.389
E - Rolls gap (G)	-11.488	-14.285	-14.339	-12.707

Figure 33: Analysis of means (ANOM) and plots of factors effects for S/N ratio for energy efficiency indicator

Analysis of variance (ANOVA) was then conducted (Table 6) and the responsibility (%) of each process parameter on the energy efficiency indicator of the cold roll forming process was calculated (Figure 34).

Table 6: Analysis of Variance (ANOVA) and responsibility (%) for each factor for S/N ratio for energy efficiency indicator

Factors	Degrees of freedom	Sum of squares	Mean square	Variance ratio F	Resp. (%)
A - Line velocity (u_{line})	4.00	58.03	14.51	0.27	21.79%
B - Inter-distance (L)	4.00	37.63	9.41	0.18	14.13%
C - Bending concept ($d\theta$)	4.00	117.74	29.43	0.55	44.22%
D - Roller radius (R)	4.00	30.27	7.57		11.37%
E - Rolls gap (G)	4.00	22.58	5.65		8.48%
Error	0.00	0.00	-		
Total	20.00	266.25			
(Error)	12.00	198.34	53.35

Figure 34: Responsibility (%) of each factor for S/N ratio for energy efficiency indicator

Main influential process parameters on the energy efficiency of the process is bending angle concept, roll forming line velocity and inter-distance between roll stations with 44.22%, 21.79% and 14.13% respectively. Roller radius and rolls gap have also an effect of 11.37% and 8.48% respectively.

Figure 35: Plot of energy efficiency indicator (%) for roll forming line velocity and number of roll stations (bending concept)

The plot of energy efficiency indicator (%) for different number of roll forming stations (bending concepts) and various roll forming line velocities is presented in Figure 35. For bending concept C5, which is consisted of eighteen roll stations, the energy efficiency is

reduced due to the reduced productivity. For bending concept C20, which is consisted of six roll stations, the energy efficiency is reduced due to the increased demands of energy. Energy efficiency is optimized at bending concept C15, which is consisted of seven roll stations, and increased as the roll forming line velocity is increasing. Maximum energy efficiency indicator is at maximum roll forming line velocity of bending concept C15 with 0.4911 (m/Joules*Hr).

4 COLD ROLL FORMING PROCESS MODELING

This chapter deals with the description and verification of the cold roll forming process computational model. In the first section the computational methods utilizing finite elements technology and the selected modeling approach are discussed. Cold roll forming process computational model input conditions are analyzed within the second section. Computational model conditions and meshing convergence for model responses of a U-channel with six roll forming stations are presented. Finally into the third section, the simulation model response for longitudinal strains (%) at edge of the flange of a U-section profile is validated with experimental data from literature. Results showed good agreement for peaks of simulation longitudinal strains responses with experimental data.

4.1 Comparison of simulation methods and modeling approach

The finite element method is a popular and general approach for modeling of sheet metal forming processes, such as stamping, deep drawing and sheet metal bending. Over the last decade, also cold roll forming process was modeled using finite elements technology. Roll forming process is classified, like other sheet metal forming processes, as a non-linear quasi-static problem. There are two finite element equation solution methods for solving such problems, the implicit and the explicit one.

Implicit method involves iterations until the convergence criteria to be satisfied for each increment. An implicit calculation procedure is that the state ($t + \Delta t$) is estimated from state ($t + \Delta t$), while in explicit method the state ($t + \Delta t$) is determined based on the information at time t (Harewood and McHugh, 2007). Generally the implicit solution method faces numerous problems while solving non-linear quasi-static problems, as troubles for achieving convergence may occur in analyses with highly non-linear material behavior and contact involvement. On the other hand explicit finite element method solver equations are solved directly to determine solution without iteration. In cases with contact involvement, the explicit method is preferred as a more robust method.

For the implicit solution procedure, the Newton-Raphson method is used with a series of linear approximations. Inertia effects of mass $[M]$ and damping $[C]$ are not involved into implicit time integration. The average accelerations-displacements are evaluated at time ($t + \Delta t$) by the following equation (Harewood and McHugh, 2007), (ANSYS, 2005):

$$\delta(u_i^{t+\Delta t}) = -[K(u_i^{t+\Delta t})]^{-1} G(u_i^{t+\Delta t}) \quad \text{Eq. (4.1)}$$

Where $\delta(u_i^{t+\Delta t})$ is the incremental displacement, K is the global stiffness matrix named also as Jacobian matrix, and $G(u_i^{t+\Delta t})$ is a set on non-linear equations in u nodal displacements. The above equation must be solved for each iteration for the change in incremental displacements $\delta(u_i^{t+\Delta t})$. This is a computational expensive operation and the time required for the solution of each iteration cannot be estimated as very small time steps are required to achieve convergence (ANSYS, 2005). The accuracy of the solution is depended by the convergence criterion, into which the updated value of $G(u_i^{t+\Delta t})$ must be less than a tolerance value (Harewood and McHugh, 2007). Complications may happen when high non-linear operations involve contact and sliding between two surfaces.

Into explicit method a central difference time integration method is used. “Explicit” is referred that the analysis assumes constant values for the velocities and the accelerations across half time intervals. Accelerations derived at the start of each increment are computed by the following equation (Harewood and McHugh, 2007), (ANSYS, 2005), (Rojeka et al. 2001):

$$\ddot{u}^i = M^{-1}(F^i - I^i) \quad \text{Eq. (4.2)}$$

Where, u is the displacement, M is the lumped mass matrix, F is the vector of externally applied forces and I is the vector of internal element forces. Each time increment is computationally inexpensive to be solved. A disadvantage of the method is the limitation of the time step due to conditional stability (Rojeka et al. 2001). The stability limit determines the size of the time increment (Harewood and McHugh, 2007)**Error! Reference source not found.:**

$$\Delta t \leq \Delta t^{critical} = \frac{2}{\omega_{max}} \quad \text{Eq. (4.3)}$$

Where ω_{max} is the maximum element eigen value, also described as the largest natural circular frequency. A practical approach for calculation of the critical time step is:

$$\Delta t = \min\left(\frac{l}{c}\right) \quad \text{Eq. (4.4)}$$

Where, l is the wave propagation velocity and c is depended on the element type, as for shell elements can be calculated (ANSYS, 2005):

$$c = \sqrt{\frac{E}{\rho(1 - \nu^2)}} \quad \text{Eq. (4.5)}$$

Where, E is the Young modulus of material, ρ is the density of the material and ν is the poisson ratio. Numerical efficiency of explicit method, low memory requirements, easy handling of contact conditions make this method appropriate for sheet metal forming applications, such as bending and roll forming processes (Rojeka et al. 2001). Moreover, implicit method is more computational expensive for such large models of cold roll forming process. Thus, explicit finite element method was preferred into current study for the simulation of the roll forming process, as many contact entities and large non-linear dynamic phenomena exist.

The procedure followed within cold roll forming process modeling is consisted of five steps:

- i)** A parametric CAD model of the roll forming line (deformable strip and rigid rollers) is generated. Such parametric CAD model allows the user easily and into a flexible manner to alternate the adjust critical dimensional parameters of the model, such as rollers diameter, inter-distance between roll stations, length of the deformable strip, rolls gap, etc.
- ii)** Parametric CAD model is imported within the explicit finite elements program (LS-Dyna) for building the cold roll forming process model. Within such step element type, material model, meshing strategy, contact, boundary and operational conditions are determined within pre-processor.
- iii)** The processing of the explicit finite elements model is conducting and the results are obtained. Computational time required for getting such simulation results depends on several factors, such number of elements, termination time and time step size. Results are analyzed and monitored within the post-processor.
- iv)** After reviewing and managing cold roll forming process results, the springback analysis could be implemented using implicit finite elements method. Cold roll forming process explicit results are inserted within the implicit solver (ANSYS) and the springback analysis is followed.
- v)** Springback analysis involves the analysis of the relief of deformation state (residual elastic stresses) derived from sheet metal forming operation. After solving the springback analysis, results for springback deformations are post-processed and analyzed. The whole procedure for the simulation of the cold roll forming process procedure is depicted into Figure 36.

Figure 36: Procedure for cold roll forming process and springback analyses

4.2 Cold roll forming simulation model

Within the following section the cold roll forming process modeling approach is described in details regarding element type, material models, meshing, contact and boundary and loading conditions.

4.2.1 Element type

For the simulation of the cold roll forming process, the shell elements were used for both the deformable strip and the rigid rolls. The fully integrated Belytschko-Lin-Tsay shell element, referred to as Shell163, was used. The Shell163 element is based on a combined co-rotational and velocity-strain formulation (Hallquist, 2006). Such an element is defined by four corner nodes. These four corner nodes define the mid surface, and the integration points are stacked vertically at the centroid of the element (ANSYS, 2005), as shown in Figure 37. Five integration points through thickness were used for the analysis of the deformable strip with the Gauss quadrature rule. This Gauss quadrature rule provides the location of each integration point.

Figure 37: Shell163 and through thickness integration points (ANSYS, 2005)

4.2.2 Material models for deformable strip and tooling

The strain rate dependent plasticity model, named as Power Law plasticity, was used for modeling of the deformable strip of the cold roll forming process simulation. The

elastoplastic behavior with isotropic hardening is provided by the following equations for elastic and strain hardening plasticity (ANSYS, 2005) :

$$\sigma = E\varepsilon, \text{ if } \varepsilon < \varepsilon_{YP} \quad \text{Eq. (4.6)}$$

$$\sigma = k\varepsilon^n = k(\varepsilon_{YP} + \bar{\varepsilon}^p)^n, \text{ if } \varepsilon \geq \varepsilon_{YP} \quad \text{Eq. (4.7)}$$

, where ε_{YP} is the elastic strain to yield and $\bar{\varepsilon}^p$ is the effective plastic strain (logarithmic), E is the young modulus of material at elastic region, k is the strength coefficient and n is hardening coefficient. The elastic strain at yield can be calculated from the following equation:

$$\varepsilon_{YP} = \left(\frac{E}{k}\right)^{\left[\frac{1}{n-1}\right]} = \left(\frac{\sigma_Y}{k}\right)^{\left[\frac{1}{n}\right]} \quad \text{Eq. (4.8)}$$

Strain rate is also accounted for using the Cowper and Symonds models that scales the yield stress with the facto: $1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{\frac{1}{P}}$. Where $\dot{\varepsilon}$ the strain rate and C, P is are the Cowper and Symonds parameters. Thus the Power Law constitutive relationship which includes the Cowper-Symonds multiplier to account for strain rate is:

$$\sigma_Y = \left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{\frac{1}{P}}\right] k(\varepsilon_{YP} + \bar{\varepsilon}^p)^n \quad \text{Eq. (4.9)}$$

For the modeling of the tooling, the rigid material model was assumed. Elements which are rigid are bypassed in the element processing and no storage is allocated for storing history variables, which makes that material type cost effective (Hallquist, 2006). When rigid bodies are defined, all of the degrees of freedom of the nodes in the body are coupled to the body's center of mass. Thus, a rigid body has only six degrees of freedom regardless the number of nodes that define it. The mass, center of mass and inertia properties of each rigid body are calculated from the body's volume and density of elements. The forces and moments acting on the body are summed from the nodal forces and moments at each time step (ANSYS, 2005). For the definition of the rigid material only the linear properties of the material are required, as the density, the young modulus of elasticity and poisson ratio. Into Table 7, the

material properties for the AHSS DP980 for the Power Law plasticity material model and the rigid material model for the tooling are defined.

