Sigma J Eng & Nat Sci 36 (3), 2018, 677-691

Sigma Journal of Engineering and Natural Sciences
Sigma Mühendislik ve Fen Bilimleri Dergisi

Research Article

THE EFFECTS OF ROLL FORMING PASS DESIGN ON EDGE STRESSES

Mücahit SOYASLAN*

Sakarya University, Department of Mechatronics Engineering, SAKARYA; ORCID:0000-0001-6658-5169

Received: 20.01.2018 Revised: 11.06.2018 Accepted: 03.09.2018

ABSTRACT

Roll forming is the process of bending welded pipe, tube, closed or open profiles from sheet metal strips by using rolls and reels. In this study, the roll design processes of the roll form machines and the stages of designing rolls according to a C-type profile with the Ubeco PROFIL® software are examined. The manufacture of rolls is the most important parameter that affects the costs in roll forming lines. It is essential to keep the number of stations and the rolls used in these stations at an optimal level according to the product to be rolled. It is possible to calculate the number of passes where the profile can be formed most appropriately, to determine how the rolls should be positioned and to obtain the technical drawings of the rolls that need to be manufactured for each station with the help of roll forming software products. This study examines the edge stresses and optimum amount of rolls at the stations where the product can be rolled without exceeding the strain limits.

Keywords: Roll forming, sheet metal forming, roll design, edge stresses, pass design.

1. INTRODUCTION

The industry manufacturing methods used today are based on the principle of the ability to manufacture in the shortest time with the most affordable cost. Different and less costly systems are developed every day. Roll forming is a profile manufacturing process that emerged in early 1900s, and it progresses every day. It is based on the logic of stage by stage bending of the sheet metals with the roll systems. The automation units added to these systems provide increasingly more efficient processes, and roll forming becomes an important manufacturing method in the production of open or closed profiles.

When the literature about roll forming is examined, it is observed that the researchers conducted studies on productivity increase in roll forming processes, simulation, stress analyses for different materials, flexible production methods, mathematical modelling and finding the number of optimum station numbers. Han et al. [1] developed a theoretical model based on the deformation mechanics and the B-spline finite element method. The model was implemented to analyse the progressive roll forming analysis of a channel section and showed that the deformation was mainly in the leg and corner regions of the channel section. Although the software work is a useful one, it needs to be modified for profiles with different shapes. Sheikh and Palavilayil [2] and Jeong et al. [3] studied the stress s imulations of the profiles by using the

* Corresponding Author: e-mail: msoyaslan@sakarya.edu.tr, tel: (264) 295 69 12

SHAPE-RF software [4]. In the roll forming industry, examples of other software that allow detailed analyses and designs in roll design like SHAPE-RF [4] include PROFIL® [5], COPRA®RF [6] and Simply Roll Design [7].

This study was conducted on a profile model and the results for a C-type profile by using the PROFIL®[5] software, and it looks similar to the publication by Sheikh and Palavilayil [2]. Lindgren [8] investigated the longitudinal peak strain at the flange edge and deformation length when the yield strength increases. These values have an important role in finding the distance between the stands when designing a machine. Similar to the study by Lindgren, Safdarian et al. [9] studied the effects on the edge stresses and waisting in curves of some parameters such as bending angle increase, sheet metal thickness, cross-section width, flow speed of the profile from the machine and distance between the stands. The results of the simulation with the MSC Marc® [10] software showed that the deformation length increases and the longitudinal stress decreases as the endurance strength increases. This confirmed the inverse proportion between the yield strength and the deformation length. Oh and Kim [11] created a cost function from the results obtained from the experiments such as the response surface methodology and used it to minimize the design constraints. Similar to the study of Oh and Kim, Zeng et al. [12] used the response surface methodology and conducted an optimization study. The most frequent defects of the roll forming process is the edge waviness [13]. Donmez and Kocabas [14, 15] made an experimental study on the defects of edge waviness in the roll forming process of thin sheet metals and found that the edge height in sheet metal has the greatest effect in the waviness defects. Gulceken [16] conducted studies on the experimental and theoretical determination of the parameters necessary for a profile analysis in the flexible roll forming process. Groche et al [17] suggested a new roll forming process with high flexibility that can be numerically controlled. They developed a single step analytical model using the material type and geometric data and decreased the roll design periods. Kasaei et al. [18] and Yoon et al. [19] changed the positions of the stands and rolls with the flexible roll forming production line they established and realized the productions of profiles in different shapes.

The finite elements analysis (FEA) of the roll designs defines the positions of the elements in the system usually before the simulation. In this case, the closed loop control possibility is removed. Jenkouk et al. [20] developed a FEA simulation system that can work on a real time closed loop control by using eight variables including turning, feeding ratio, roll paths, etc. A remarkable practical area of roll forming processes is the fact that the defects of the manufacturing profiles can be eliminated while the effects of various properties of different material on the production process are decreased. Wiebenga et al. [21] suggested that optimum processes can be obtained by using adjustable instruments together with robust optimization techniques in the last stand of the roll forming process. Shim et al. [22] suggested the use of a double stage stand in regions with axial ripples to minimize the profile effects and to increase the product quality, as it provided success in their experimental works.

