Longitudinal Bow Estimation of U-Shape Profile in Cold Roll Formed for Commercial Aluminum Alloys

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***Abstract*—Due to the increasing demand for improvement in automobile industries makes a new way for the manufacturing processes which is having the safety of laborers, energy efficient and low cost. The emergence of new alloys makes these manufacturing processes more interesting for all areas of automotive and structural applications. New aluminum alloy can achieve the same strength as well as effectively reduce the material thickness while having perfect corrosion resistance. The demand for new materials forming technique has been widely increased in the market, so the insiders pay close attention to new technology. Roll forming is the method for these alloys to deform into its final shape with a smooth surface and good tolerance. In this paper, we have set up two kinds of roll forming models for the U-shape profile of Aluminum Alloy AA5052 using LS-DYNA software in the cold roll forming process (CLFP). UBECO PROFILE software is used for the numerical modeling of flower pattern and roll configuration of CLFP. In one experiment configuration normal forming is happened in a natural way with no extra modification to control the longitudinal bow defect while in the second model the supporting stand is used at the end of the rolling process in order to minimize the longitudinal bow of the final shape. The sheets in both two models have been measured the contour bow defect of displacement and the stress are used to analyze the deformation of the sheet. From the results, it was concluded that the supporting stand plays an important role in minimizing the longitudinal bow defect in the cold roll forming process.**

***Index Terms*—aluminum alloy AA5052, cold roll forming process (CLFP), LS-DYNA, UBECO PROFILE, longitudinal bow defect, supporting stand**

I. Introduction

Recently aluminum alloy usage is increased compared to other alloys, due to its attractive physical aspects such as high corrosion resistance, lightweight, high strength and easy recycling [1]. Previously, traditional methods such as extrusion and forging have been used for the manufacturing process of different profile shapes. Until recently, cold roll forming process which is used for the manufacturing of structure section with low cost [2]. Roll forming is a metal forming process in which metallic sheets and strips are bended or formed into the desired shape by a series of operations. The process mainly consists of passing a sheet into successive pairs of rolls until the desired section is completed [3]. This process offers several advantages such as the manufacturing of complex geometries with high strength and dimensional accuracy. Due to the flexibility of this process roll forming is widely used in automotive, railway, ship construction and building industries [4].

In roll forming the production process is continuous and more flexible which makes it highly commercial. There is no need for changing or replacing the roll toll for any kind of thickness and sheet length. Compared with the stamping and bending process, roll forming is more flexible, especially for variable cross-section profiles [5]. The roll forming process at room temperature is called cold roll forming (CRF). The cold roll forming process can be used in industrial applications for creating channels from sheets with complex cross-section [6]. Especially in automotive industry the car bumper structure with materials of different cross-section from 0.5mm to 8mm thick sheets. In forming industries forming rolls is to be designed with proper roll gape and roll angle in order to prevent the defects of folding and wrinkling [7].

Zhang Dongjuan and Cui Zhenshan had developed an analytical model for predicting the sheet spring back after U-bending based on the Hill’s 48 yield criterion and plane strain condition [8]. Also, three materials hardening kinetic, isotropic and combined hardening have been used to consider the effect in the bending process. R.Safdarian and H. Moslemi Naeini studied the effect of some roll forming parameters of the channel section are investigated on the edge longitudinal strain and bow defect of products [9]. The relationship between the parameters and defect has been recovered with simulation and experiment method. Kwun Sing Tsang and others have designed a roll forming simulation with the simulation program (COPRA FEA-RF) [10]. The influence of some factors on the forming length decisively has been analyzed and the sensitivity of these factors has been considered. At last, the experiments have been set up to verify the simulation results. Bow defect in roll forming is affected by many forming parameters and sometimes they depend on the combination of several factors includes roll gape and the angle between each

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forming rolls, increment in angle of successive stands, sheet thickness and flange width [11]-[15].

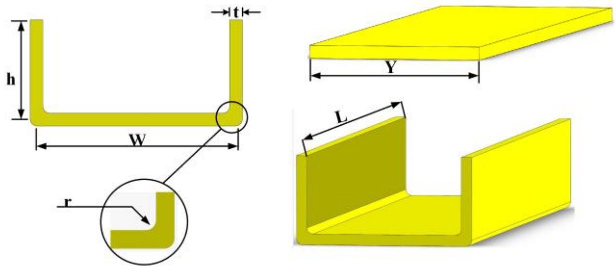


Figure 1. Geometrical characteristics of a symmetrical channel section.