Table 7: Material properties for AHSS DP980 and rigid rolls (Futura IP, 2008), (ANSYS, 2005)

Property	Units	Value
AHSS DP980 properties for deformable strip (Power Law Plasticity material model)		
Density (ρ)	Kg/mm ³	7.87 e^{-6}
Young modulus of elasticity (E)	MPa	1.8844 e^5
Poison ratio (ν)	-	0.295
Strength coefficient (k)	-	1566.59
Hardening coefficient (n)	-	0.14
Cowper-Symonds coef. (C)	s ⁻¹	2.3893 e^6
Cowper-Symonds coef. (P)	-	3.4543
Elastic strain at yield (ϵ_{YP})	-	0.003085
Tooling steel for rigid rolls		
Density (ρ)	Kg/mm ³	7.87 e^{-6}
Young modulus of elasticity (E)	MPa	2.07 e^5
Poison ratio (ν)	-	0.3

4.2.3 Contact, boundary and loading conditions

For the contact of the deformable strip with the rigid roll, the automatic surface-to-surface option was followed. The friction coefficient was initially set to for static to 0.2 and dynamic contact as calculated for rolling friction coefficient (C_{rr}), as stated also into Bui et al. (2007), in order for the friction between the elements to be simulated. For the loading conditions, the rolls were fully constrained and the deformable strip was pulled through them with a constant velocity. For symmetric cross section only the half geometry is simulated, as significant computational cost savings to be occurred. Boundary conditions for simulating the half geometry were followed as the deformable strip was constrained in lateral displacements only on the nodes of the symmetry's line.

4.2.4 Meshing convergence

Meshing is the discretization of the geometry into elements. Elements size, and consequently the number of elements of the model, plays a major role on the model responses convergence. As model responses convergence it can be defined as the procedure that during the alternation of the elements number is alternated, the alternation of model responses is within a specific limit (5%). For the implementation of the meshing convergence the geometry of the initial simulation of a U-section profile was selected. The geometry along with the flower diagram design for the forming of the profile with six forming stations is shown into Figure 38.

Figure 38: Cross section of U-channel (left), flower diagram of U-channel (middle layer, half geometry due to symmetry) with six forming stations (with $A=15^\circ$ bending angle increment) (right)

Into Figure 39, the parametric CAD of the roll forming line of the U-section profile is shown, as ready for importing for FEM calculations of cold roll forming process.

Figure 39: Parametric CAD of the roll forming line model to be inserted into FEM

Based on the parametric CAD geometry, the simulation model was built into explicit dynamics simulation software (LS-Dyna). Regarding the roll forming line, six roll forming stations were created as stationary rigid rolls. For the reduction of the computational cost the area of the rolls was reduced to a minimum. The areas that the deformable strip comes in

contact with rigid rolls were imported. This will allow to the reduction of the number of elements required for the rigid rolls. The distance between the roll stations was set to 500mm, resulting into about 3 meters length of the roll forming line. Utilizing FEM options for the element types, material models, contact and boundary conditions the model was built, and meshing was conducted (Figure 40)

Figure 40: Cold roll forming simulation FEM for the U-section profile (half geometry due to symmetry)

For selecting the element size, the convergence procedure was followed. As increasing the elements size, the number of elements is also increasing. The model responses, for total energy and maximum elastic longitudinal strains, were monitored as the number of elements was increased, as shown within Figure 41.

Figure 41: Meshing convergence (12.000 elements within 5% step difference) for two model responses, i) total energy and ii) maximum elastic longitudinal strains at the edge of the flange of the profile

The convergence limit of 5% was set for both model responses step difference. Meshing of simulation model with 12.000 elements provide both model responses convergence within the model responses step difference limit of 5%.

4.3 Cold roll forming simulation model validation

Cold roll forming model was also validated for elastic longitudinal strains response with experimental data from literature (Damm, 1989). Elastic longitudinal strains were selected for validation, due to their importance and effect of such strain on product defects (Halmos, 2006). Simulation results for a U-channel with three roll forming stations were compared with experimental from literature. Longitudinal strain peaks are in good agreement with experimental peaks for each roll forming station, as shown within Figure 42.

Figure 42: Cold roll forming model validation with experimental data from literature for peaks of longitudinal strains (%) at each roll forming station (Damm, 1989)

5 COLD ROLL FORMING PROCESS ENERGY EFFICIENCY OPTIMIZATION

The present chapter focuses on the development of the robust design optimization methodology for energy efficiency indicator, utilizing hybrid modeling approach. Initially the robust design methodology utilizing orthogonal arrays is analyzed and optimization procedure is defined. Afterwards the quality characteristic constraints are defined and linked with computational model responses. Finally, cold roll forming process guidelines are analyzed and countermeasures for processing defects are presented.

5.1 Robust design methodology through hybrid modeling approach

The hybrid modeling approach for robust design optimization includes the utilization of both analytical and computational models for the determination of an optimum energy efficiency and feasible solution for cold roll forming process. Objective of robust design optimization of manufacturing processes is to determine the settings of “easy-to-control” parameters (control factors) as to achieve the best process performance that is also insensitive to the variability of “hard-to-control” parameters (noise factors) (Li et al., 2002).

The optimization problem boundary conditions are defined within P-diagram, as inputs include control, noise and fixed variables, and outputs include objective response and quality constraints (Figure 43):

- *Control Variables [x]* (easy-to-control variables), which are set from the designer or engineer during the design process and optimization and consist of Design Variables [D] and Process Variables [P].
- *Noise Variables [N]* (hard-to-control variables), which represent a source of variations that cannot be fully controlled from the design and process point of view.
- *Fixed Variables [F]*, which describe deterministic parameters of the system, the equipment and product design (customer requirements)
- *Objective Responses [R]*, which are the output of the manufacturing process since they can be measured and lead to the determination of the objective functions, which are described under certain *Quality Constraints [C]*.

Figure 43: P-diagram for the optimization of a manufacturing system/process

Robust optimization problem should take into account the effects on the noise variables on the objective functions and implicit constraints, which makes the system performance less sensitive to variation of noise parameters (Jurecka, 2007). Thus, the aim of the robust optimization under uncertainty is to manipulate the control and noise parameters in a way that the variability of the response is minimized (Yang and El-Haik, 2003), (Bucher, 2005), (Roos et al., 2006), (Phadke, 1989).

The proposed robust design optimization methodology utilizing hybrid modeling approach is depicted within Figure 44. Based on the defined control and noise variables of the manufacturing system/process, the design of experiments (DoE) is defined. Such DoE includes the orthogonal arrays for both control and noise variables, with definition of respective levels. Then the robust design algorithm is followed with the utilization of the analytical energy efficiency model, as shown into Figure 45.

Figure 44: Manufacturing system / process optimization approach using hybrid modeling approach

Robust design algorithm is analyzed within five steps: **i)** DoE for the noise factors and the simulation of variation in noise factors as to identify the major factors and (potentially) reduce the number of them as to save computation time and cost, **ii)** DoE for the control factors, **iii)** the simulation algorithm based on analytical energy model input and orthogonal arrays for control and noise factors as to identify statistical summary, mean and variance of the responses, **iv)** data analysis of the responses using analysis of means and variance and **v)** the determination of the optimum energy efficient response.

Figure 45: DoE / Robust design algorithm using orthogonal arrays and analytical energy efficiency model

The set of control variable levels from the determined optimum energy efficient response is then used for building the FEM. Then the quality characteristic constraints are checked using FEM. If all constraints are met, then the energy efficient and feasible process design is determined. If not all constraints are met, then the control variable levels are alternated based on the process guidelines. Then a second optimum set of control variables is determined and checked again utilizing FEM. This closed loop is implemented until all the quality characteristic constraints to be met through FEM.

5.2 Quality characteristics constraints and process guidelines / countermeasures

Main cold roll forming processing defects are warping (longitudinal bow), twisting, edge waviness (buckling) and edge cracking, as shown into Figure 46. These defects are produced and affected by redundant deformations, such as longitudinal strains (elongation and shrinkage) at the edge, uneven distribution of longitudinal strains on profile, strains on thickness reduction (strain in thickness direction), and transverse strains (major strains). Based on such redundant deformations, which drive the defects occurrence, several quality characteristic constraints could be set. Moreover dimensional stability (dimensional error) of

final produced profile with springback compensation is another critical issue for the quality characteristic of roll forming product.

Figure 46: Main defects caused by redundant deformations on roll formed products (Halmos, 2006)

Quality characteristic constraints are defined as functions of redundant deformations during processing. Such constraints are checked through FEM responses within the optimization methodology. Cold roll forming process FEM is constructed based on the determined optimum set of levels for energy efficiency indicator, based on modeling approach from Paralikas et al. (2010). These quality characteristic constraints (Figure 47) are: **i)** longitudinal strains distribution on cross section (elongation and shrinkage peaks) and unevenness of distribution of strains between flange and web of profile for checking longitudinal bow and twist, **ii)** average values of longitudinal strains peaks (elongation and shrinkage) at edge of profile for checking longitudinal bow and twist, **iii)** longitudinal strains peaks not surpassing yield point of material at edge of the profile for checking longitudinal bow and edge waviness, **iv)** major strain on FLD for checking edge cracking, **v)** strains in thickness direction for checking edge cracking and **vi)** dimensional error on final produced profile with springback.

Figure 47: Cold roll forming defects, FEM responses and respective quality characteristic constraints

Longitudinal strains distribution on cross section (flange and web) can affect bow and twist of roll formed profiles. Uneven distribution between flange and web can cause undesired defects (Halmos, 2006). Thus, the difference of mean values of longitudinal strains distribution between flange and web (at elongation and shrinkage peaks) should be minimized as:

$$\Delta \varepsilon_{long}^{-(web-flange)} \rightarrow \min \quad \text{Eq. (5.1)}$$

Moreover, another critical quality characteristic constrain for avoiding bow and twist is the minimization of the average value of peaks of longitudinal strains (elongation and shrinkage) at the edge of the profile. This quality characteristic can be calculated as:

$$\bar{\varepsilon}_{long}^{peak} \rightarrow \min \quad \text{Eq. (5.2)}$$

Longitudinal strains peaks (elongation and compression) at the edge of the roll formed profile are responsible for main defects, such as edge wave (buckling) and warping (bow) (Halmos, 2006). If elastic longitudinal strains at the edge of the profile surpass yield point of material,

then plastic deformations are accumulated at the edge and waviness and bow defects may occur. There is an elastic strain range ($\Delta\sigma_{\text{strain}}$) (Figure 48) that elastic longitudinal strains should not exceed. Thus all longitudinal strain peaks (elongation and shrinkage) should not surpass the yield point of material and compressive strength as avoiding edge buckling, as:

$$\varepsilon_{TYP} > \forall \varepsilon_{\text{long.}}^{\text{peak}} > \varepsilon_{CYP} \quad \text{Eq. (5.3)}$$

Figure 48: Tensile and compressive stress-strain curve for metals (Marciniak et al. 2002)

Mapping of major and minor strains of roll formed profile on material FLC can predict warping (bow) and twisting defects (Halmos, 2006). Failure modes assigned on the FLC is shown within Figure 49, and the forming window is appearing under the critical forming point FLC_0 . Different areas around FLC provide information about the deformation state of the produced profile and their effects on product and produced defects. Such defects can be fracture, tearing, shearing and wrinkling that can produce bow and twist. The critical forming limit (FLC_0) is the minimum value of major strain when minor strain is zero, and can be described with a function of n-value (work hardening exponent) and strip thickness for different steel types and grades (International Iron & Steel Institute, 2006).