This paper examines the basic processes of the roll forming line and focuses on the roll design which has become the heart of the roll forming process. As the roll manufacturing is a costly process, it is the most important factor affecting the costs in roll forming lines. It is essential to keep the number of stations and the rolls used in these stations at an optimal level according to the product to be rolled. There are various software which makes it is possible to calculate the number of stations where the profile to be used can be formed most appropriately, to determine how the rolls should be positioned and to obtain the drawings of the rolls that need to be manufactured for each station. The purpose is to roll the product with the most convenient number of stations without forcing the stress limits. Therefore, the edge stresses should be examined when passing from one station to another. In this study, the rolls are designed by using the Ubeco PROFIL® [5], which is a roll forming design software. The stages of roll design and the method of stand design for C-type profile are expressed. In the applications, roll arrangements were made according to the profile shapes at the stations and the drawings of the produced rolls that exported to CAD software are shown. With the applications of machine layouts with different station numbers, the profile passes were observed and the most convenient production conditions were obtained according to the given shape of the profile.

2. ROLL DESIGN PROCESS

Halmos [13] explained all the details of roll design and provided various examples. During the roll forming process, a flat sheet metal takes form progressively towards its final shape, and this process takes place by turning the shaped rolls when the profile material passes the stations. Figure 1 shows the way of progressive forming of a sheet metal. The purpose here is to shape the material without forcing the stress by using the least number of stations. Too rapid forming, i.e. using very few stations, will create excess stress in the material and deform the manufactured profile material. The operation ranges of the conventional roll forming machines were confirmed by the simulation and experimental works as shown in Table 1 [24].

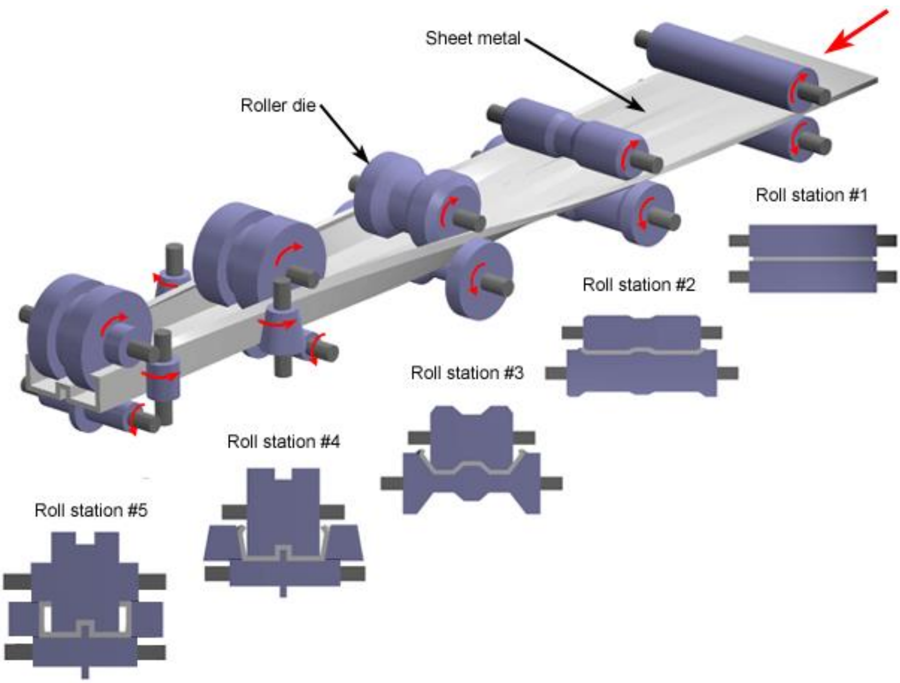

Figure 1. Progressive forming of a sheet metal using roll forming process [23]

Table 1. Operation range of the roll forming machines [24]

Variable	Measurement range
Strip width (mm)	5-2000
Strip thickness (mm)	0,15-10
Section tolerance (mm)	± 0,38
Angle tolerance (degree)	±1-2°
Line Speed (m/min)	30-100
Production Volume (m/8 h)	7600-12200

Using extra stations will require additional rolls which will create a non-economical process. Figure 2 includes the changes in the profiles according to the number of stations. The designer determines the required number of stations necessary for the proper form of the material. For example, a short edge material can be made in one, two, three or more passes depending on different factors. Bending process can be completed in consecutive stations or require additional operations. For example, an edge of 90° can be made in the first three passes of 30°, 60° and 90° respectively, or it can be completed in two passes to make up first to 60° and then to 90° [13]. Then the designer should determine the flow of the material. Forming can be started by providing balls (Figure 3.a) in the centre or lips (Figure 3.b) in the edges in the next stations. If the designer adds additional stations for a less risky forming, then the manufactured machine will not be competitive because rolls are expensive. On the other hand, using fewer stations than required will cause the rolls to be costlier, requiring back up rolls and causing high scrap value and high set up times. The first roll design method is the scientific method by Fred Gradous [25] which is still being used.