Flexible roll forming has an error in shape due to the conversion of a sheet from initial shape to final desired shape in the forming process, such as warping and twist. Jong-Cheol Park proposed a new process called incremental counter forming (ICF) to reduce the shape error of roll formed profiles by using two roll sets of idle contouring rolls [16]. Some roll forming process consist of contour plates which counter the movement of main rolls, by using traditional forming techniques causes a rise in longitudinal strain during the forming process, results in different defects like longitudinal bowing and spring back. Solve the maximum forming strain between the passes based on the average strain for all passes by using bending angle distribution function also causes a significant decrease in the longitudinal bowing and spring back [17]. Jingsi Jiao introduces for the first time a mathematical model for the anticipation of web-warping defect, which is deflection in height of the web area by the total length of profile. This defect strongly depends on longitudinal strain formed in the flange of the part. The author proposed a new model based on evaluating longitudinal edge strain in the flange with variable width [18]. The same study proposed by A. Abvabi which identified the effect of residual stress on V-section roll forming of DP780 steel strip. The results showed that the thickness reduction in the rolling process decreases the maximum bow height while the spring back angle and end flare increase with the improvement of model accuracy with FEA (Finite Element Analysis) [19].

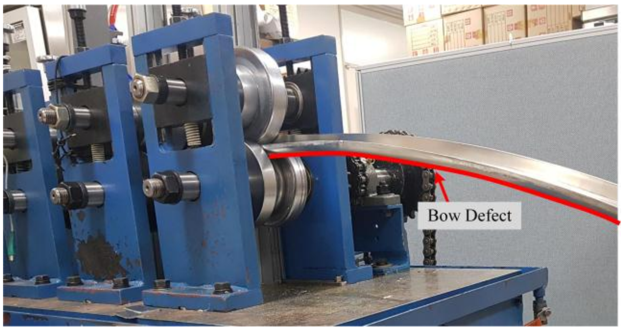


Figure 2. Bowing defect in U-shaped cold roll-formed product.

With the current rise in technology, it's important to enhance the quality of the cold roll forming process in order to improve the accuracy of the products, for this reason, research study is required to minimized defects that occur in cold roll forming process. As from the review of previous studies, we conclude that the profile bowing is one of the most common defects in the cold roll forming process. Although, these past studies propose many methods and different parameters which has a significant effect on longitudinal bow defect in different type of materials and channel shapes, but shape accuracy can be further improved for cold roll forming process. The main objective of our research study is to propose a new approach which can be implemented immediately without making a major modification to roll forming industries which are currently under operation. We proposed a new method for the reduction of profile bow during a cold roll forming process, by application of supporting stand at the end of forming process. In roll forming when the profile passes through the last roll stand the sheet tends to bend in downward direction because of bow effect as shown in Fig. 1. Thus, supporting stand apply force in the opposite direction of a bow, as a result the final profile has relatively small bow comparing to roll setup with no supporting stand. In order to study the influence of our proposed method on the U-channel profile in cold roll forming process, experiments have been performed for 1 and 2mm thick sheets of Aluminum Alloy 5052. While keeping the roll speed 30, 60 and 100 mm/sec the results from the experiment shows a significant decline in longitudinal bow defect in the cold roll forming process.

II. Experimental Tests

A. *Cold Roll Forming Line Features*

In order to achieve the perfect desired shape in cold roll forming process, it is necessary to install a guiding mechanism at the start of cold roll forming machine. if the strip's longitudinal direction is not perfectly in line with the forming line, then lack of uniformity will produce varying channel flange widths. The roll forming machine we are using the study of four roll stands along with guiding mechanism at the start of set up as shown in Fig. 3(c). The working of guiding mechanism in our experiment is crucial because it controls the longitudinal direction movement of a sheet into the forming line where the sheet enters into the first roll stand. If the sheet is not perfectly aligned with forming line then the resulting final sheet will have different flange width as shown in Fig. 3(a) and 3(b).

