Experimental and numerical investigation of cold roll forming process

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Abstract. This research work is focused on the cold roll forming process to produce U-channel from the flat sheet. The mechanical properties of aluminum alloy was obtained from the tensile test and subsequently, the properties were incorporated into LS-DYNA to define the material plastic region. The forming process involves the progressive sheet deformation by passing it through a roll pass at constant roll speed. Each sets are designed at different bending angle to increase the deformation until the final geometry is achieved and here, the forming machine with four roll stands were used to manufacture the parts. As a sheet is going into different passes at the same time, the sheet plastic deformation is so complex and highly non-linear because of various stress and strain developments. From experimental results, at low roll speed (RS) the longitudinal bow was observed in the formed parts and to investigate, numerical simulation was modeled at various roll speed and found that as roll speed increasing the longitudinal bow noticed to be decreasing. To confirm the finite element results, one more experiment at high speed was performed and the obtained results showed better agreement with the simulation results. Before confirming the accuracy, many issues were encountered and modified such as mesh size at roller and blank, contact mechanism, choosing element formulation and friction coefficient. Furthermore, the adaptive meshing procedure was adopted to efficiently remesh the sheet at contact locations. The research procedures presented can be utilized to perform the forming process for any existed or new material to form a desired shape for a specific applications in the automobile and aerospace industries.

1. Introduction

The performance of automobile and aerospace parts is becoming the main consideration these days based on the safety regulations. Al6061 aluminum alloy is one of the most common and versatile material for the structural applications in both automobile and aerospace industries owing to its mechanical properties. In specific, its precipitation hardening alloy, containing magnesium and silicon alloy elements in major quantity which exhibits high strength, fatigue resistance, high level weldability, corrosion resistance and oxidation effect, etc. [1]. Al6061 aluminum alloy material is widely used in various industrial structural parts such as manufacturing trucks, railway vehicles and air frames as well as different aircraft parts like wings, tail sections, bulk-head, etc. These day to day applications are evident that long constant cross sectional structural shapes can be produced through the metal forming process like hot forging, stamping and roll forming process. Out of these metal forming process, roll forming process has gained more attention from both academic and industrial side considering its immense production capability on the long constant and variable cross sectional parts. Roll forming process involves a wide range of process that manufacture parts with various cross sections based on its applications. [2–4,5]. Normally, the desired parts are manufactured by passing the sheet metal into multiple roll stages. To perform the mass production, the passes for the suitable design are modeled in prior to control both time and cost consumption economically. However, the roll stage design with proper roll positions is a main problem, such as in the automobile and aerospace industries, because the parts are unique and the product life should be consistent throughout the cycle of usage. So considering the product shapes and quality production leads to put more effort on the flower design in order to control the defects and the shape error in the production unit. Due to modern technology, with the help of numerical tools, the new production methods can be developed to reduce the aforementioned issues and the mass production in terms of a quality production is possible nowadays. In particular, recently, several researchers has been published a great number of articles considering the roll forming process for a specific applications. [6,7–10,11,12,13,14].