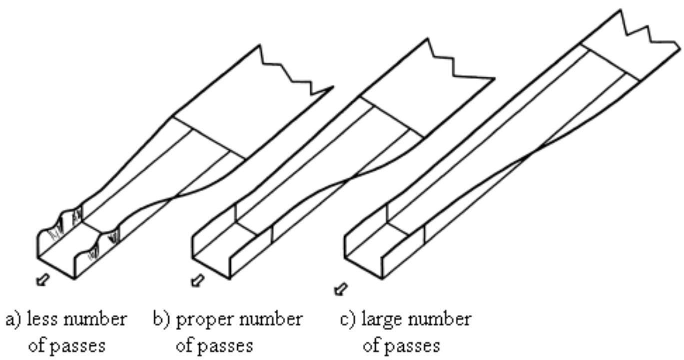

Figure 2. Changes in the product by the number of stations [13]

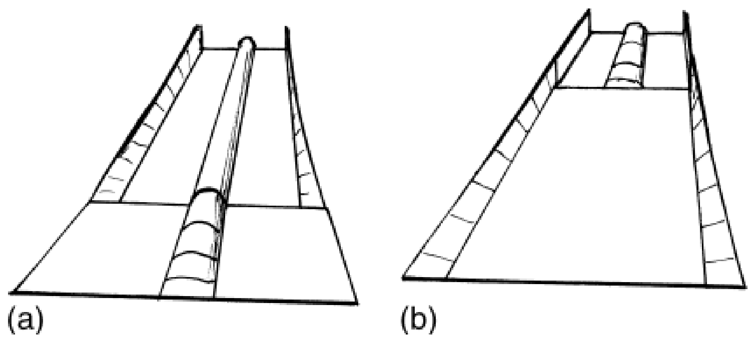

Figure 3. Forming methods (a) in the center (b) on the edges [13]

The number of stations and forming quantities are determined by creating the section of the material for each station. For example, if the designer designs the material in a way that the material takes forms from the centre as in Figure 3.a, it is followed by the lip stations on the edges and by the process of forming the legs. Figure 4 shows a split flower diagram while Figure 5 shows a typical flower diagram. In addition to top, side and front views, the 3-D models can easily be produced by the data transferred to the CAD software. When the designer is satisfied with the flower diagram, he moves to the roll design stage. The most probable rules of having operator friendly rolls are the following: creating a smooth and soft flow of material; being generous about the number of forming passes; avoiding short horizontal distances and small entry connections; and considering all requirements [13]. In addition, the material to form should be suitable for the process, a suitable type of lubricant should be used and there should be a well-trained operator in the setup of roll forming lines. If all conditions are convenient, good roll sets can manufacture millions of meters long products of high quality.

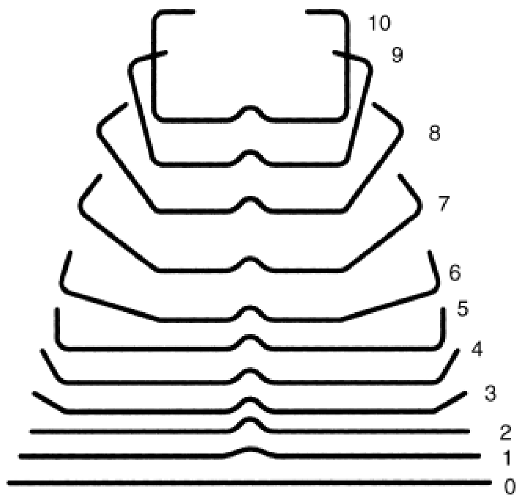

Figure 4. Roll forming split flower diagram [13]

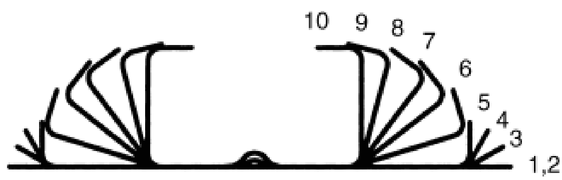

Figure 5. Roll forming typical flower diagram [13]

3. MATHEMATICAL ANALYSIS OF THE ROLL FORMING PROCESS

The cross section of the roll forming product is one of the most important factors in roll design. Designs can be optionally classified as open, closed, medium complex, very complex and panel. The section depth is the maximum vertical height of the profile at exit from the last station. The depth (also called "leg length" or "leg height" or "corrugation depth") has a great impact on the number of stations [13]. In cases like folding, the maximum vertical length can form on a station other than the last station. More stations are required for deeper sections. Figure 6 shows the theoretical flow of a U-profile. Band length extends from point A to point B along the beam ℓ. The number of stations is n and the distance between stands is m. The edges of the strip extend along the helical roll with the same leg length as h. The beam ℓ and the progress length s are as given in Eq. (1) and Eq. (2) [13].