TABLE I. Input Parameters Influencing Bowing Defect

Parameters	Unit	1st stage	2nd stage	3rd stage	4th stage
Bend angle increment (B.A.I)	Degree	22.5	45	67.5	90
Sheet thickness (t)	mm	1, 2	1,2	1,2	1,2
Distance between successive roll stands	mm	220	220	220	220

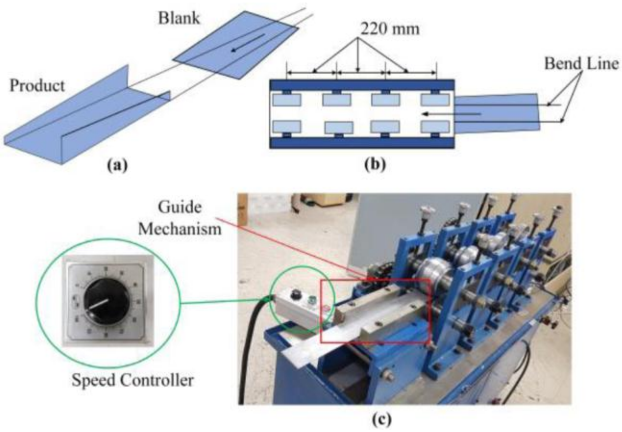


Figure 3. Sheet positioning at the beginning of the forming line and guide mechanism.

The total height of the machine from the ground is 1092mm and length of the table is 1280mm. The distance from the center of one roll stand to another successive roll stand is 220 mm and its height is 340 mm from the working table. Supporting stand configuration for cold roll forming experiment is indicated in Fig. 4. The deformation angle for each consecutive roll stand from start to end is 22.5, 45, 67.5 and 90 degrees respectively which is 22.5 degrees of increment for each roll stand.

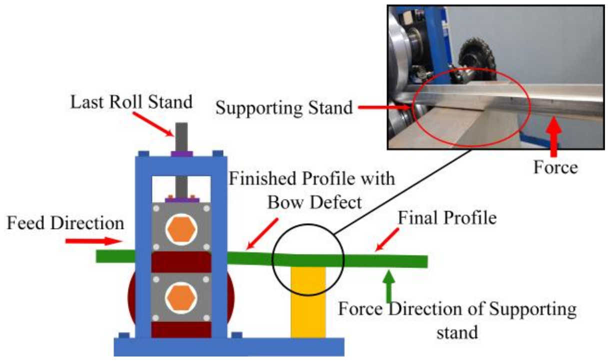


Figure 4. Supporting stand configuration for cold roll forming experiment.

The forming rolls are driven by a motor under the plate, which provides the rotational power through chains to the forming rolls. The speed of the motor is controlled by rotating the knob, the machine can be run from 10 to 90 mm/s speed according to the requirement of the experiment. Each roll stand of the forming machine has two mills in which the upper roll is adjustable and lower roll is fixed. The gap is controlled by the screw bolt and springs over the stand for different types of thickness sheets. In this way, the gap between the rolls can adapt to the thickness of the sheet and other forming conditions.

B. *Measurement of Roll Forming Defects*

A typical example of bow defect in U-channel section from our experiment is shown in Fig. 2. The method which is used to measure the bow defect in our final product is shown in Fig. 5. First of all, the sheet is market with 15 different points which is equidistance from each other and the distance between two successive points is 50mm which is fallow in Fig. 5 (b). In the second step, sheet is placed on a uniform surface table of base length Lo while all the vertices of the sheet are touching the table surface. The bow defect in sheet is measured by calculating the vertical distance dB from the baseline at 15 different points as shown in Fig. 5(a)(b). The maximum value of the bow is at point 7 which is the center point of the final shape and its value is 7mm which decreases by moving toward left or right end of the sheet.

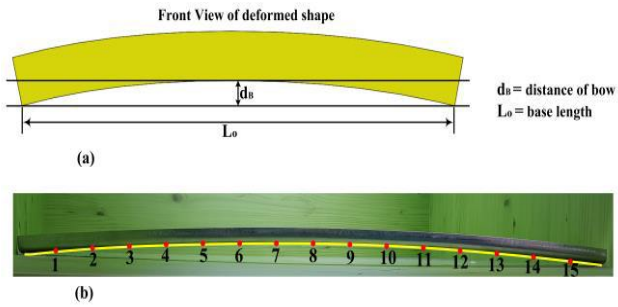


Figure 5. Calculation of Bowing defect in U-shaped cold roll-formed product.