Figure 49: Forming limit diagram (FLD) and forming window (Marciniak et al. 2002)

Thus the quality characteristic for major strains can be formulated as:

$$FLC_0 \geq \varepsilon_1 \quad \text{Eq. (5.4)}$$

Edge cracking could be predicted through monitoring of strains in thickness direction. Such strains should not surpass the ultimate elongation point (UEP) of material, as causing edge splitting. Thus, quality characteristic for thickness reduction can be formulated as:

$$0 < \varepsilon_3^{peak} < \varepsilon_{UEP} \quad \text{Eq. (5.5)}$$

Dimensional stability of the final cross section is another critical quality issue for the cold roll forming process. Dimensional error could be defined as the absolute difference of target value (design) with the actual predicted value with springback (FEM), as:

$$D_{error} = |Target - Actual| \quad \text{Eq. (5.6)}$$

For maintaining desired quality characteristics of the produced profile, the dimensional error should be within the cross-sectional tolerance range. Typical cold roll forming process cross-sectional tolerances are from $\pm 0.2\text{mm}$ to 0.8mm (Halmos, 2006). Thus the quality characteristic for the cross-sectional dimensional error could be formulated as:

$$D_{error} \leq D_{Tolerance} \quad \text{Eq. (5.7)}$$

In case the calculated (through FEM) optimum energy efficient solution cannot meet any of the quality characteristic constrain, then process variables could be alternated. Such alternation of the process variables can be done based on specific guidelines as roll formed product to meet such quality constraints. Several guidelines have been emerged from previous studies and literature (Paralikas et al. 2010a), (Paralikas et al. 2010b), (Paralikas et al. 2009), (Halmos, 2006). These can be applied and alternate undesired quality characteristic measures as to avoid cold roll forming product defects, as shown within Table 8.

Table 8: Guidelines for alternate quality characteristic constraints / countermeasures

N o	Defect Types	Redundant Deformations responsible	Process Guidelines / Countermeasures
1	Bow & Twist	Magnitude and non-uniformity transversal distribution of longitudinal membrane strain (elongation and shrinkage)	1.Appropriate number of roll passes 2.Roll positions and roll profiles design (smoothing flow line, downhill natural flow) 3.Entry and intermediate guides
2	Edge waviness (buckling)	Magnitude of longitudinal membrane strain at the coil edge (elongation and shrinkage)	1.Inter-distance between roll stations 2.Roll positions and roll profiles design (smoothing flow line, downhill natural flow)
3	Edge cracking (splitting)	Transversal tensile elongation at corner portions (major strain), strain in thickness direction	1.Minimize excessive longitudinal elongation/shrinkage that affects transversal elongation 2.Roll profiles design (gradually decrease of bending radii)
4	Springback	Relief of residual elastic stresses after forming	1.Over-bending at the end of the mill – or integration of over-bending within roll profiles design

6 CASE STUDY

In this chapter, the developments presented in the dissertation are examined and assessed with the help of case study. A U-channel profile was selected as a case study, as being extensively used in many industrial sectors and applications, such as framing, trim, brackets, slides, supports, stiffeners, rails, etc. Moreover such paradigm can be used as a basis for analyzing more complex profiles. The robust design algorithm was implemented utilizing the analytical model, and first energy efficient solution was calculated. Afterwards the quality characteristic constraints were checked through computational model results. First energy efficient solution, derived from the robust design algorithm, was updated as to become feasible based on process guidelines / countermeasures for the quality characteristic constraints, which do not meet quality characteristic constraints. A second energy efficient solution was derived, compared with the first, and quality characteristics were checked again. Finally, quality characteristic improvements were demonstrated for the second energy efficient solution compared with a benchmarking case for overall energy efficiency performance.

6.1 U-channel profile – Identification of variables and benchmark

For the application and demonstration of the robust design optimization methodology utilizing hybrid modeling approach a U-channel section was selected, as shown into Figure

50. This type of profile was selected due to its usage in a wide range of mass production applications, such as framing, trim, brackets, slides, supports, stiffeners and rails.

Figure 50: U-section profile and main dimensions ($A=50\text{mm}$, $w=200\text{mm}$, $L=1000\text{mm}$, $r=4\text{mm}$)

One paradigm of the extensive usage of such a U-channel profile is the mounting brackets of solar panels (Unirac, 2011), as shown in detailed views within Figure 51. Such mounting brackets and pole, required about 10 meters of U-channel profile each.

Figure 51: Benchmark for the use of U-channel profile on a photovoltaic mounting frame (Unirac, 2011)

For the application of the case study, benchmarking data for cold roll forming process of a U-channel profile should be set. Such benchmarking data will be used for comparison with robust optimization results, as indicating the level of energy efficiency enhancement for optimum solution. Benchmarking data, as shown within Table 9, are the most commonly used from cold roll forming machine builders and engineers from literature and market

(Gasparini, 2011), (Dreistern, 2011), (Samco Machinery, 2011), (Halmos, G., 2006), (Johnson Bros., 2011), (Samson, 2011).

Table 9: Benchmarking data for cold roll forming of U-channel profile (Gasparini, 2011), (Dreistern, 2011), (Samco Machinery, 2011), (Halmos, G., 2005), (Johnson Bros., 2011), (Samson, 2011)

No	Control Factors [x] of Benchmark	Value	Benchmark Energy Efficiency Indicator (m/J*Hr)
1	Bending Angle concept – (BAC)	10 RS	0.2155
2	Roller diameter – (D_L)	160 mm	
3	Line velocity (linear) – (V)	300 mm/sec	
4	Roll stations inter-distance – (L_R)	500 mm	
5	Rolls gap (clearance) – (G)	2%	

The energy efficiency indicator for the benchmarking data has been calculated using the analytical model, as shown within Table 9. Such energy efficiency indicator will be compared with optimum solutions, as demonstrating the advancements of using the proposed methodology for cold roll forming process.

The response for the robust design optimization is the energy efficiency indicator of the cold roll forming process, as calculated from analytical model described into previous chapter. Several specified inputs are given by the designer / customer for the product, as critical dimensions, material type, material thickness, etc. These inputs are considered as fixed variables, along with the material type to be used for the production of the U-channel profile. All these fixed variables along with the desired tolerances from the designer / customer are provided into Table 10.

Table 10: Roll formed product critical design parameters provided by the designer – customer

No	Fixed Variables	Units	Value
1	Inside bending radii – (r_i)	mm	4.0
2	Length of the flange – (A)	mm	50
3	Length of the web – (w)	mm	200
4	Total strip width (calculated) – (L)	mm	296.5
5	Final bending angle – (A_{final})	degrees	90
6	Material type	-	DP-600
7	Strip thickness (nominal) -	mm	2.0

Further to the fixed variables defined from the machine designer and customer, there are several other control variables defined by tooling design (Design Variables – DVs) and the processing (Process Variables – PVs). The design variables (DVs) and process variables (PVs) are selected based on the technical and geometrical specifications of a commercial roll forming machine (Dreistern, 2011), as shown within Table 11.

Table 11: Design and process variables as control factors for the cold roll forming process based on commercial roll forming machine (Dreistern, 2011)

No	Factors type	Control Factors	Units	Range
1	DV	Bending Angle concept – (BAC)	degrees	C5 - C20
2	DV	Roller diameter – (D_L)	mm	100 - 220
3	PV	Line velocity (linear) – (V)	mm/sec	100 – 310
4	PV	Roll stations inter-distance – (L_R)	mm	480 - 540
5	PV	Rolls gap (clearance) – (G)	% of nominal strip thickness (2.0 mm)	1% - 3% (0.02-0.06 mm)

One critical parameter, which determines the required number of roll stands, is the bending angle concept. Four bending concepts were identified that result to respective number of roll stands, as shown into Table 12. Based on experience, the entrance and exit angle of the roll forming line should be 5-10 degrees (Halmos, 2006). Thus, all the bending concepts start with 5 degrees, and end with 5 or 10 degrees.

Table 12: Bending angle concepts for U-channel profile

ID	1 RS	2 RS	3 RS	4 RS	5 RS	6 RS	7 RS	8 RS	9 RS	10 RS	...	18 RS	Total	No. RS
C5	5	5	5	5	5	5	5	5	5	5	..	5	90	18
C10	5	10	10	10	10	10	10	10	10	5			90	10
C15	5	15	15	15	15	15	10						90	7
C20	5	20	20	20	20	5							90	6

Noise variables (NVs), which are difficult or too expensive to be controlled, can be alternated randomly within a specific range. These NVs are friction coefficient, material thickness and critical material parameters, as shown within Table 13. This is due to the fact that during the production of the profile the friction conditions may vary randomly by the lubrication application and tool wear. Moreover, material thickness and critical material parameters may

vary from coil to coil and among suppliers for the same type of material. The strip thickness may vary along the length of the strip basically due to the rolling process variability from the coil production, which is depicted within Table 13 (Arcellormittal, 2001), (Kunitsyn et al., 2011).

Table 13: Noise variables for the optimization problem with mean target values

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

There are three methods to sample the domain of the noise factors and evaluate the mean and variance. These are: **i)** Monte Carlo simulation, **ii)** Taylor series expansion and **iii)** Orthogonal array based simulation (Phadke, 1989). The orthogonal array based simulation was chosen, as it provides significant advantages against the other two methods. Orthogonal array based simulation needs fewer experimental runs than Monte Carlo method without losing any accuracy level. Also when interactions between the noise factors are strong, it provides more accurate estimates of mean and variance compared with the Taylor Series expansion. Furthermore results from orthogonal array based simulation are the same as the Taylor series expansion.

Orthogonal array based simulation, samples the domain of the noise factors, and three levels for each factor are taken. These three levels are defined by the mean and standard deviation of each noise factor, as : $(\mu_i - \sqrt{3/2}\sigma_i), \mu_i, (\mu_i + \sqrt{3/2}\sigma_i)$. Then the noise factors are assigned to the orthogonal arrays to determine the testing conditions (sampling points) for evaluating the response. Standard deviation can be calculated if we assume that the range, within Table 13, is the 95.44% of the population of the normal distribution. Table 14 summarizes the range, minimum, maximum and standard deviation of the noise factors. Tolerances (%) are calculated based on the specified ranges within Table 13. Standard deviation can be calculated as:

$$4\sigma = [Range] \rightarrow \sigma = [Range]/4 \quad \text{Eq. (6.1)}$$

Table 14: Calculated values, ranges and standard deviations for the noise factors

No	Noise Factor	Tolerance (%)	Min value	Max value	Mean (μ_i)	Range	Standard deviation (σ_i)
1	Crr	50 %	0.00598	0.01794	0.01196	0.01072	0.00268
2	K	10 %	765.32	1052.315	956.65	191.33	47.8325
3	N	10 %	0.1539	0.1881	0.171	0.0342	0.00855
4	t	5 %	1.92	2.08	2.0	0.16	0.05

It was assumed that noise variables are following a Gaussian distribution, as they are clustered around the mean value. This mean is the target (nominal value), but in practice this target value may be alternated based on a specific standard deviation.

6.2 Robust design simulation and data analysis for energy efficiency indicator

Based on robust design algorithm described within previous chapter, the orthogonal arrays for noise and control variables were specified. For control variables the $L_{16}(4^5)$ orthogonal array was selected as there are five factors with four levels each, which yields to 16 runs (Phadke, 1989). For noise variables the $L_9(3^4)$ orthogonal array was selected as there are four factors with three levels each, which yields to 9 runs each. Orthogonal arrays with respective levels on each run are presented within Appendix D.

Each row of the control factors orthogonal array corresponds as an input to the noise factors orthogonal array, as described within Step 3 of robust design algorithm into Figure 45. This yields to simulation amount of (16 x 9) 144 runs. Results for 16 sets of runs are shown within Appendix D for mean variance and the summary statistic based on the larger-the-better type problem. The larger-the-better type problem was selected for the S/N ratio of the mean and variance values, as quality characteristic is continuous and non-negative and the goal is to be maximized (Phadke, 1989). Based on calculated summary statistic, the analysis of means (ANOM) for the S/N ratio was conducted (Table 15).