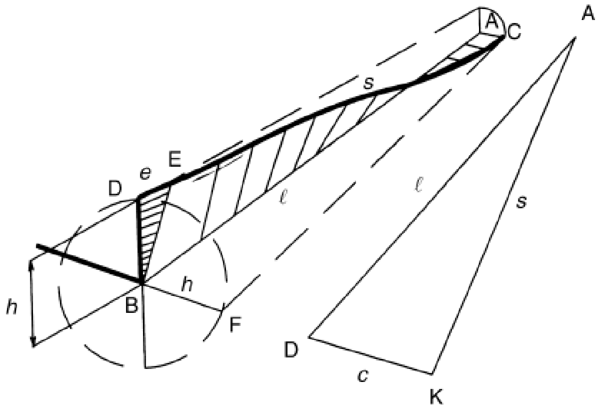

Figure 6. Theoretical illustration of the travel of the profile edge [13]

$$\ell = n * m \tag{1}$$

$$s = \sqrt{\ell^2 + c^2} \tag{2}$$

In Eq. (2), *c* is the arc length from point *F* to point *D*. In this case the progress length *s* is expressed with Eq. (3).

$$s = \sqrt{\ell^2 + (h^2/4)\pi^2} = \sqrt{\ell^2 + 2.467h^2} \tag{3}$$

The elongation (the amount of length between ℓ and *s*) is expressed in percentage. The theoretical elongation amount *e* is shown in Eq. (4).

$$e = \frac{s-\ell}{\ell} 100\% \tag{4}$$

When the height is doubled, the elongation increases by four times. Similarly, when the height is increased by four times, the elongation increases by sixteen times. There is a square proportion between height and elongation. A similar relation is observed between the station number and the elongation amount or the horizontal length and the elongation amount. Reducing the number of stations to half increases the elongation amount four times. If the horizontal distance is reduced to half then the elongation increases by four times. The above mathematical approach was developed when forming the materials. In reality, the edge flow cannot be smooth. Therefore, the real elongation amount will be more than the value that is calculated with Eq. (4). If the stress exceeds the elasticity limit, then there will be bows, cambers or twists. As this limit is related with *Y* (yield stress), the waviness is reduced by a higher *Y* value and lower *E* (modulus of elasticity) value if other conditions are the same [13].

4. MODELING WITH PROFIL® SOFTWARE

There are different machine options and open profile shapes in the Ubeco PROFIL® software. The selected machine can be changed later. The profile selection can be done by using the ready icons or can be drawn in a CAD software and imported to the PROFIL® software. These icons are suitable for simple open profiles in different shapes, and it is not possible to draw profiles in complex structure by using them. For example, to make a C profile design, the "C-profile" icon is selected and the profile's edge lengths, and corner radius values are entered as shown in Figure 7. This realizes the two-dimensional design of the profile that is intended to be manufactured.

The material St24-2 was used to create a design with a wall thickness of 2 mm and a distance of 300 mm between stands. The yield strength (R_e) and the tensile strength (R_m) values of the selected material are 380 N/mm^2 and 450 N/mm^2 respectively [5]. The corresponding standard of the material is DIN 1614-1:1986 with St 24 grade and springback factor is 0.99 [26]. It is low carbon non-alloyed mild steel for cold rolling with the obligation of batch annealing and the amount of Cr+Ni+Cu+Mo is maximum 0.21 % [27]. In the profile stress analysis (PSA) [5], the surface of the strip is divided into small rectangular shell elements and the longitudinal stresses are calculated at the edges and the whole profile. The meshing properties are as follows: 4 mm of line segments, 20° of small arc segment angle, 4 mm of large arc segment length, 8 mm of length of the shell segments in longitudinal direction and the radius of the centerline of the sheet is 2.5 times larger than sheet thickness. PSA is a very quick method and can be used while designing the stations and the termination times are very similar and there is no significant difference for different station numbers.

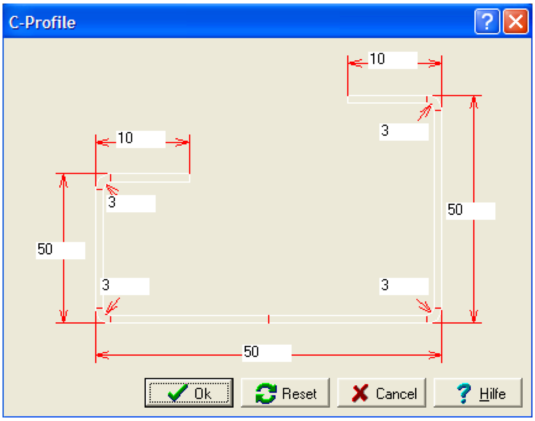

Figure 7. C-profile dimensions

The C-profile that emerged with the entered dimensions is shown in Figure 8. The critical properties like the wall thickness of the material, the material type, the distance between stands, the material width and the machine type are entered as shown in Figure 9.