Since the previous research study shows that parameters including bend radius, sheet thickness, flange width, increment in angle and distance between two successive stands have significance on bow defect. So, these parameters for our experiment setup are shown in Table I.

III. Finite Element Modeling of SPIF Process

The cold roll forming sequence of the channel was developed in LS-DYNA tool using the material card of AA5052 material and consequently, simulated for obtaining the final shape coordinates, the presence of plastic strains and the effective stress distributions across the formed profile. For defining the material properties of commercial aluminum alloy in the numerical tool, The stress-strain curves are approximated by the Hollomon power law, Eq.(1), to describe the material strain hardening behavior.

TABLE II. Mechanical Properties of AA3003 Material

Density (g/cc)	Poisson's ratio	Young's modulus (GPa)	Tensile strength (MPa)	Yield strength (MPa)	Strain hardening coefficient
2.66	0.33	70.3	356	155	0.16

$$\sigma = K\varepsilon^n \tag{1}$$

Thereafter, the formed numerical profile is compared against the original expected profile and produced profile from the real-time experiments to comment about the accuracy of numerical modeling. The advantages of achieving the plastic strains and stress distributions are that it will help us to modify the design in terms of roll gap, roll positions such as horizontal and vertical alignments, distance between the roll stands and changes in bending angle at each stage. Due to rigid boundary conditions on the rollers, each and every roll in the stand was defined by using a rigid material property and the rigid boundary conditions (constrained displacements in all three directions, rotations constrained in y and z directions and no constraint in the x-direction) are applied in the global directions coordinated system. The same sheet specimen dimensions used in the experiment were adopted to develop the finite element (FE) blank model with AA5052 material. In order to include the plastic deformation, the material properties and the power law equation parameters computed from the tensile test were incorporated into the simulation through the material card (MAT018 MAT POWER LAW PLASTICITY) as shown in Fig. 6.

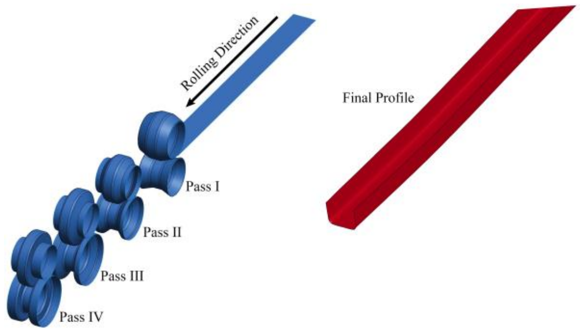


Figure 6. Finite element modeling of cold roll forming process.

In this research work, additionally, the effective stress distributions are measured at different roll conditions in order to check for the effect of supporting stands. Moreover, the adaptive meshing procedures were adopted for reducing the computational time and the procedures were identified to be effective and efficient in terms of both accuracy and time reduction.

IV. Results and Discussion

A. Longitudinal Bow Estimation

The method of calculating longitudinal bow of U-shape profile is discussed previously in the experimental section. By using that aforementioned procedures, for the AA5052 material sheet with thickness of 1 mm and 2 mm configurations are studied for 30, 60 and 90 mm/s of roll speeds. For the sheet thickness of 1 mm, the experimental observations from without stand support (WOS) configuration is depicted in Fig. 7(a).

The longitudinal bow height is marginally small in 30 mm/s roll speed compared to 60 mm/s of roll speed. Similarly, for the sheet thickness of 2 mm, the longitudinal bow height is measured and shown in Fig. 7(b), which again shows that the height of bow is smaller in the low roll speed compared against the high roll speed. At last, the longitudinal bow is measured for 1 mm sheet thickness with support (WS) configuration. The results are depicted in Fig. 7(c). This time three roll speed is used to get the clear results and conclusions has been made about the application of supporting stand. We can see that without the application of supporting stand, the maximum value of bow was computed as 17.5 mm, whereas in case of supporting stand, it is estimated as 6 mm. These results are evidence that the bow height is significantly reduced for tested roll speeds using the supporting stand configuration.