Table 15: Analysis of Means (ANOM) for the energy efficiency indicator response

Control Factors / ANOVA for S/N of the mean	Levels			
	1	2	3	4
A - Bending angle concept	-20.077	-16.515	-16.564	-21.128
B - Roller radius (R) - m	-15.739	-17.537	-19.689	-21.319
C – Line velocity (U) - m/sec	-21.183	-18.433	-17.500	-17.168
D - Rolls inter-distance (m)	-17.049	-18.054	-19.206	-19.975
E - Rolls gap (% of nom. t)	-15.551	-17.385	-19.452	-21.896

The plot of factor effects is then depicted within Figure 52 for the S/N ratio of the mean and variance of energy efficiency indicator response.

Figure 52: Plot of control factor effects for the S/N ratio of the energy efficiency indicator response

Based on the plot of 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. Optimum and worst set of factors levels are calculated (Table 16) and response characteristics (total work, number of roll stations, line length and cycle time) were calculated.

Table 16: Optimum and worst levels based on summary statistic of mean for power response

Control Factors	Levels			
	Optimum levels		Worst levels	
A -Bending angle concept	A2	C10	A4	C20

B - Roller radius (R) - m	B1 0.1	B4 0.22
C – Line velocity (U) - m/sec	C4 0.31	C1 0.1
D - Rolls inter-distance (m)	D1 0.48	D4 0.54
E - Rolls gap (% of nom. t)	E1 1	E4 3.1
Production rate (parts/hour)	192.41	84.9
Total power input (W/m)	29.75	43.53
Energy efficiency indicator (m/J*Hr)	0.3283	0.046
No. of RS	10	6

The analysis of variance (ANOVA) and the responsibility (%) for each control factor on the power response was then calculated within Table 17.

Table 17: Analysis of Variance (ANOVA) and responsibility (%) for each control factor

Control Factors	Degrees of freedom	Sum of squares	Mean square	Variance ratio F	Respons. (%)
A -Bending angle concept	3.00	68.24	22.75	0.35	23.62%
B - Roller radius (R) - m	3.00	71.57	23.86	0.36	24.77%
C – Line velocity (U) - m/sec	3.00	39.82	13.27	0.20	13.79%
D - Rolls inter-distance (m)	3.00	19.83	6.61		6.86%
E - Rolls gap (% of nom. t)	3.00	89.44	29.81	0.45	30.96%
Error	0.00	0.00	-		
Total	15.00	288.90			
(Error)	9.00	197.50	65.83		

Based on the ANOVA the responsibilities (%) of control variables on the energy efficiency indicator response have been calculated (Figure 53). Main responsibilities are 30.96%, 24.77% and 23.62% for rolls gap, rollers radius and bending concept variables respectively. Roll forming line velocity and rolls inter-distance variables have 13.79% and 6.86% responsibility on energy efficiency indicator respectively.

Figure 53: Responsibility (%) of each factor on energy efficiency indicator response for U-channel profile case study

6.3 Verification of the quality characteristic constraints

Based on the optimum set of process parameters levels, as shown into Table 16, a FEM analysis was implemented for the 1st optimum of cold roll forming of the U-channel profile. An explicit dynamics FEM was used for the cold roll forming process simulation as discussed within (Paralikas et al., 2010a) utilizing shell elements for both deformable strip and rigid rolls.

Table 18: Quality characteristics checking results for 1st Optimum solution

	1 st Optimum (EEF_V1)	Quality characteristics of 1 st Optimum (EEF_V1)
Energy efficiency indicator	0.3283 (m/J*hr)	-
Tensile peaks		
Mean difference of longitudinal strains distribution on profile	+ 0.04 %	$\Delta \varepsilon_{long}^{(web-flange)} \rightarrow \min$
Mean of longitudinal peaks	+ 12.07 %	$17.5\% = \varepsilon_{TFP} > \forall \varepsilon_{long}^{peak}$
Compression peaks		
Mean difference of longitudinal strains distribution on profile	- 0.049 %	$\Delta \varepsilon_{long}^{(web-flange)} \rightarrow \min$
Mean of longitudinal peaks	- 16.11 %	$\forall \varepsilon_{long}^{peak} > \varepsilon_{CTP} = -17.5\%$
Thickness reduction	- 0.178 %	$\varepsilon_3^{min} = -0.178 > UEP_{DP800} = -0.179$
Major strain	+ 0.225 %	$\varepsilon_1^{max} = 0.225 < FLC_0 = 0.223$
Maximum dimensional error	0.438 mm	$D_{error}^{flange} = 0.439 > 0.4 = D_{tolerance}$

■ : Feasible

■ : Close to constrain

■ : Not feasible

Quality constraints were checked utilizing FEM responses (Figure 47) of cold roll forming process with optimum set of process parameters (control factors) and mean values of the noise factors. Several quality characteristic constraints for 1st optimum (EEF_V1) have not met, as shown within Table 18. Alternation of 1st optimum (EEF_V1) model was imposed based on the process/design guidelines and counter-measures from Table 8. The selection of alternation should be done taking into account the minimum effect of such changes on the energy efficiency indicator. Thus, an effects analysis was implemented based on sensitivity analysis of the energy efficiency indicator with process parameters, as shown within Table 19.

Table 19: Effects analysis for cold roll forming process guidelines on energy efficiency indicator

No	Process / Design Parameter alternation	Level of effect of change on energy efficiency indicator	Comments / Effects on energy efficiency indicator
1	Bending angle concept	High	Add more stations, length
2	Roller radius	High	Add more rotating mass
3	Line velocity	Medium to High	Increase rotational speed
4	Rolls inter-distance	Medium	Increase line length
5	Rolls gap	High	More frictional work
6	Flow line (downhill)	Low	Follow a more “natural” flow

Following such effects analysis (Table 19), the parameters with low and medium effect on energy efficiency indicator were selected, such as rolls inter-distance and flow line (downhill). Such selection of parameters is covering process defects alleviation, as shown within analysis of 1st optimum solution into Table 18.

Line alternations as following 2nd Optimum (EEF_V2) solution (Figure 54) are covering: **i)** lowering of the roll station axis with 2mm vertical step from rolls station to rolls station, and **ii)** increase of roll stations inter-distance of 20mm each, resulting in total increase of roll forming line length of 140mm. Such set of alternations in roll forming line are causing a decrease of energy efficiency indication of 1.6%, while meeting all and improving several quality characteristics.

Figure 54: EEF_V1 FEM solution and alternations for EEF_V2 FEM solution through closed loop

A second computational model was build following alternations for 2nd Optimum (EEF_V2), based on the first one, and run as checking quality characteristic constraints. The results of the computational models were compared and presented hereafter.

The difference between the average values of longitudinal strains distribution at flange and web for elongation and shrinkage peaks are predicted within Figure 55 and Figure 56. For elongation peaks the average difference (between flange and web) is 0.04% for EEF_V1 and

0.0295% for EEV_V2, as resulting in 26.5% decrease. For shrinkage peaks the average difference (between flange and web) is -0.049% for EEV_V1 and -0.0398% for EEV_V2, as resulting in 18.7% decrease. The average values of the peaks for elongation is 0.0854% for EEV_V1 and 0.0693% for EEV_V2, as resulting in 18.8% decrease. The average values of the peaks for shrinkage is -0.1108% for EEV_V1 and -0.0962% for EEV_V2, as resulting in 13.1% decrease. Moreover, all peaks of longitudinal strains for elongation and shrinkage are within the elastic limits of DP600 material, as:

$$-0.175\% > \forall \varepsilon_{long}^{peak} > 0.175\% \quad \text{Eq. (6.2)}$$

Figure 55: Longitudinal strains along roll forming direction and elongation peak distribution on cross section at 8th roll station for EEV_V1 and EEV_V2

Figure 56: Longitudinal strains along roll forming direction and shrinkage peak distribution on cross section at 3rd roll station for EEF_V1 and EEF_V2

Major strains peak has decrease of 13.9% from EEF_V1 to EEF_V2 solution (Figure 57) as meeting quality characteristic constrain:

$$\varepsilon_1^{\max} = 0.194 < FLC_0 = 0.223$$

Eq. (6.3)

Figure 57: Major-minor strains at FLD of DP600 for EEV_V1 and EEV_V2

Strains in thickness direction peak have been decrease of about 8.4% from EEV_V1 to EEV_V2 solution (Figure 58), as meeting quality characteristic constrain:

$$\varepsilon_3^{\min} = -0.163 > UEP_{DP600} = -0.179 \quad \text{Eq. (6.4)}$$

Figure 58: Strains in thickness direction along final roll formed profile for EEV_V1 and EEV_V2

The cross-sectional dimensional error on the flange has been decrease of 45.3% from EEF_V1 to EEF_V2 solution (Figure 59). The dimensional error for EEF_V2 is within the typical tolerance of cold roll forming process, as:

$$D_{error}^{flange} = 0.239 < 0.8 = T_{section} \quad \text{Eq. (6.5)}$$

Figure 59: Final produced cross section and dimensional errors for EEF_V1 and EEF_V2

Results for the quality characteristic checking through computational model are quoted within Table 20, for both 1st Optimum (EEF_V1) and 2nd Optimum (EEF_V2) solutions. It can be observed that the 2nd Optimum (EEF_V2) solution is a feasible one, as all quality characteristic constraints is within limits. Moreover, the quality characteristics have been improved considerably with the application of the alternation to the roll forming line using process guidelines / countermeasures. On the other hand, energy efficiency indicator has been decreased only 1.6 %, as a result of the increase of the roll forming line length.

Table 20: Quality characteristics checking results for 2nd Optimum solution (EEF_V2) and comparison of difference with 1st Optimum solution (EEF_V1)

	1 st Optimum (EEF_V1)	2 nd Optimum (EEF_V2)	Quality characteristics of 2 nd Optimum (EEF_V2)	Diff.
Energy efficiency indicator	0.3283 (m/J*hr)	0.3231 (m/J*hr)	-	-1.6 %
Tensile peaks				
Mean difference of longitudinal strains distribution on profile	+ 0.04 %	+ 0.0295 %	$\Delta \bar{\varepsilon}_{long}^{(web-flange)} \rightarrow \min$	- 26.5 %
Mean of longitudinal peaks	+ 12.07 %	+ 13.19 %	$17.5\% = \varepsilon_{TF} > \forall \varepsilon_{long}^{peak}$	+ 9.27 %
Compression peaks				
Mean difference of longitudinal strains distribution on profile	- 0.049 %	- 0.0398 %	$\Delta \bar{\varepsilon}_{long}^{(web-flange)} \rightarrow \min$	- 18.7 %
Mean of longitudinal peaks	- 16.11 %	- 15.11 %	$\forall \varepsilon_{long}^{peak} > \varepsilon_{CF} = -17.5\%$	- 6.2 %
Thickness reduction	- 0.178 %	- 0.163 %	$\varepsilon_s^{min} = -0.163 > UEP_{EP600} = -0.179$	- 13.9 %
Major strain	+ 0.225 %	+ 0.194 %	$\varepsilon_1^{max} = 0.194 < FLC_0 = 0.223$	- 8.4 %
Maximum dimensional error	0.438 mm	0.239 mm	$D_{error}^{flange} = 0.239 < 0.4 = D_{tolerance}$	- 45.3 %

6.4 Benchmark analysis for the U-channel profile

Benchmarking analysis was implemented within current section, as demonstrating the effectiveness of the proposed robust design optimization methodology for cold roll forming process energy efficiency against the current process setup. Moreover, the results could be demonstrated within a mass production paradigm, as showing real environmental and financial benefits within a solar park investment (Athens International Airport solar park).

For 2nd Optimum solution (EEF_V2) there is an increase of 1% of productivity (meters of profile produced per hour) compared with the benchmarked data. The total specific energy consumption was reduced by 32.64% compared with benchmark specific energy consumption, as shown within Figure 60.