Many studies have been carried out on bowing in conventional roll forming and flexible roll forming. Li et al. [14] investigated the performance of advanced high strength steels (AHSS) in chain-die forming process comparing with the conventional roll forming procedure by experiment and simulation. They reported that from the systematic comparison, apart from the bow effects on web and flange, the spring back effect after chain forming is found to be much larger than that of roll forming and requires more effort to achieve a desired part. In a roll formed profiles with variable cross section, park et al. [15] examined the longitudinal strain distribution in the concave and straight zones with the help of forming parameters of the incremental counter forming (ICF) process (an idle roll) during the roll forming. As a results, the shape error was corrected by reducing the longitudinal strain at flange and web sections using the ICF process. The twist effect in the asymmetrical channel sections made of the mild steel (st12) material with different flange lengths was studied by Tajik et al. [16] and found that the reason for the twist is due to the larger forming force on the long flange than the short flange. In addition, they concluded that the twist effect can be reduced by modeling asymmetrical forming rolls to form both flanges more symmetrically. In the flexible roll forming process, the effects of process variables on the longitudinal strain and longitudinal bow were examined both experimentally and numerically for U-sections made up of three different sheet materials and blank shapes such as trapezoid, convex and concave by woo et al. [17] After the detailed investigation, they introduced leveling roll into the forming process and as an outcome, the longitudinal bow was reduced with the use of three blank shapes and the leveling roll in the forming process. Badr et al. [18] investigated the effect of forming method on part shape quality in high strength Ti-6Al-4V sheet and reported that both experimental and numerical results suggest that spring back is lower in the constant radius forming method than that of the constant arc length procedure. In addition, they stated that the major shape defects in roll forming such as bow and spring back are not only influenced by material properties, the forming sequence and inter-stand distances and also due to the forming strategy.

The aim of the present work is to investigate the cold roll forming process to produce U-channel from the flat sheet by both experiment and simulation. The room temperature tensile test was performed to achieve the mechanical properties of aluminum alloy material. A roll forming process to obtain the U-channel was established and implemented into the finite element model using LS-DYNA tool. The longitudinal bow was measured from the experimental formed parts and compared with the numerical results. After the model verification, the evolution of longitudinal strain at lower and upper surfaces are measured at the bending section and discussed here. In addition, numerous simulations were performed to discuss the bow effect at different speeds and are experimentally compared using the verified numerical model.

2. Cold roll forming procedures

The chemical composition of Al6061 aluminum alloy, used in this research, is summarized in Table 1. In order to obtain the mechanical material properties, uniaxial tensile tests were conducted on Al6061 aluminum alloy sheet samples with the thickness of 2mm. Before modeling the experiment, the