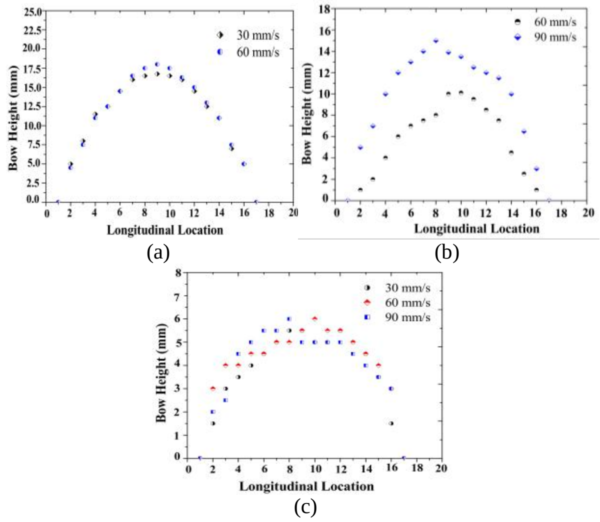


Figure 7. Longitudinal Bow defect (a) 1mm sheet (WOS) (b) 2mm sheet (WOS) (c) 1mm sheet (WS) at 30, 60 and 90 mm/s forming speed.

B. Geometry Comparison

In this section, we discuss the shape accuracy of our final product. This section is consist of two main parts, at first, the comparison is made between cad geometry and simulation model. At second part, the shape profile from simulation results is tested against the experiment profile for making the final conclusion. For 1 mm sheet thickness, U-shaped expected cad model is designed with the bend radius of 5 mm for extracting the coordinates of the profile. Now U-shape profile is modeled and designed each roll stages in UBECO-PROFIL software to run the numerical simulation. Subsequently, the simulated profile is extracted and compared with the actual profile as shown in Fig. 8.

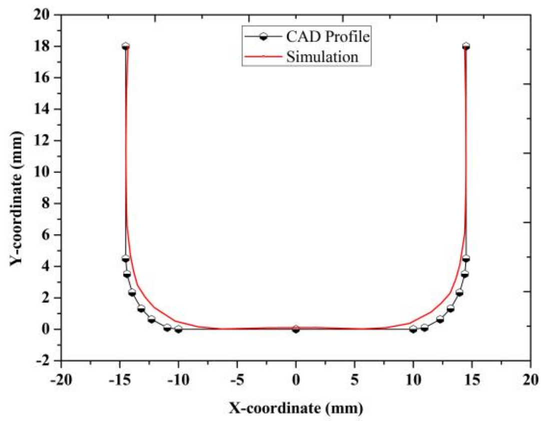


Figure 8. Geometry comparison between Cad and Simulation model.

Fig. 10 is evident that the implementation of the FE model is done properly and the small deviation in the bend radius is due to the consideration of shell elements. As the shell elements are modeled with a thickness of 1 mm, the thickness development starts from the mid-plane and it is obvious that the mid-plane geometry bend radius is 4.5 mm and not the same as the designed profile with the bend radius of 5 mm.

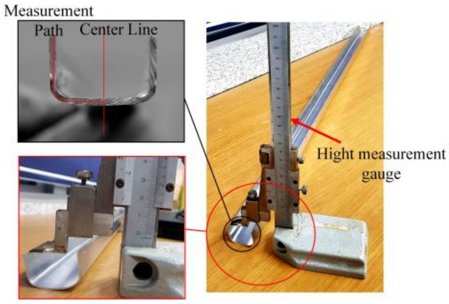


Figure 9. U-shape profile accuracy measurement.

Again, for calculating the dimensions of U-shape, we used the instruments such as Vernier caliper and height measurement gauge as shown in Fig. 9. The resultant height from the formed shape is perfectly matching with the actual and simulated profile as highlighted. The model implementation is perfect as shown in Fig. 11, now we can evaluate the presence of stress and strains in the formed profile. This U-shape profile can be manufactured with both hot and cold roll forming process. In hot roll forming, the sheet thickness is big and there is influence of temperature on formed shape so it is important to study about the temperature effects on forming shape of hot rolled formed parts. But in order to get the strength and good surface finish of profile the experiment is carried out in room temperature, which is called cold roll forming process. In cold roll forming process there is no use of temperature in the experiment process so the effect of temperature on formed profile is negligible. Although there is small temperature due to the friction between blank sheet and forming rolls, its effect is not significant and negligible compared to other forming factors [20].