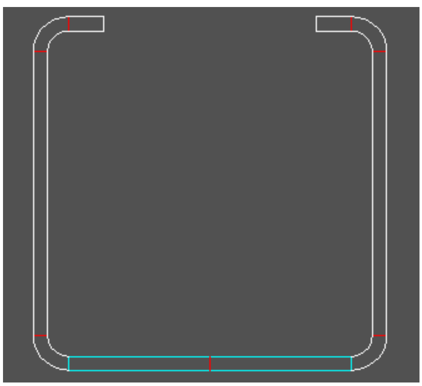

Figure 8. C-profile that is created with the entered dimensions

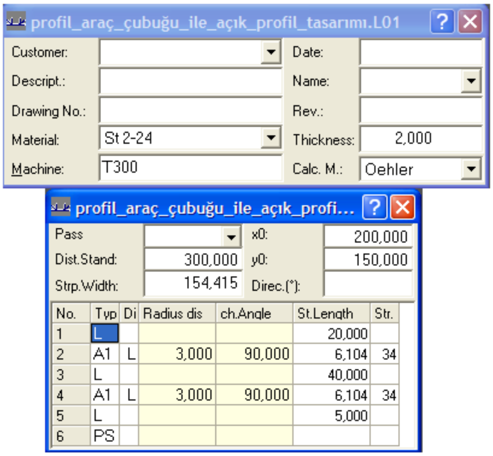

Figure 9. Machine and material properties

5. RESULTS AND DISCUSSIONS

In the optimization study, parameters such as the distance between the machine stands, the material type and the profile shape are fixed except number of the stands. Edge stresses and amount of rolls have been selected as the objective function. Profile and roll design was obtained between six and twelve passes and also the angle of profile bending between the stands was not changed. The roll forming process was repeated with the most appropriate angle values and the six pass machine design with the highest edge stress values and the ten pass machine design with the optimum objective values were shared. Other pass numbers have not been addressed. The purpose of this publication is to present the worst and best possibilities that may arise. It is known that changing the spacing between the stands or changing the bending angles affects the number of passes, but in this study only the effect of the number of stands parameter on the edge stresses and amount of rolls is examined.

5.1. Machine Design for Rolling a C-Profile in Six Passes

First, the manufacture of the product in six stations was considered. Therefore, an open profile was selected and then the flower pattern diagram of the profile was obtained (Figure 10). Although it was anticipated that this production cannot be made in six stations with the preferred distance between the stands, this application was conducted to observe the extent of exceeding the yield stress limit of the used material by the edge stresses. Figure 11 shows the edge stress values that took place after the bending process in six stations. The yield stress (R_e) limit value of the selected material is 380 N/mm^2.

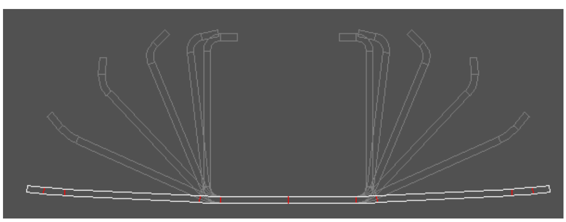

Figure 10. Flower pattern diagram of profile with six passes

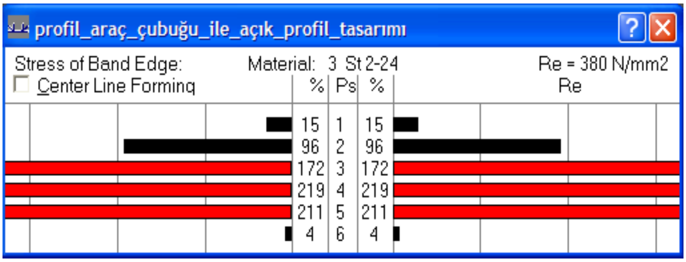

Figure 11. Edge stress ratios of profile with six passes (maximum value:219% of the yield strength)

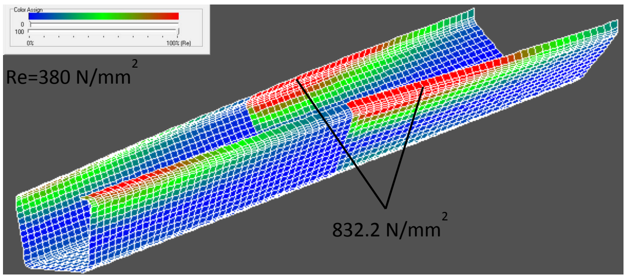

Figure 12. Stress analysis of the profile during passing from the third station to the fourth station

L01 refers to the final pass and L06 refers to the first pass. The second, third and fourth passes were found to have the most stresses. Figure 12 shows the shape and stresses of the material when passing from the third pass to the fourth pass according to the PSA. When Figure 11 was examined, the edge stress value in the L04 pass was measured as 832.2 N/mm^2 and a value was obtained which was 2.19 times the yield stress limit of the used material. The profile colours in Figure 12 show that the yield stress limit values are exceeded. The red coloured area refers to high edge stresses.

As shown in Figure 11 and Figure 12, the yield stress limit is exceeded in edge stresses in six stations according to the machine values entered in the bending process of the C-profile. Therefore, the number of stations should be increased to ensure the defect free manufacture of the C-profile.