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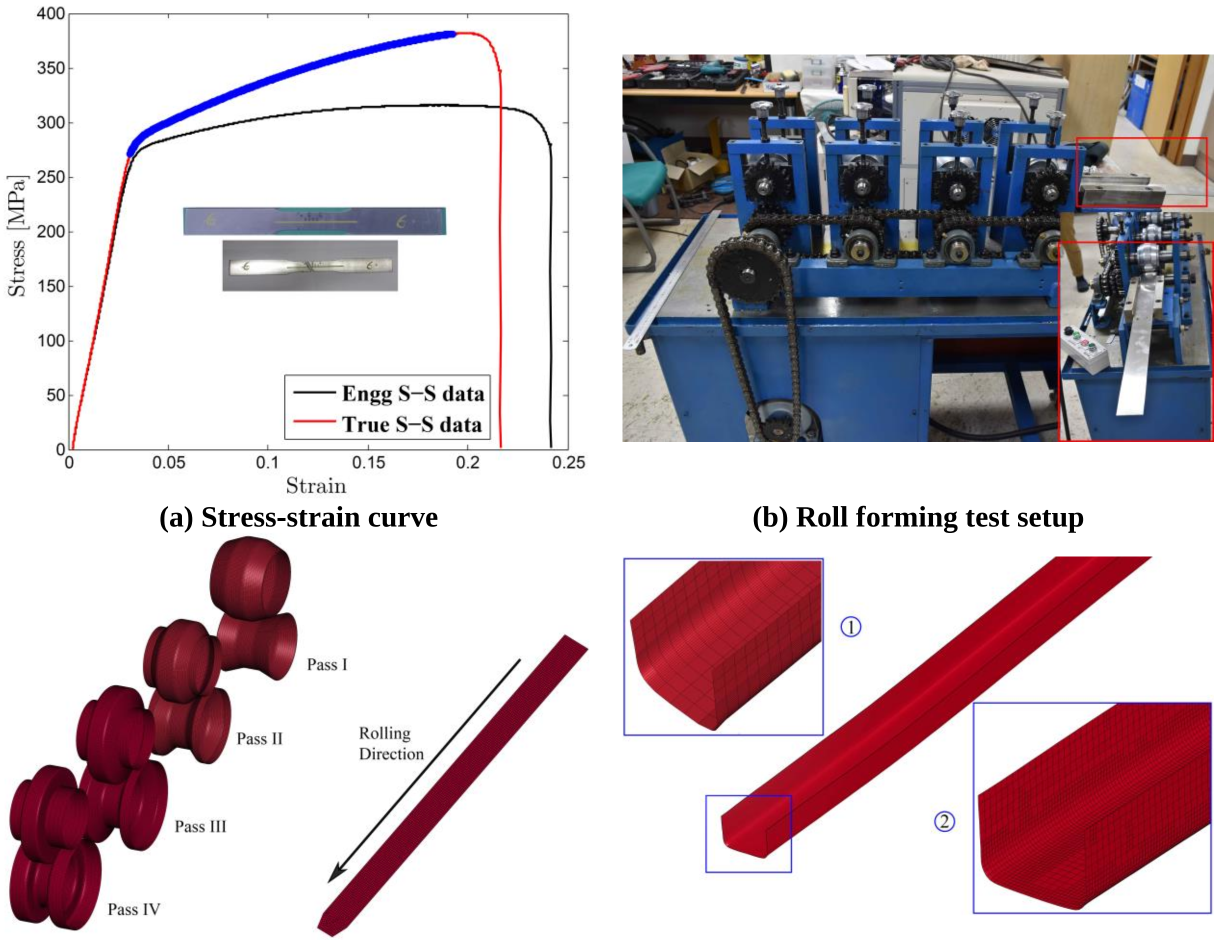
specimen samples were prepared with respect to the rolling direction based on the Korean Industrial Standard (KSB0802). The experiments were carried out using UH-FX Series Hydraulic Universal Tensile Testing (HUTT) machine equipped by an extensometer with the gauge length of 50 mm. The load–displacement curves were obtained from this test, and subsequently, the standard tensile test equations were employed to compute the stress–strain curves from the measurements and the samples used in the experiment are displayed in Fig.1(a).

Table 1 . Chemical composition of Al6061 alloy (in wt. %)

Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
97.8	0.4-0.8	Max 0.7	0.15-0.40	Max 0.15	0.8-1.2	0.04-0.35	Max 0.25	Max 0.15



(a) Stress-strain curve **(b) Roll forming test setup**

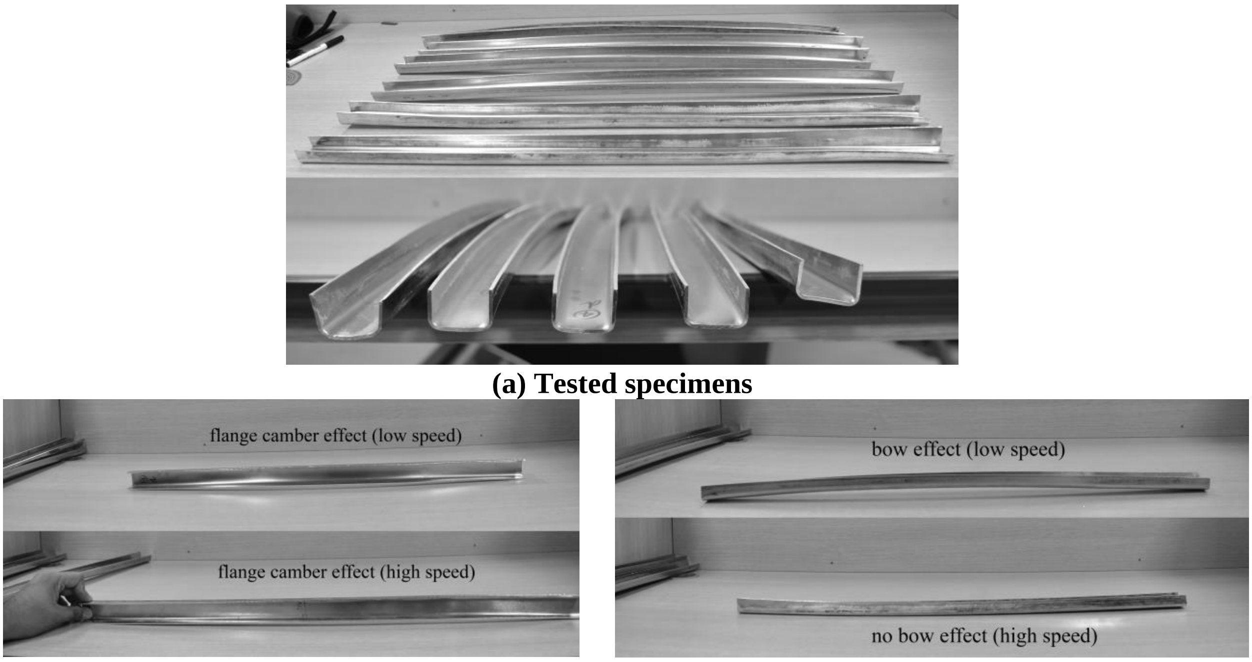
(c) Finite element model **(d) Mesh methods (1) contact mesh (2) adaptive mesh**