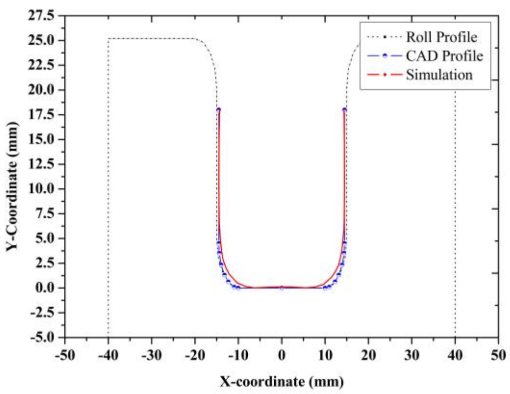


Figure 10. Geometry comparison between Simulation and experimental model.

C. Plastic Strain in Formed Shapes

In order to understand the deformation behavior in the cold roll forming process, the strain developments in the different regions of the formed products are investigated. The simulations were modeled considering the shell elements with 7 integration points through the thickness direction for various roll speed such as 30 mm/s, 60 mm/s and 90 mm/s and the sheet thickness of 1mm. Here, the roll speed is modified at each roll stand evenly for evaluating the effects of stress and strain. The numerical results from the supporting stand configuration is used to explain the plastic strain distributions at different forming conditions.

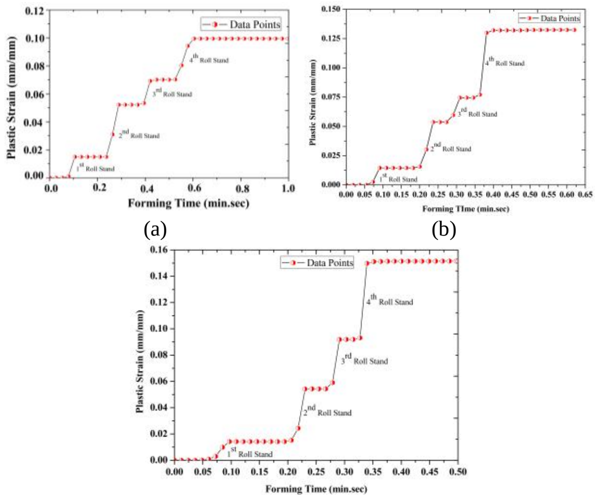


Figure 11. Plastic strain distribution at 30, 60 and 90 mm/s roll speed.

For roll speed, 30 mm/s, the strain value is computed after the last roll stand as it reaches to the maximum value of 0.10 (mm/mm) as shown in Fig. 11(a). Similarly, the plastic strains for roll speeds such as 60 and 90 mm/s were computed as 0.132 and 0.148 labeled in Fig. 11(b) and 11(c) respectively. From all three graphs, we conclude that the values of plastic strain are inversely proportional to the forming speed. Because in roll forming, the forming speed is directly proportional to roll speed, if the roll speed is high the part deforms quickly compared to low roll speed. For example, at 30 mm/s roll speed, when the forming time is 1 minute, the plastic strain is estimated as 0.1 and compared to 90 mm/s roll speed, it is minimum as the forming time is less than that of the first roll forming speed.

D. Presence of Stress in the Forming Regions

Stress distribution in the forming regions at 30 mm/s roll speed are presented and discussed in detail with and without consideration of supporting stand at the roll exit. The stress variations achieved from the numerical modeling is presented in Fig. 12.