5.2. Machine Design for Rolling a C-profile in Ten Passes

The previous application shows the problems emerge when it is intended to manufacture the profile in six stations. The station number was changed between six and twelve to eliminate these problems and new stress values was calculated according to these number of stations. The machine with ten passes gave the optimum objective values. Figure 13 shows the flower pattern diagram of the profile for ten stations. As it can be seen from the flower diagram, the passes between stations are soft and it is possible to estimate that the bending process will be free of problems. Although there may be a solution with fewer stations with changing some other parameters, but in this study other parameters are not examined. So it was obtained that the machine with ten stations is optimum which is far from the yield stress limit values of the material. Figure 14 shows the 3-D model of the passes of the profile between stations. Figure 15 shows the split flower diagram of the material for ten stations. It is possible to examine what the static values are at any station. As an example, the static values of the sixth station are shown in Figure 16.

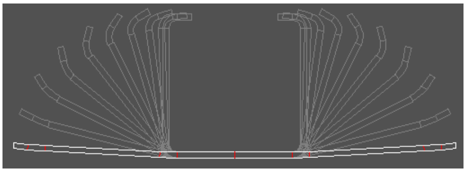

Figure 13. Flower pattern diagram of profile with ten passes

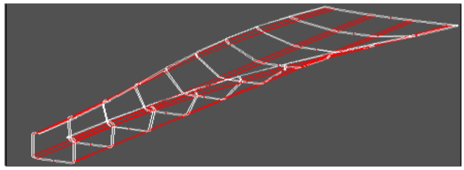

Figure 14. 3-D model of the passes between stations

The stresses in passes from one station to other station did not reach the yield stress limit values in this example. Also the amount of rolls with ten passes are at the optimum levels considering to higher number of stands. When the bending process was conducted in ten stations, the emerging edge stress values are shown in Figure 17. As mentioned above, L01 refers to the final station and L10 refers to the first station. If we examine Figure 17, the edge stress value of the third station was measured as the highest value with 277.4 N/mm^2 which was 0.73 times of the yield stress limit of the material. Therefore, the design profile can be manufactured free of problems as the stress limit values are not forced when ten stations are used. The shape and stresses of the material when passing from the second station to the third station are shown in Figure 18 according to the profile stress analysis.

After the optimum station number is obtained, the roll designs for the stands where the profile will pass need to be made. We have already mentioned about the importance of the rolls to be used in the roll forming machines in the process costs. Therefore, the start and finish points of the rolls to be used in the passes of the profile from the stations should be carefully determined and the top, bottom, right and left roll sets should be designed. In order to ensure that the extensions in the rolls are not more than necessary, these extensions should be kept at the optimum level during the roll design. Figure 19 shows the roll layout for L01 which is the final station, and Figure 20 shows the solid models of the profile and the rolls.

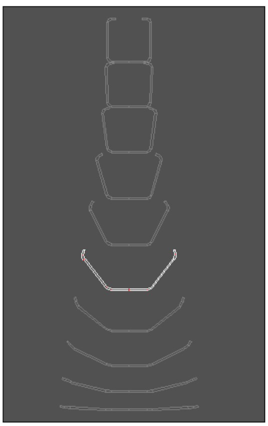

Figure 15. Split flower diagram with ten passes

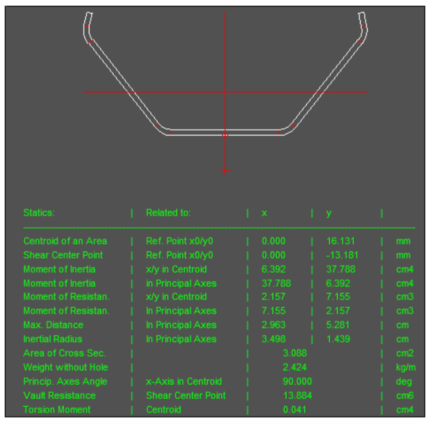

Figure 16. Static values of the sixth pass

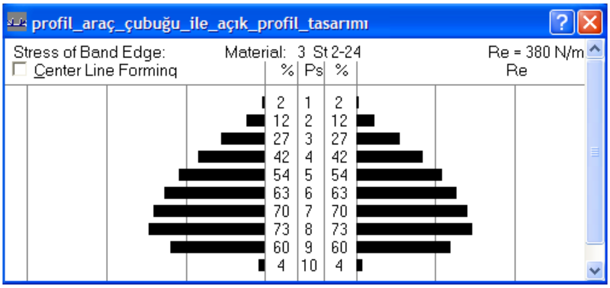

Figure 17. Edge stress ratios of the profile with ten passes (maximum value:73% of the yield strength)

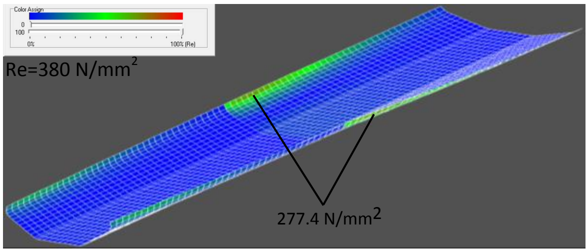

Figure 18. Stress analysis of the profile during passing from the second station to the third station