Figure 1 Cold roll forming procedures.

Table 2 Mechanical properties of Al6061 aluminum alloy

Density(kg m-3)	σ_u(MPa)	σ_y(MPa)	E(GPa)	υ	Elongation (%)
2710	340	271	68.6	0.33	19

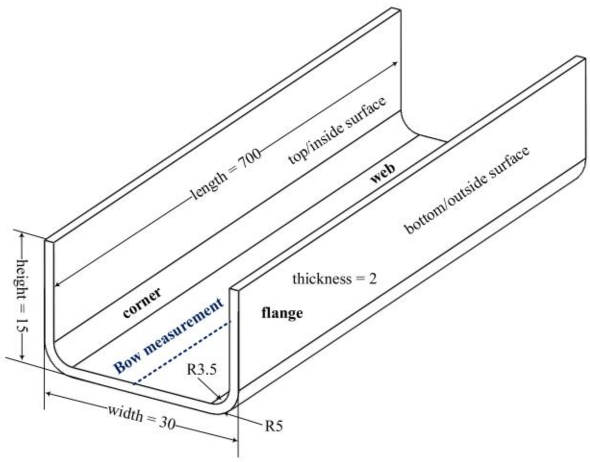
The cold roll forming experimental set-up utilized in this research work is illustrated in Fig.1(b). The roll forming machine is consists of four stages and one guide in order to achieve the desired U-channel section in the final stage output. In detail, the roll stages were designed to produce different bending angle at each stages and the bending angles were 22.5°, 45°, 67.5° and 90°, respectively. In this study, Al6061 aluminum alloy was adopted as a testing material and the material properties are summarized in Table.2. The Al6061 aluminum alloy specimen dimensions are: 700 mm length, 60 mm width and 2mm thickness and the each forming stage horizontal distance is 220 mm. During the forming process, the aluminum sheet was manually guided into the initial roll with the help of guide placed in front of the first roll stage as shown and highlighted in Fig.1(b). At first, the sheets were tested at low forming speed and from the formed product, the shape error was identified due to longitudinal bow effect and flange camber effect as depicted in Fig.2. To confirm this results, multiple specimens were tested under the same forming conditions and an outcome on the shape quality was same as aforementioned. In order to check the reason of this issues, the detailed study was conducted by examining the formed product, the defect positions and the roll positions such as horizontal and vertical roll distance, center-line alignment and roll gap. From the study, it was found that during the low speed forming, the sheet material takes so much time stay in the each roll stand before it move into other stages. Because of the slow forming time, the forming sheet was experiencing too much vertical roll forming force in the longitudinal direction and it causes the longitudinal bow phenomenon on the formed product. So, in the next step, the roll speed was increased and the same procedures were carried out to produce the U-channel sections. From the formed product, it was found that the longitudinal bow got reduced as depicted in Fig.2(c).