Figure 60: Comparison of benchmark with 1st and 2nd Optimum for total energy consumption (J/m) and productivity (PPH)

Based on such results, the energy efficiency indicator can be calculated for both benchmark and optimum solutions, as shown within Figure 61. The overall energy efficiency indicator for the 2nd Optimum compared with benchmark was increased by 49.92%.

Figure 61: Comparison on benchmark with 1st and 2nd Optimum for energy efficiency indicator

Taking into account such results for productivity, energy consumption and energy efficiency indicator, the paradigm of the application of U-channel production for building Athens International Airport solar park (Athens International Airport, 2011) is followed. With that case study, the benefits in mass production could be demonstrated for environmental and financial impacts.

For building Athens International Airport solar park (the biggest airport solar park in Europe) there is a need of covering area of 160.000 m² with solar panels. 80 poles per 1000m² can be installed, which yields to the need of installation of 12.800 poles. Thus, as taking into account that each pole needs the production of 10 meters of U-channel profile, there is the need of production in total 128.000 meters of profile, as shown within Figure 62. Time and total energy for profiles production using benchmarking data and 2nd Optimum solution (EEF_V2) were calculated. There is 1% reduction of time required and 32.64% reduction of total energy consumption, which yields to saving of 124 MWh over project-time. Financial impact, based on industrial cost rates of energy (Public Power Corporation, 2011), is about 7500 Euros savings for total production of profiles.

Figure 62: Results of benchmarking analysis for Athens International Airport El. Venizelos solar park (Athens International Airport, 2011), (Public Power Corporation, 2011)

7 CONCLUSIONS

In this chapter the results of the dissertation's developments are discussed and conclusions are drawn. The innovations of the work are pointed out and topics that still remain open for further research and development are referred.

As described in the introduction, the main objective of the dissertation was the development of methodology for the robust design optimization of the energy efficiency of cold roll forming process. Towards this target, analytical model for the calculation of the energy efficiency indicator was developed and a computational one for checking of quality characteristic constraints. Robust optimization methodology was proposed for control factors, utilizing hybrid modeling approach, as taking into account the uncertainty of the noise factors. Moreover, as checking quality characteristic constraints, utilizing computational model, a closed loop was implemented as to prove feasibility of the optimum solution. Finally, the case study revealed the benefits of the proposed methodology within a U-channel profile in mass production. Recapitulating, the major results and conclusions of the present dissertation are presented hereafter:

- No previous methodology developed for the energy efficiency definition and optimization of the cold roll forming process. The energy efficiency indicator was defined as the ratio of the useful output of the process to the total energy consumption.

- There is calculation of the optimum solution for the energy efficiency of the cold roll forming process, as taking into account the uncertainty of noise factors for computer experiments
- No previous attempt for optimization utilizing hybrid modeling, as using an analytical and a computational one. Analytical model used for the calculation of the energy efficiency indicator and a computational one for checking feasibility through quality characteristic constraints.
- Calculation of the required number of forming stations for energy efficient solution. Previous attempt for calculation of number of forming stations required was implemented using equations with empirical factors.
- Based on computational model convergence, the computational models for cold roll forming process are computational expensive. They require for providing solution in explicit dynamics about 3.5 days (85 hours).

Moreover, major results and conclusions of case study of the dissertation are presented hereafter:

- Within case study there is a demonstration of the application of methodology for optimization of cold roll forming process energy efficiency with five control factors and four noise factors.
- Case study revealed the practicality and ability for industrial exploitation of the proposed methodology as 144 computer experiments required with that configuration of factors. Using computational inexpensive analytical model for such a huge number of computer experiments proves for the practicality and applicability of the proposed methodology.
- Only two computational models required for checking and proving feasibility of the optimum solution through quality characteristic constraints. Implementation of the closed loop for alternation of the first optimum solution leads to:

- Reduction of mean of peaks of longitudinal strains in the order of **15%**
 - Reduction of the bending line thickness reduction in the order of **8.5%**
 - Reduction of peaks of major strains in the order of **14%**
 - Reduction of dimensional error of the final profile after springback in the order of **45%**
- Moreover there is a comparison of the 2nd optimum solution (EEF_V2) with a benchmark. The benchmark covers the application of the U-channel profile within a solar panel mounting bracket. Results compared with benchmark showed:
 - Increase of productivity by **1%**
 - Decrease of the total energy consumption by **32.64%**
 - Increase of the energy efficiency indicator by **49.92%**

7.1 Further work

Although the present dissertation presented a complete solution for the optimization of the cold roll forming process energy efficiency, there are still open topics that need further research and development. In brief, these topics are:

- Application of the methodology for cold roll forming process optimization of energy efficiency in more complex geometrical profiles.
- Application of the methodology for cold roll forming process optimization of energy efficiency for more advanced materials.
- Application of the methodology for cold roll forming process optimization of energy efficiency in non symmetrical profiles.
- Investigation of methodology in further sheet metal forming and bending processes, that is in in-line with cold roll forming process.

REFERENCES

- [1] Almeida, A., Greenberg, S., (2004), Electric motors, Encyclopedia of Energy, Volume 2, Elsevier Inc.
- [2] Alsamhan, A., Pillinger, I., Hartely, P., (2004), The development of real time re-meshing technique for simulating cold-roll-forming using FE methods, Journal of Materials Processing Technology, 147:1–9
- [3] Alvarez, W., (2006), Roll form tool design, Industrial Press Inc.
- [4] ANSYS Release 10.0, (2005), ANSYS LS-Dyna User Guide, ANSYS Inc.
- [5] Arcelormittal, Hot rolling according to requirements, URL: http://www.arcelormittal.com/gent/prg/selfware.pl?id_sitemap=107&language=EN
- [6] Athens International Airport Solar Park Press Release, 2011: <http://www.aia.gr/entry.asp?pageid=741&tablepageid=12&langid=2&entryid=374>
- [7] Barthelemy, J. F. M., Haftka, R., (1993), Approximations concepts for optimal structural design – a review. Structural Optimization, 5(3):129–144
- [8] Bhattacharyya, D., Smith, P.D., Yee, C.H., Collins, I.F., (1984), The prediction of deformation length in cold roll forming, Jour. of Mech. Work. Technol., 9:181–191
- [9] Boman, R., Papeleux, L., Bui, Q.V., Ponthot, J.P., (2006), Application of the Arbitrary Lagrangian Eulerian formulation to the numerical simulation of cold roll forming process, Journal of Materials Processing Technology 177:621–625

- [10] Bonte, M. H. A., van den Boogaard, A. H., Huétink, J., (2008), An optimization strategy for industrial metal forming processes Modeling, screening and solving of optimization problems in metal forming, *Struct Multidisc Optim*, 35:571–586, DOI 10.1007/s00158-007-0206-3
- [11] Bucher, C., (2005), *Stochastic Analysis in Structural Optimization*, Weimarer Optimierungs- und Stochastiktag 2.0 – 1./2.
- [12] Bui, Q.V., Ponthot, J.P., (2007), Numerical simulation of cold roll-forming processes, *J. Mater. Process. Tech.*, doi:10.1016/j.jmatprotec.2007.08.073
- [13] Chachuata, B., Srinivasan, B., Bonvinc, D., (2009), Adaptation strategies for real-time optimization, *Computers and Chemical Engineering*, 33:1557–1567
- [14] Chrysosolouris, G., (2005), *Manufacturing Systems-Theory and Practice*, 2nd Edition, Springer-Verlag.
- [15] Damm K., (1989) Ermittlung von Längsformänderungen beim Walzprofilieren von Standardprofilen auf einer mehrgerüstigen Anlage, Institut für Produktionstechnik und Umformmaschinen, Technische Universität Darmstadt , Dissertation
- [16] Donglai, W., Zhenshan, C., Jun, C., (2008), Optimization and tolerance prediction of sheet metal forming process using response surface model, *Computational Materials Science*, 42:228–233, doi:10.1016/j.commatsci.2007.07.014
- [17] Dreistern GmbH & Co. KG, Roll forming machines, URL: <http://www.dreistern.com/eng/products/rollforming/rollforming.htm>
- [18] Fang, K., Li, R., Sudjiano, A., (2006), *Design and modeling for computer experiments*, Chapman & Hall/CRC
- [19] Fellipe, A., (2008), “Surrogate modeling techniques and heuristic optimization methods applied to design and identification problems”, Universidade federal de uberlandia faculdade de engenharia mecanica, PhD dissertation
- [20] FUTURA internal report, (2008), MFMs’ processing and environmental specifications; Material characterization database.
- [21] Gasparini Roll Forming machines website, 2011: <http://www.gasparini-spa.com/eng/>
- [22] Hallquist, J.O., (2006), *LS-Dyna Theory manual*, Livermore Software Technology Corp
- [23] Halmos, G.T., (2006), *Roll forming handbook*, CRC

-
- [24] Han, Z-W, Liu, C., Lu, W-P, Ren, L-Q, Tong, J., (2005), Spline finite strip analysis of forming parameters in roll forming a channel section, *Journal of Materials Processing Technology* 159:383–388
- [25] Harewood, F.J., McHugh, P.E., (2007), Comparison of the implicit and explicit finite element methods using crystal plasticity, *Computational Materials Science* 39:481–494
- [26] Hong, S., Lee, S., Kim, N., (2001), A parametric study on forming length in roll forming, *Journal of Materials Processing Technology*, 113: 774-778
- [27] Hou, B., Wang, W., Li, S., Lin, S., Xia, Z. C., (2010), Stochastic analysis and robust optimization for a deck lid inner panel stamping, *Materials and Design*, 31:1191–1199, doi:10.1016/j.matdes.2009.09.033
- [28] Hu, W., Yao, L-G., Hua, Z.-Z., (2008), Optimization of sheet metal forming processes by adaptive response surface based on intelligent sampling method, *Journal of materials processing technology*, 197:77–88, doi:10.1016/j.jmatprotec.2007.06.018
- [29] Ingarao, G., Lorenzo, R., Micari, F., (2009), Internal pressure and counterpunch action design in Y-shaped tube hydroforming processes: A multi-objective optimization approach, *Computers and Structures* 87:591–602, doi:10.1016/j.compstruc.2009.02.003
- [30] International Energy Agency (IEA), *World energy outlook 2010*
- [31] International Iron & Steel Institute, (2006), *Advanced High Strength Steel (AHSS) application guidelines*, Committee on Automotive applications
- [32] Jakumeit, J., Herdy, M., Nitsche, M., (2005), Parameter optimization of the sheet metal forming process using an iterative parallel Kriging algorithm, *Struct Multidisc Optim*, 29:498–507, DOI 10.1007/s00158-004-0455-3
- [33] Jeong, S.H., Lee, S.H., Kim, G.H., Seo, H.J., Kim, T.H., (2007), Computer simulation of U-channel for under-rail roll forming using rigid-plastic finite element methods, *J. Mater. Process. Tech.*, doi:10.1016/j.jmatprotec.2007.11.130
- [34] Johnson Bros. metal forming co. website, 2011: <http://www.johnsonrollforming.com/display.php/display/A1/category/2>
- [35] Jurecka, F., (2007), *Robust Design Optimization Based on Metamodeling Techniques*, Technical University of Munich, PhD Dissertation
-