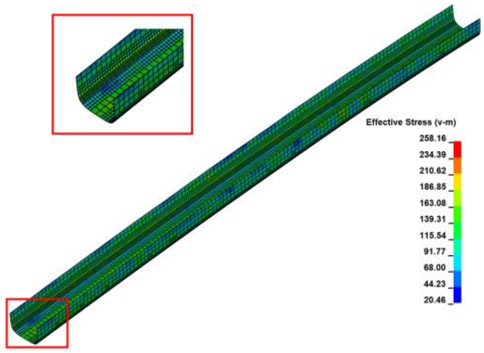
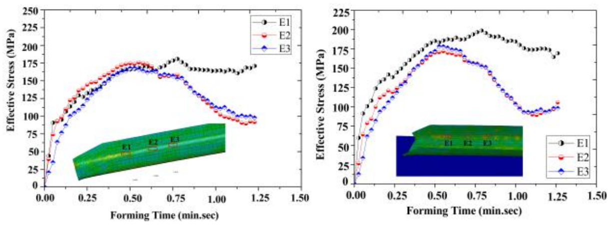


Figure 12. Effective stress distribution in the formed profile (60 mm/s).

At the time when half of the sheet is deformed and half is passing through the last roll stand, profile has residual stresses on the deformed shape due to the action of working rolls. It can be eliminated by keeping the length of sheet small, by taking out the formed part or cutting process releases the residual stresses and moments, which can result in distortion at both ends of the part. So, understanding the presence of stress in the formed can lead to find out the causes of distortions and can help researcher to modify the roll design for preventing the defects in roll formed parts. In this comparison, two different experimental setups are used in which the result is produced from with and without the application of supporting stand. The stress at three different locations considering one element selection are accounted in order to understand stress evolutions in the forming product with respect to forming time as shown in Fig. 13. The element points, which selected for evaluation, are located in the front section of deformed U-shape after roll forming operation. These points are indicted in Fig. 14 using symbols, E1, the first element, E2, and E3, the subsequent elements. Here in Fig. 13(a), the roll speed is 30 mm/s while there is no application of support stand in the setup. On the other hand, in Fig. 13(b), the roll speed is same but there is a presence of supporting stand in which the control of freedom in the downward is taken into account for controlling the bow in the longitudinal direction. The simulation time for both graphs looks more compare to previous illustrated graphs, because for the identification of remaining effect of stress after exiting the final roll stand.



(a) (b)

Figure 13. Effective stress for 1 mm sheet at 30 mm/s roll speed (without supporting stand).

From Fig. 13(a), it can be seen that at the bending region, the effective stress is found to be lower in the shell element (E1) than the other two shell elements (E2, E3) which is located behind the first element (E1). Moreover, the stress is found to be more if the element is located close to the exit of roll stand and vice versa. On the other hand, in Fig. 13(b), the stress value is found to be more in the first element (E1) than that of other two elements (E2, E3). This clearly states that the presence of a supporting tool opposes the part deflection in the downward direction. Due to the small differences in the stress value shows that there is no effect on shape accuracy of final profile.

V. Conclusions

Extensive cold roll forming experiments are conducted for three different roll speeds such as 30 mm/s, 60 mm/s and 90 mm/s and also two configurations such as with and without supporting stand configurations.

For evaluating the presence of strain and stress distributions, the numerical modeling procedures were developed in UBECO-PROFIL and LS-DYNA tools for running the cold roll forming process. In addition, the supporting stand was modeled as a rigid body and used to control the downward motion of the forming sheet.

From the numerical results, the U-shape profile coordinates are extracted and tested against both expected geometry and experimental observations. From comparison results, it was found that there is no noticeable difference between the tested samples and it proves the proper implementation of finite element models.

The plastic strain was found to be increasing gradually once the sheet enters into the first roll till the completion of the whole process and the strain was noticed to be steady and stable if there is no contact with the rolls. From the outcome of all the graphs, it was found that the plastic strain is inversely proportional to the forming time. On the contrary, by increasing the forming speed, the plastic strain also decreases and vice versa.

Moreover, the effective stress from the elements (E1, E2 and E3) in the bending region at three different locations with respect to the forming time was computed for 30 mm/s roll speed with and without the application of supporting stand. It can be seen that the effective stress was higher with supporting stand in the first element (E1) than that of the other two elements (E2 and E3) and vice versa.

Overall, it was found that the influence of supporting stand on reducing the bow defects show the positive results on the final formed part for all the forming conditions. In addition, the idea of supporting stand is cost-effective, efficient and easy to install in the current working roll forming process lines.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

In this research work, conceptualization, experiments, finite element modeling, investigation, validation, and original draft preparation were done by the authors Muhammad Sajjad and Mohanraj Murugesan, and the supervision was carried out by Dong Won Jung.

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