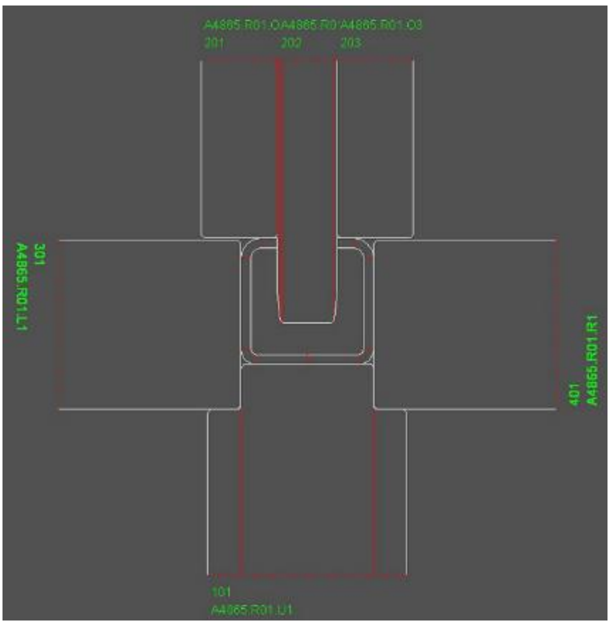

Figure 19. The drawings of all rolls with the profile of the L01 station

The rolls of all stations can be designed in the way explained above, and NC codes can be generated for each roll. After that, rolls are manufactured with the help of a CNC machine. The solid models of the rolls and the profile shapes at the stations can be transferred to CAD software. Figure 21 shows the profile shapes in the stations, and the roll layouts positioned according to these shapes. It is more advantageous to start from the right and left roll designs during the roll design stage. If there is a problem in the roll layout in any station, the technical drawing of the profile is sent to the CAD software, and more detailed rolls can be designed with this software. Figure 22 shows the split flower models of the profiles at all stations respectively without rolls. The stress values for the first machine design with six stands (worst possibility) and the second machine design with ten stands with optimum objective values are shown in Table 2. It can be easily understood from the Table 2 that there are big differences between best and worst possible machine designs. If these differences are not considered and only the amount of rolls is thought, the process will have terrible defects on the manufactured profile. So it must be given more attention for producing of rolls with optimum objective values like edge stresses and amount of rolls.

Figure 20. The profile and solid models of rolls at the L01 station

Figure 21. Solid models of the rolls and profiles at all stations

Figure 22. Solid models of the profiles at all stations

Table 2. Stress values for different machines

Station order	First Machine (with six passes), N/mm^2	Yield Stress Limit (%)	Second Machine (with ten passes), N/mm^2	Yield Stress Limit (%)
1	15.2	% 4	15.2	% 4
2	801.8	% 211	228	% 60
3	832.2	% 219	277.4	% 73
4	653.6	% 172	266	% 70
5	364.8	% 96	239.4	% 63
6	57	% 15	205.2	% 54
7	-	-	159.6	% 42
8	-	-	102.6	% 27
9	-	-	45.6	% 12
10	-	-	7.6	% 2

The yield stress limit value of the used material is 380 N/mm^2.

6. CONCLUSIONS

This study explains the design calculations of the rolls used in the roll forming lines. The optimum rolls' arrangements for a C-type profile are obtained with Ubeco PROFIL® software. The fact that the roll components in the machines are important instruments for the roll forming process was discussed and also the essential matters to consider in designing these instruments were mentioned. If one wishes to obtain sufficient processes in the roll forming operation, the machine design software should be used and how the edge stresses take place during the passes between stations should be observed before the manufacturing of the rolls. The distance between the stands or the number of stands should be determined according to edge stresses. As the defects occurring during the roll design stage will cause high costs, much attention should be paid to this stage. While it is known that the use of the high number of stations is beneficial for the edge stresses, but the amount of the rolls must also be taken into consideration as an objective function in terms of costs.

The machine design with six stations caused the emergence of a process much above the safety limits for the C-profile and an edge stress as high as 219% of the yield stress limit was obtained when passing from the third pass to the fourth pass. Therefore, the number of stations was increased, and the process steps were repeated. The machine design with ten passes gave the optimum edge stresses and optimum amount of rolls. The maximum edge stress in this machine design was at 73% of the yield stress limit. In this case, the number of stations selected for the production of C-type profile shape stayed within the safety stress limits and thus roll designs were obtained. As there is no detailed optimization study on determining the number of stations and rolls according to multiple parameter changing, the future work will be about multiple parameter optimization at roll forming lines.

Acknowledgements

The author offers acknowledgement to Mr. E. E. Bosdurmaz, the owner of Argedesk which is the Turkey representative of the Ubeco PROFIL® software; to R. Brandegger, owner of Ubeco GmbH who allows the use of screen images of PROFIL®; to G. T. Halmos, the editor of Roll Forming Handbook and to The Scientific and Technological Research Council of Turkey (TUBITAK) for its 2211-C program support.