- [36] Kunitsyn, G. A., Golubchik, E. M., Smirnov, P. N., (2011), Ongoing control of the transverse thickness fluctuation of cold-rolled high-strength strip, *Steel in Translation*, Vol. 39, 10:920-924, DOI: 10.3103/S0967091209100192
- [37] Lange, K., (1985), *Handbook of Metal Forming*, McGraw-Hill
- [38] Li, D. Y., Peng, Y. H., Yin, J. L., (2007), Optimization of metal-forming process via a hybrid intelligent optimization technique, *Struct Multidisc Optim*, 34:229–241, DOI 10.1007/s00158-006-0075-1
- [39] Li, W., Hu, S. J., Cheng, S-W., (2002), Robust Design and Analysis for Manufacturing Processes with Parameter Interdependency, *SME journal of manufacturing systems*, Vol. 21/2:93-100
- [40] Lindgren, M., (2005), Modeling and simulation of the roll forming process, Licentiate thesis, Lulea University of technology
- [41] Lindgren, M., (2007a), Cold roll forming of a U-channel made of high strength steel, *J. Mater. Process. Tech.*, doi:10.1016/j.jmatprotec.2006.12.017
- [42] Lindgren, M., (2007b), Experimental investigations of the roll load and roll torque when high strength steel is roll formed, *Journal of Materials Processing Technology*, vol. 191:44–47
- [43] Marciniak, Z., Duncan, J. L., Hu, S.J., (2002), *Mechanics of Sheet Metal Forming*, Butterworth-Heinemann, ISBN 0750653000
- [44] Oh, M., Kim, N., (2008), Optimum design of roll forming process of slide rail using design of experiments, *Journal of Mechanical Science and Technology*, 22:1537-1543, DOI 10.1007/s12206-008-0430-9
- [45] Panton, S.M., Duncan, J.L., Zhu, S.D., (1996), Longitudinal and shear strain development in cold roll forming, *Journal of Materials Processing Technology*, 60:219-224
- [46] Paralikas, J., Salonitis K. and Chryssolouris G., (2010b), “Investigation of the effect of roll forming pass design on main redundant deformations on profiles from AHSS”, *International Journal of Advanced Manufacturing Technology*
- [47] Paralikas, J., Salonitis K., Chryssolouris G., (2009), Investigation of the roll forming process parameters’ effect on the quality of an AHSS open profile, *International Journal of Advanced Manufacturing Technology*, 44: 223-237, DOI 10.1007/s00170-008-1822-9
- [48] Paralikas, J., Salonitis K., Chryssolouris G., (2010a), Optimization of the roll forming process parameters - A semi empirical approach, *International Journal of*

-
- Advanced Manufacturing Technology, 47: 1041-1052, DOI 10.1007/s00170-009-2252-z
- [49] Patterson, M. G., (1996), What is energy efficiency? Concepts, indicators and methodological issues, Energy Policy. Vol. 24, No. 5:377-390.
 - [50] Phadke, M. S., (1989), Quality Engineering using robust design, Prentice Hall PTR; US Ed edition.
 - [51] Public Power Corporation S.A. website, 2011: <http://www.dei.gr/Default.aspx>
 - [52] Rojeka, J., Zienkiewicz, O.C., Onatec, E., Posteka. E., (2001), Advances in FE explicit formulation for simulation of metalforming processes, Journal of Materials Processing Technology 119:41–47
 - [53] Roos, D., Adam, U., Bucher, C., (2006), Robust design optimization, Weimar Optimization and Stochastic Days 3.0
 - [54] Salonitis K., Paralikas, J., Chrysosolouris, G., (2008), Roll Forming of AHSS: Numerical Simulation and investigation of effects of main process parameters on quality, 1st International Conference of Engineering Against Fracture, Patras, Greece
 - [55] Samco Machinery Roll Forming solutions website, 2011: <http://www.samco-machinery.com/>
 - [56] Samson Roll formed products company website, 2011: <http://www.samsonrollform.com/UChannels.aspx>
 - [57] Sun, G., Li, G., Gong, Z., Cui, Z., Yang, X., Li, Q., (2010), Multiobjective robust optimization method for drawbead design in sheet metal forming, Materials and Design, 31:1917–1929, doi:10.1016/j.matdes.2009.10.050
 - [58] Tang, Y., Chen, Y., (2009), Robust design of sheet metal forming process based on adaptive importance sampling, Struct Multidisc Optim, 39:531–544, DOI 10.1007/s00158-008-0343-3
 - [59] Tehrani, M.S., Naeini, H.M., Hartley, P., Khademizadeh, H., (2006), Localized edge buckling in cold roll-forming of circular tube section, Journal of Materials Processing Technology 177: 617–620
 - [60] Unirac website, 2011: <http://www.unirac.com>
 - [61] Wei, L., Yuying, Y., (2008), Multi-objective optimization of sheet metal forming process using Pareto-based genetic algorithm, Journal of materials processing technology, 208:499–506, doi:10.1016/j.jmatprotec.2008.01.014
-

- [62] Wick, C., Benedict, J., Veilleux, R., (1984), Tool and manufacturing engineers handbook, Volume 2 Forming, SME
- [63] World Auto Steel, (2011), “Advanced High-Strength Steel Application Guidelines Version 4.1”
- [64] Yang, K., El-Haik, B., (2003), Design For Six Sigma; A roadmap for Product Development, McGraw-Hill, Inc., New York, USA, ISBN 0-07-141208-5
- [65] Zeng, G., Li, S. H., Yu, Z. Q., Lai, X. M., (2009), Optimization design of roll profiles for cold roll forming based on response surface method, *Materials and Design*, 30:1930–1938, doi:10.1016/j.matdes.2008.09.018
- [66] Zhang, G., Hu, S. J., Wu, X., (2003), Numerical Analysis and Optimization of Hemming Processes, *Journal of Manufacturing Processes*, Vol. 5/No. 1
- [67] Zhi-wu, H., Cai, L., Wei-ping, L., (2002), Numerical simulation of roll forming for channel section with outer edge, *Applied Mathematics and Mechanics*, Vol 23, No 3

APPENDIX A NOMENCLATURE

η_{RF}	is the energy efficiency indicator of the roll forming process (m/Joule*Hr)
PRH	is the production rate of the roll forming mill per unit of time (number of 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)
U_{line}	is the roll forming line velocity (m/sec)
N_{rolls}	is the number of roll stations of the line (-)
L_{rolls}	is the inter-distance between roll stations (m)
$P_{motor,in}$	is the power of motor input from the grid (Joules/sec)
η_{motor}	is the electric motor efficiency (%)
η_{drive}	is the drivetrain motor efficiency (%)
$P_{shaft,out}$	is the power of shaft input from the drivetrain system (Joules/sec)
E_{total}	is the total energy of the mill (without drivetrain and motor losses) for roll forming of one meter of product (Joules/m)
E_{kin}	is the kinetic energy of the roll forming mill (Joules/m)
E_{int}^{def}	is the internal deformation work per meter of produced product (Joules/m)

E_{fr}^{pull}	is the friction work through pulling of the material within the mill per meter of produced product (Joules/m)
E_{kin}^{shaft}	is the kinetic energy of the rotated shaft (Joules)
E_{kin}^{rolls}	is the kinetic energy of rotated rollers (Joules)
I_{shaft}	is the second moment of inertia for rotated shafts (kg·m ²)
I_{rolls}	is the second moment of inertia for rotated rollers (kg·m ²)
ω_{roll}	is the rotational velocity of the rollers (rad/sec)
ε	is the bending strain (-)
R	is the radius of bending curvature at neutral axis (m)
y	is the distance from the neutral axis of bending (m)
r	is the inner radius of bending curvature (m)
$\dot{\varepsilon}$	is the bending strain rate (1/sec)
$\Delta\theta$	is the bending angle increment (rad)
u_{bend}	is the velocity of the edge of the flange (m/sec)
A	is the flange width (m)
ω_{roll}	is the angular velocity of the rollers (rad/sec)
$E_{bending}$	is the bending energy per meter of produced product (Joules/m)
$E_{stretching}$	is the stretching energy per meter of produced product (Joules/m)
R_{roll}	is the radius of the roller (m)
L_1^{geo}	is the geometrical length of the edge of the flange (m)
L_1^{def}	is the deformed length of the edge of the flange (m)
$S(X)$	is the shape function (-)
$L_{S(X)}$	is the correction factor of the shape function
$M_{bending}$	is the bending moment (Nt*m/m)
C, P	are the Cowper-Symond strain rate parameters (-)
K	is the strength coefficient of the material (MPa)
n	is the hardening parameters of the material (-)
t	is the strip thickness of the material (m)
V_{flange}	is the volume of material of the flange (m ³) .

$L_{product}$	is the length of the produced product (m)
$\varepsilon_{elastic}$	is the elastic longitudinal strain at the flange (-)
ε_{YP}	is the yield point of material (-)
$\varepsilon_{plastic}$	is the plastic longitudinal strain at the flange (-)
E_{strip}	is the Young modulus of the material of the deformable strip (Nt/m ²)
$\varepsilon_{contact}$	is the elastic contact strain (-)
$A_{contact}$	is the contact area between the roller and the deformable strip (m ²)
d	is the roll gap (expressed as the sagitta in trigonometry, in m)
θ	is the contact angle of the roller on the strip (in rad)
w	is the length of the web of the roller (m)

APPENDIX B LIST OF FIGURES

FIGURE 1: ROLL FORMING PROCESS (SCHEMATICS).....	2
FIGURE 2: OUTER EDGE TRAVELS GREATER DISTANCE THAN WEB THROUGH SUCCESSIVE ROLLERS	2
FIGURE 3: TYPICAL FLOWER PATTERN FOR A ROLL FORMED PROFILE.....	2
FIGURE 4: COLD ROLL FORMING FLEXIBILITY IN TOOLING CHANGES, TOOLING ADJUSTABILITY WITH NO COST AND LOW SETUP TIMES	3
FIGURE 5: COMPARISON OF PROFILING PROCESS WITHIN RANKING SYSTEM (1 TO 5) FOR DIFFERENT PERFORMANCE MEASURES	4
FIGURE 6: OVERVIEW OF MATERIALS USED IN COLD ROLL FORMING PROCESS IN AUTOMOTIVE INDUSTRY (BLUE BOXES) (FUTURA IP, 2008).....	7
FIGURE 7: EVALUATION MATRIX OF DIFFERENT MATERIALS AND APPLICATION FIELDS INTO AUTOMOTIVE BiW (FUTURA IP, 2008)	8
FIGURE 8: EVOLUTION OF MATERIALS CONCEPTS FOR EVOLUTION OF MERCEDES-BENZ C-CLASS (BR203 TO BR204) (AHSS: ADVANCED HIGH STRENGTH STEELS, HSS: HIGH STRENGTH STEELS, UHSS: ULTRA HIGH STRENGTH STEELS) (FUTURA IP, 2008).....	9
FIGURE 9: SCHEMATIC OF AHSS STEELS (SHOWN IN COLOR) COMPARED TO LOW STRENGTH STEELS (DARK GREY) AND TRADITIONAL HSS (LIGHT GREY) (WORLD AUTO STEEL, 2011)	10
FIGURE 10: PROPERTIES AND MICROSTRUCTURE OF THE AHSS CATEGORIES (WORLD AUTO STEEL, 2011).....	10
FIGURE 11: COLD ROLL FORMING PROCESS APPLICATIONS.....	12
FIGURE 12: ROLL FORMED AUTOMOTIVE BiW SILLS AND SCALABILITY FOR DIFFERENT FLOOR LENGTHS	12
FIGURE 13: HISTORICAL EVOLUTION OF THE COLD ROLL FORMING PROCESS AND ENERGY CONSUMPTION BY SECTOR	14
FIGURE 14: COLD ROLL FORMING PROCESS ENERGY EFFICIENCY PYLONS AND OPTIMIZATION TARGETS.....	14
FIGURE 15: ENERGY EFFICIENCY OPTIMIZATION METHODOLOGY FOR THE COLD ROLL FORMING PROCESS	16
FIGURE 16: CURRENT APPROACH FOR OPTIMIZATION USING COMPUTER EXPERIMENTS	17

FIGURE 17: PROPOSED APPROACH FOR OPTIMIZATION USING COMPUTER EXPERIMENTS	17
FIGURE 18: QUALITATIVE COMPARISON OF OPTIMIZATION METHODS - USING PHYSICAL EXPERIMENTS COMPUTER EXPERIMENTS, META-MODELS AND HYBRID MODELING PROCEDURES - FOR DEVELOPMENT TIME AND COMPUTATIONAL COST	25
FIGURE 19: COLD ROLL FORMING LINE SCHEMATIC FOR POWER DISTRIBUTION	33
FIGURE 20: DEFORMED ELEMENTS DURING BENDING OF THE STRIP	35
FIGURE 21: SCHEMATIC FOR VELOCITIES AND MAIN GEOMETRICAL DIMENSIONS FOR ONE ROLL FORMING BETWEEN TWO ROLL STANDS	36
FIGURE 22: CALCULATED "SHAPE FUNCTION" FOR DIFFERENT VALUES OF FACTOR "N"	37
FIGURE 23: CALCULATED "SHAPE FUNCTION" VALUES ACROSS INTER-DISTANCE LENGTHS FOR DIFFERENT VALUES OF N	38
FIGURE 24: BENDING STRAIN RATE FOR DIFFERENT INTER-DISTANCES BETWEEN ROLL STATIONS ALONG COLD ROLL FORMING LINE VELOCITY RANGE	38
FIGURE 25: STRESS DISTRIBUTION FOR A POWER-LAW-HARDENING SHEET BENT WITHOUT TENSION (MARCINIAK ET AL. 2002)	39
FIGURE 26: COLD ROLL FORMING PROCESS SCHEMATIC - OUTER EDGE TRAVELS GREATER DISTANCE THAN BENDING LINE THROUGH SUCCESSIVE ROLLERS	40
FIGURE 27: TOTAL LONGITUDINAL MEMBRANE STRAIN PROFILE ALONG FLANGE LENGTH DURING ROLL FORMING BETWEEN TWO ROLL STANDS	40
FIGURE 28: ROLL STANDS PROFILE (HALF DUE TO SYMMETRY) AND RELIEF ANGLE APPLIED ON THE UPPER ROLLER	42
FIGURE 29: CONTACT FORCE PROFILE ON THE CONTACT AREA OF ROLLER WEB ON THE STRIP SURFACE	43
FIGURE 30: EXPERIMENTAL CONDITIONS AND COMPARISON OF EXPERIMENTAL RESULTS FOR ENERGY CONSUMPTION** (LINDGREN 2007B) WITH ANALYTICAL MODEL RESULTS	46
FIGURE 31: U-SECTION PROFILE AND MAIN DIMENSIONS: A=50MM, W=200MM, L _{PRODUCT} =1M, R=4MM	46
FIGURE 32: COLD ROLL FORMING OF A U-CHANNEL (HALF GEOMETRY DUE TO SYMMETRY) MAIN PROCESS PARAMETERS (INTER-DISTANCE BETWEEN ROLL STANDS – L, ROLL FORMING LINE VELOCITY – U _{LINE} , ROLLER RADIUS – R, AND BENDING ANGLE - D θ)	47
FIGURE 33: ANALYSIS OF MEANS (ANOM) AND PLOTS OF FACTORS EFFECTS FOR S/N RATIO FOR ENERGY EFFICIENCY INDICATOR	50
FIGURE 34: RESPONSIBILITY (%) OF EACH FACTOR FOR S/N RATIO FOR ENERGY EFFICIENCY INDICATOR	51
FIGURE 35: PLOT OF ENERGY EFFICIENCY INDICATOR (%) FOR ROLL FORMING LINE VELOCITY AND NUMBER OF ROLL STATIONS (BENDING CONCEPT)	51
FIGURE 36: PROCEDURE FOR COLD ROLL FORMING PROCESS AND SPRINGBACK ANALYSES	56
FIGURE 37: SHELL163 AND THROUGH THICKNESS INTEGRATION POINTS (ANSYS, 2005)	57
FIGURE 38: CROSS SECTION OF U-CHANNEL (LEFT), FLOWER DIAGRAM OF U-CHANNEL (MIDDLE LAYER, HALF GEOMETRY DUE TO SYMMETRY) WITH SIX FORMING STATIONS (WITH A=15DEGREES BENDING ANGLE INCREMENT) (RIGHT)	60
FIGURE 39: PARAMETRIC CAD OF THE ROLL FORMING LINE MODEL TO BE INSERTED INTO FEM	60

FIGURE 40: COLD ROLL FORMING SIMULATION FEM FOR THE U-SECTION PROFILE (HALF GEOMETRY DUE TO SYMMETRY).....	61
FIGURE 41: MESHING CONVERGENCE (12.000 ELEMENTS WITHIN 5% STEP DIFFERENCE) FOR TWO MODEL RESPONSES, I) TOTAL ENERGY AND II) MAXIMUM ELASTIC LONGITUDINAL STRAINS AT THE EDGE OF THE FLANGE OF THE PROFILE	62
FIGURE 42: COLD ROLL FORMING MODEL VALIDATION WITH EXPERIMENTAL DATA FROM LITERATURE FOR PEAKS OF LONGITUDINAL STRAINS (%) AT EACH ROLL FORMING STATION (DAMM, 1989)	63
FIGURE 43: P-DIAGRAM FOR THE OPTIMIZATION OF A MANUFACTURING SYSTEM/PROCESS	66
FIGURE 44: MANUFACTURING SYSTEM / PROCESS OPTIMIZATION APPROACH USING HYBRID MODELING APPROACH	67
FIGURE 45: DoE / ROBUST DESIGN ALGORITHM USING ORTHOGONAL ARRAYS AND ANALYTICAL ENERGY EFFICIENCY MODEL.....	68
FIGURE 46: MAIN DEFECTS CAUSED BY REDUNDANT DEFORMATIONS ON ROLL FORMED PRODUCTS (HALMOS, 2006)	69
FIGURE 47: COLD ROLL FORMING DEFECTS, FEM RESPONSES AND RESPECTIVE QUALITY CHARACTERISTIC CONSTRAINTS	70
FIGURE 48: TENSILE AND COMPRESSIVE STRESS-STRAIN CURVE FOR METALS (MARCINIAK ET AL. 2002).....	71
FIGURE 49: FORMING LIMIT DIAGRAM (FLD) AND FORMING WINDOW (MARCINIAK ET AL. 2002).....	72
FIGURE 50: U-SECTION PROFILE AND MAIN DIMENSIONS (A=50MM, W=200MM, L=1000MM, R=4MM)	76
FIGURE 51: BENCHMARK FOR THE USE OF U-CHANNEL PROFILE ON A PHOTOVOLTAIC MOUNTING FRAME (UNIRAC, 2011)	76
FIGURE 52: PLOT OF CONTROL FACTOR EFFECTS FOR THE S/N RATIO OF THE ENERGY EFFICIENCY INDICATOR RESPONSE	81
FIGURE 53: RESPONSIBILITY (%) OF EACH FACTOR ON ENERGY EFFICIENCY INDICATOR RESPONSE FOR U-CHANNEL PROFILE CASE STUDY	83
FIGURE 54: EEV_V1 FEM SOLUTION AND ALTERNATIONS FOR EEV_V2 FEM SOLUTION THROUGH CLOSED LOOP	85
FIGURE 55: LONGITUDINAL STRAINS ALONG ROLL FORMING DIRECTION AND ELONGATION PEAK DISTRIBUTION ON CROSS SECTION AT 8 TH ROLL STATION FOR EEV_V1 AND EEV_V2	86
FIGURE 56: LONGITUDINAL STRAINS ALONG ROLL FORMING DIRECTION AND SHRINKAGE PEAK DISTRIBUTION ON CROSS SECTION AT 3 RD ROLL STATION FOR EEV_V1 AND EEV_V2	87
FIGURE 57: MAJOR-MINOR STRAINS AT FLD OF DP600 FOR EEV_V1 AND EEV_V2	88
FIGURE 58: STRAINS IN THICKNESS DIRECTION ALONG FINAL ROLL FORMED PROFILE FOR EEV_V1 AND EEV_V2	88
FIGURE 59: FINAL PRODUCED CROSS SECTION AND DIMENSIONAL ERRORS FOR EEV_V1 AND EEV_V2	89
FIGURE 60: COMPARISON OF BENCHMARK WITH 1 ST AND 2 ND OPTIMUM FOR TOTAL ENERGY CONSUMPTION (J/M) AND PRODUCTIVITY (PPH)	91
FIGURE 61: COMPARISON ON BENCHMARK WITH 1 ST AND 2 ND OPTIMUM FOR ENERGY EFFICIENCY INDICATOR.....	91
FIGURE 62: RESULTS OF BENCHMARKING ANALYSIS FOR ATHENS INTERNATIONAL AIRPORT EL. VENIZELOS SOLAR PARK (ATHENS INTERNATIONAL AIRPORT, 2011), (PUBLIC POWER CORPORATION, 2011).....	92

APPENDIX C LIST OF TABLES

TABLE 1: MECHANICAL AND FORMING PROPERTIES OF DP STEELS SERIES (DP450-DP980) (FUTURA IP, 2008) ...	11
TABLE 2: ANALYSIS OF THE BENDING CONCEPTS WITHIN THE ROLL FORMING MILL (ALL IN DEGREES)	47
TABLE 3: FACTORS FOR MATRIX EXPERIMENTS AND RESPECTIVE LEVELS VALUES	48
TABLE 4: $L_{16}(4^5)$ ORTHOGONAL ARRAY WITH ROLL FORMING PROCESS FACTORS AND LEVELS, RESPONSE FOR EACH RUN AND STATISTICAL SUMMARY FOR EACH RUN	49
TABLE 5: AVERAGE OF SUMMARY STATISTIC BY FACTOR LEVELS FOR S/N RATIO FOR ENERGY EFFICIENCY INDICATOR	49
TABLE 6: ANALYSIS OF VARIANCE (ANOVA) AND RESPONSIBILITY (%) FOR EACH FACTOR FOR S/N RATIO FOR ENERGY EFFICIENCY INDICATOR	50
TABLE 7: MATERIAL PROPERTIES FOR AHSS DP980 AND RIGID ROLLS (FUTURA IP, 2008), (ANSYS, 2005)	59
TABLE 8: GUIDELINES FOR ALTERNATE QUALITY CHARACTERISTIC CONSTRAINTS / COUNTERMEASURES	73
TABLE 9: BENCHMARKING DATA FOR COLD ROLL FORMING OF U-CHANNEL PROFILE (GASPARINI, 2011), (DREISTERN, 2011), (SAMCO MACHINERY, 2011), (HALMOS, G., 2005), (JOHNSON BROS., 2011), (SAMSON, 2011)	77
TABLE 10: ROLL FORMED PRODUCT CRITICAL DESIGN PARAMETERS PROVIDED BY THE DESIGNER – CUSTOMER ...	77
TABLE 11: DESIGN AND PROCESS VARIABLES AS CONTROL FACTORS FOR THE COLD ROLL FORMING PROCESS BASED ON COMMERCIAL ROLL FORMING MACHINE (DREISTERN, 2011)	78
TABLE 12: BENDING ANGLE CONCEPTS FOR U-CHANNEL PROFILE	78
TABLE 13: NOISE VARIABLES FOR THE OPTIMIZATION PROBLEM WITH MEAN TARGET VALUES	79
TABLE 14: CALCULATED VALUES, RANGES AND STANDARD DEVIATIONS FOR THE NOISE FACTORS	80
TABLE 15: ANALYSIS OF MEANS (ANOM) FOR THE ENERGY EFFICIENCY INDICATOR RESPONSE	81
TABLE 16: OPTIMUM AND WORST LEVELS BASED ON SUMMARY STATISTIC OF MEAN FOR POWER RESPONSE	81
TABLE 17: ANALYSIS OF VARIANCE (ANOVA) AND RESPONSIBILITY (%) FOR EACH CONTROL FACTOR	82
TABLE 18: QUALITY CHARACTERISTICS CHECKING RESULTS FOR 1 ST OPTIMUM SOLUTION	84