REFERENCES

[1] Han Z.-W., Ren L. Q., C. Liu & Lu W. P. (2001). Modelling of cold roll forming of steel strip. *Materials Science and Technology*, 17.4: 415-418.

[2] Sheikh, M. A., & Palavilayil R. R. (2006). An assessment of finite element software for application to the roll-forming process. *Journal of Materials Processing Technology*, 180.1: 221-232.

[3] Jeong, S. H., Lee, S.H., Kim, G.H., Seo, H.J., Kim, T.H. (2008). Computer simulation of U-channel for under-rail roll forming using rigid-plastic finite element methods. *Journal of Materials Processing Technology,* 201.1: 118-122.

[4] SHAPE Corp., Metal Processing. Retrieved December 10, 2016, from http://www.shapecorp.com/about/steel-processing/, 2009.

[5] UBECO PROFIL, Rollform Design Software. Retrieved December 15, 2016, from http://www.ubeco.com/profil.htm.

[6] Data M Scandinavia AB, Software for Roll Forming-COPRA®RF (2012). Retrieved February 5, 2017, from http://www.datam.de/en/products-solutions.

[7] Roll Forming Services Inc., Roll Forming Software-Simply Roll Design (2011). Retrieved February 5, 2017, from http://www.rollformingservices.com/software.

[8] Lindgren, M. (2007). Cold roll forming of a U-channel made of high strength steel. *Journal of Materials Processing Technology*, 186.1: 77-81.

[9] Safdarian, R., & Naeini H.M. (2015). The effects of forming parameters on the cold roll forming of channel section. *Thin-Walled Structures*, 92: 130-136.

[10] MSC software, Marc Advanced Nonlinear Simulation Solution (2017). Retrieved October 10, 2017, from http://www.mscsoftware.com/product/marc.

[11] Oh, M., & Kim, N. (2008). Optimum design of roll forming process of slide rail using design of experiments. *Journal of Mechanical Science And Technology*, 22.8: 1537-1543.

[12] 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 & Design* 30.6: 1930-1938.

[13] Halmos, George T. (2006). *Roll Forming Handbook*, ISBN: 0-8247-9563-6, Taylor & Francis Group (CRC press).

[14] Donmez, O. E. & Kocabas H. (2008) Experimental Investigation of Edge Waviness During Cold Roll Forming of Thin Sheet Metal. *İTÜ Dergisi/d Mühendislik* 8.2: 127-135.

[15] Donmez, O. E. (2015). Experimental Investigation and Finite Element Analysis of Edge Waviness Defect During Cold Roll Forming of Thin Sheet Metal. PhD Thesis, *Istanbul Technical University, Institute of Science*, Istanbul.

[16] Gülceken, E. (2006). Modelling of a Flexible Roll Forming, Master Thesis, *Istanbul Technical University, Institute of Science*, Istanbul.

[17] Groche, P., Zettler, A., Berner, S. & Schneider, G. (2011). Development and verification of a one-step-model for the design of flexible roll formed parts. *International Journal of Material Forming*, 4.4: 371-377.

[18] M.M. Kasaei, M.M., Naeini, H.M., Abbaszadeh B., Silva, M.B., Martins, P.A.F. (2016). Flexible roll forming. *Materials Forming and Machining: Research and Development* 51.

[19] Yoon, J.S., Kim, J. & Kang, B.S. (2016). Deformation analysis and shape prediction for sheet forming using flexibly reconfigurable roll forming. *Journal of Materials Processing Technology*, 233: 192-205.

[20] Jenkouk, V., Hirt G., Franzke M., Zhang T. (2012). Finite element analysis of the ring rolling process with integrated closed-loop control. *CIRP Annals-Manufacturing Technology*, 61.1: 267-270.

[21] Wiebenga, J. H., Weissb M., Rolfe B., van den Boogaard, A.H. (2013. Product defect compensation by robust optimization of a cold roll forming process. *Journal of Materials Processing Technology*. 213.6: 978-986.

[22] Shim, D.S., Kim, K.P., Lee, K.Y. (2016). Double-stage forming using critical pre-bending radius in roll bending of pipe with rectangular cross-section. *Journal of Materials Processing Technology*. 236: 189-203.

[23] Sheet Metal Forming, (2009). Retrieved October 10, 2017, from http://www.custompartnet.com/wu/sheet-metal-forming.

[24] Livatyalı, H. (2006). Bilgisayar Destekli Roll Form Makara Tasarımı: Zanaatın Teknolojiyle Birleşmesi. *TurkCADCAM.net Dergisi*, Volume 2.

[25] Gradous Fred, (1966). *Roll form design - how many passses*, Tool. Prod., pp. 115.

[26] K. H. Grote and E. K. Antonsson, (2009). *Springer Handbook of Mechanical Engineering*, ISBN: 978-3-540-49132-3, Springer Publishing, pp: 593.

[27] Erdemir Group, (2005), *Cold Rolled Flat Steel Products*, pp: 13, 21.