TABLE 19: EFFECTS ANALYSIS FOR COLD ROLL FORMING PROCESS GUIDELINES ON ENERGY EFFICIENCY INDICATOR	84
TABLE 20: QUALITY CHARACTERISTICS CHECKING RESULTS FOR 2 ND OPTIMUM SOLUTION (EEF_V2) AND COMPARISON OF DIFFERENCE WITH 1 ST OPTIMUM SOLUTION (EEF_V1)	90
TABLE 21: LEVELS FOR THE CONTROL FACTORS.....	113
TABLE 22: LEVELS FOR THE NOISE FACTORS AND STANDARD DEVIATION FOR THE GAUSSIAN DISTRIBUTION	113
TABLE 23: L ₁₆ (4 ⁵) ORTHOGONAL ARRAY FOR THE CONTROL FACTORS AND RESPECTIVE LEVEL VALUES	114
TABLE 24: L ₉ (3 ⁴) ORTHOGONAL ARRAY FOR THE NOISE FACTORS AND RESPECTIVE LEVEL VALUES.....	114
TABLE 25: MEAN, VARIANCE AND S/N RATIO FOR THE ENERGY EFFICIENCY INDICATOR	115

APPENDIX D - ORTHOGONAL ARRAYS FOR CONTROL AND NOISE FACTORS AND S/N RATIOS

Table 21: Levels for the control factors

Control Factors	Units	Levels			
		Level-1	Level-2	Level-3	Level-4
A -Bending angle concept	-	C5	C10	C15	C20
B - Roller radius (R) - m	m	0.1	0.14	0.18	0.22
C – Line velocity (U) - m/sec	m/sec	0.1	0.17	0.24	0.31
D - Rolls inter-distance (m)	m	480	500	520	540
E - Rolls gap (% of nom. t)	%	1	1.7	2.4	3.1

Table 22: Levels for the noise factors and standard deviation for the Gaussian distribution

Noise Factor	Mean (μ_i)	Standard deviation (σ_i)	Levels		
			Level-1 ($\mu_i - \sqrt{3/2} \sigma_i$)	Level-2 (μ_i)	Level-3 ($\mu_i + \sqrt{3/2} \sigma_i$)
A - Rolling friction coefficient – (Crr)	0.01196	0.00268	0.008678	0.01196	0.0152423
B - Material parameter: Strength coefficient – (K)	956.65	47.8325	898.0674	956.65	1015.2326

C - Material parameter: Hardening coefficient – (n)	0.171	0.00855	0.160528	0.171	0.1814715
D - Thickness of material – (t)	2.0	0.05	1.938763	2.0	2.0612372

Table 23: $L_{16}(4^5)$ orthogonal array for the control factors and respective level values

Run no.	Control Factors				
	A -Bending angle concept	B - Roller radius - m	C – Line velocity – m/sec	D - Rolls inter- distance - m	E - Rolls gap (% of nom. t)
1	C5	0.1	0.1	480	1
2	C5	0.14	0.17	500	1.7
3	C5	0.18	0.24	520	2.4
4	C5	0.22	0.31	540	3.1
5	C10	0.1	0.17	520	3.1
6	C10	0.14	0.1	540	2.4
7	C10	0.18	0.31	480	1.7
8	C10	0.22	0.24	500	1
9	C15	0.1	0.24	540	1.7
10	C15	0.14	0.31	520	1
11	C15	0.18	0.1	500	3.1
12	C15	0.22	0.17	480	2.4
13	C20	0.1	0.31	500	2.4
14	C20	0.14	0.24	480	3.1
15	C20	0.18	0.17	540	1
16	C20	0.22	0.1	520	1.7

Table 24: $L_9(3^4)$ orthogonal array for the noise factors and respective level values

Run no.	Noise Factors			
	A -Rolling friction coefficient – (Crr)	B - Material parameter: Strength coefficient –	C – Material parameter: Hardening coefficient – (n)	D - Thickness of material – (t)

(K)				
1	0.008678	898.0674	0.160528	1.938763
2	0.008678	956.65	0.171	2
3	0.008678	1015.2326	0.1814715	2.0612372
4	0.01196	898.0674	0.171	2.0612372
5	0.01196	956.65	0.1814715	1.938763
6	0.01196	1015.2326	0.160528	2
7	0.015242	898.0674	0.1814715	2
8	0.015242	956.65	0.160528	2.0612372
9	0.015242	1015.2326	0.171	1.938763

Table 25: Mean, variance and S/N ratio for the energy efficiency indicator

Row No. of Control OA	Mean (μ)	Variance (σ^2)	S/N ratio $\eta = -10\log_{10}((1/\mu^2)*(1+3(\sigma^2/\mu^2)))$
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

BRIEF BIOGRAPHICAL NOTE – PUBLICATIONS

Ioannis N. Paralikas was born in Athens, Greece on the 16th of February 1983. He received his Diploma on Mechanical and Aeronautical Engineering from the Department of Mechanical Engineering and Aeronautics of the University of Patras on July of 2005 with the grade of 7.93. From July 2006, after the accomplishment of his military services in Hellenic army, he is PhD candidate at the University of Patras. From that time, he has been involved with a number of research EU funded projects as well as with the educational activities of the Laboratory for Manufacturing Systems and Automation. He is member of the Technical Chamber of Greece (TEE) and of the Hellenic Association of Mechanical and Electrical Engineers.

During his occupation to the Laboratory of Manufacturing Systems and Automation he published a number of peer reviewed papers in both international and national scientific journals and conferences:

Journal publications

1. **Paralikas**, J., Salonitis K. and Chryssolouris G., (2012), “Energy efficiency of cold roll forming process”, Submitted to International Journal of Advanced Manufacturing Technology.
2. **Paralikas**, J., Fysikopoulos, A., Pandremenos, J. and G. Chryssolouris, (2011), “Product modularity and assembly systems: An automotive case study”, CIRP annals, Manufacturing Technology 60:165–168
3. **Paralikas**, J., Salonitis K. and Chryssolouris G., (2010), “Investigation of the effect of roll forming pass design on main redundant deformations on profiles from AHSS”, International Journal of Advanced Manufacturing Technology, DOI 10.1007/s00170-011-3208-7
4. Salonitis, K., Pandremenos, J., **Paralikas**, J. and Chryssolouris G., (2010), “Multifunctional materials : Engineering applications and Processing Challenges”, International Journal of Advanced Manufacturing Technology, DOI: 10.1007/s00170-009-2428-6

5. **Paralikas**, J., Salonitis K., Chryssolouris G., (2010), Optimization of the roll forming process parameters - A semi empirical approach, *International Journal of Advanced Manufacturing Technology*, 47: 1041-1052, DOI 10.1007/s00170-009-2252-z
6. **Paralikas**, J., Salonitis K., Chryssolouris G., (2009), Investigation of the roll forming process parameters' effect on the quality of an AHSS open profile, *International Journal of Advanced Manufacturing Technology*, 44: 223-237, DOI 10.1007/s00170-008-1822-9
7. Pandremenos J., **Paralikas** J., Salonitis K. and Chryssolouris G., (2008), "Modularity Concepts for the Automotive Industry: A Critical Review", *CIRP Journal of Manufacturing Science and Technology*

Publications in proceedings of international conferences

8. **Paralikas**, J., Salonitis, K., Chryssolouris, G., (2011), "Robust design optimization of energy efficiency: Cold roll forming process", 7th International Conference on Digital Enterprise Technology, Athens, Greece
9. **Paralikas**, J., Salonitis K. and Chryssolouris G., (2011), "Cold roll forming process tooling design effects on AHSS profiles quality", 2nd International Conference of Engineering Against Fracture, 22-24 of June, Mykonos, Greece
10. **Paralikas**, J., Salonitis K. and Chryssolouris G., (2010), Production of a variable cross sectional profile from AHSS – A sequential roll forming approach, 43th CIRP conference on Manufacturing Systems, Vienna
11. Pandremenos, J., **Paralikas**, J., Fysikopoulos, A., Salonitis, K. and Chryssolouris G., (2010), Environmental assessment of automotive joining processes, 43th CIRP conference on Manufacturing Systems, Vienna
12. **Paralikas**, J., Salonitis K. and Chryssolouris G., (2009), "Investigation of the roll forming flower design techniques on main redundant deformations on symmetrical profiles from AHSS", RollForm 2009 conference, Bilbao, Spain
13. Pandremenos J., J. **Paralikas**, G. Chryssolouris, B. Dybala and J.W. Gunnink, "RM product development: design principles, simulation and tool", to be published in the

- proceedings of the International Conference on Additive Technologies (ICAT 2008), Ptuj, Slovenia, (September 2008)
14. Salonitis K., Pandremenos J., **Paralikas J.** and Chryssolouris G. (2008) «Multifunctional materials used in automotive industry: a critical review», 1st International Conference of Engineering Against Fracture, Patras, Greece, (May 2008)
 15. Salonitis K., J. **Paralikas** and G. Chryssolouris (2008) «Roll Forming of AHSS: Numerical Simulation and investigation of effects of main process parameters on quality», 1st International Conference of Engineering Against Fracture, Patras, Greece, (May 2008)
 16. Pandremenos J., J. **Paralikas**, K. Salonitis and G. Chryssolouris, "Modularity Concepts for the Automotive Industry: A Critical Review", Proceedings of the CIRP Design Conference: Design Synthesis, Enschede, Netherlands, (April 2008), ISBN 978-90-365-2634-0
 17. Stavropoulos, P., K. Salonitis, A. Stournaras, J. Pandremenos, J. **Paralikas** and G. Chryssolouris, "Advances and Challenges for tool Condition Monitoring in Micro-Milling", Proceedings of the IFAC Workshop on Manufacturing Modelling, Management and Control, Budapest, Hungary, (November 2007), pp. 157-162.
 18. Salonitis, K., P. Stavropoulos, J. **Paralikas** and G. Chryssolouris, "Modeling of Cold Roll forming process: a preliminary theoretical investigation", Proceedings of the IFAC Workshop on Manufacturing Modelling, Management and Control, Budapest, Hungary, (November 2007), pp. 211-216.
 19. Stavropoulos, P., K. Salonitis, A. Stournaras, J. Pandremenos, J. **Paralikas** and G. Chryssolouris, "Tool Condition Monitoring in Micro-Milling – A Critical Review", Advances in Manufacturing Technology XXI, Proceedings of the 5th International Conference on Manufacturing Research, Leicester, U.K., (September 2007), pp. 324-328.
 20. Stournaras, A., P. Stavropoulos, J. Pandremenos, J. **Paralikas** and G. Chryssolouris, "A Statistical Analysis of Laser Cutting Quality of Aluminium Alloy 5083", Proceedings of the 40th CIRP International Seminar on Manufacturing Systems, Liverpool, U.K., (May-June 2007).

21. Stavropoulos, P., K. Salonitis, A. Stournaras, J. Pandremenos, J. **Paralikas** and G. Chrysosolouris, "Experimental Investigation of Micro-milling Process Quality", Proceedings of the 40th CIRP International Seminar on Manufacturing Systems, Liverpool, U.K., (May-June 2007).

Publications in proceedings of national conferences

22. Σταυρόπουλος, Π., Κ. Σαλωνίτης, Α. Στουρνάρας, Ι. **Παραλίκας** και Γ. Χρυσολούρης, "Ανασκόπηση μεθόδων παρακολούθησης της διεργασίας μικρο-φρεξαρίσματος", Εισηγήσεις του 2ου Πανελληνίου Συνεδρίου Μηχανολόγων Ηλεκτρολόγων, ISBN 978-960-89776-0-0, Αθήνα, Ελλάδα, (Μάιος 2007).