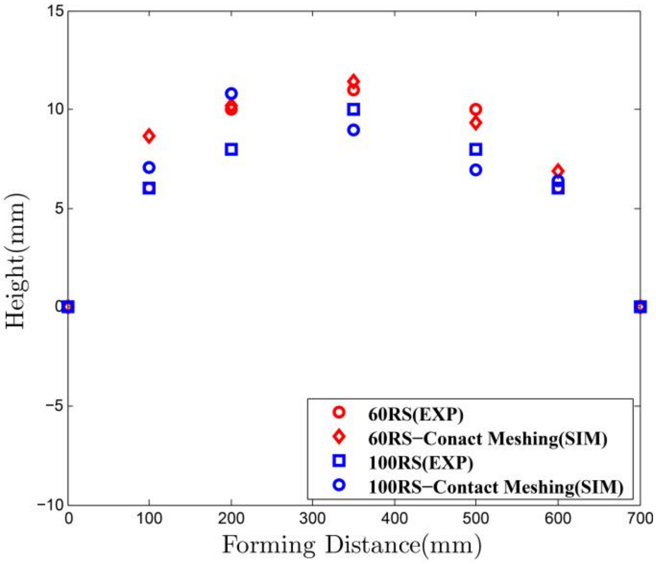


(a) Tested specimens

(b) Flange camber comparison **(c) Longitudinal bow comparison**

Figure 2 Manufactured U-channel parts.





(a) CAD geometry with specifications **(b) Comparison of bow measurement**

Figure 3 Verification results between experiment and simulation

The numerical simulation of the cold roll forming process was modeled in LS-DYNA commercial tool as shown in Fig.1(c). Due to rigid boundary conditions on the rollers, each and every roll in the stand was defined by using a rigid material properties and the rigid boundary conditions (constrained displacements in all three directions, rotations constrained in *y* and *z* directions and no constraint in *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 Al6061 aluminum alloy 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 numerical simulation through the material card (MAT018 MAT POWER LAW PLASTICITY). From literature survey, it was identified that roll forming is a pure bending method, so shell elements are well suited for pure bending method to effectively solve the cold roll forming problem. In element formulation, elform type 16 with 5 integration points was chosen as it can be useful when we consider both forming and spring back problem together. Also stiffness-based Hourglass control card with type 4 was used to control the unwanted deformation as it is generally more effective for structural parts when we consider shell elements. In addition, two kind of meshing methods such as contact area meshing and adaptive meshing procedure were adopted to check the accuracy of finite element solution compared with the experimental measurements as shown in Fig.1(d).

The numerical simulation results are useful to evaluate the deformation process and to find the high strain and stress regions to discuss about the problem in the forming process and further it can be modified by adjusting forming parameters such as bending sequence, roll speed, roll positions and roll passes distance, etc. After running the simulation at roll speed 60mm/sec, the numerical model was checked by comparing with the experimental ones. As seen in Fig.3(b), it was observed that the results found to be adequate with experimental measurements in terms of longitudinal bow measurements and the bow measurement place is highlighted in Fig.3(a). This results comparison proves that the numerical model developed can be further utilized to run for other roll speed in order to investigate the bow effect and also the model can be used to discuss the presence of stress and strain in the formed part. Numerous FE simulation were modeled considering different roll speed and the results from 100mm/sec roll speed was consider for the discussion eventually. Numerically it was found that the bow tends to be reduced and to confirm this, one more experiment was conducted. From observations, the results showed better agreement with the experimental data as illustrated in Fig.3(b).

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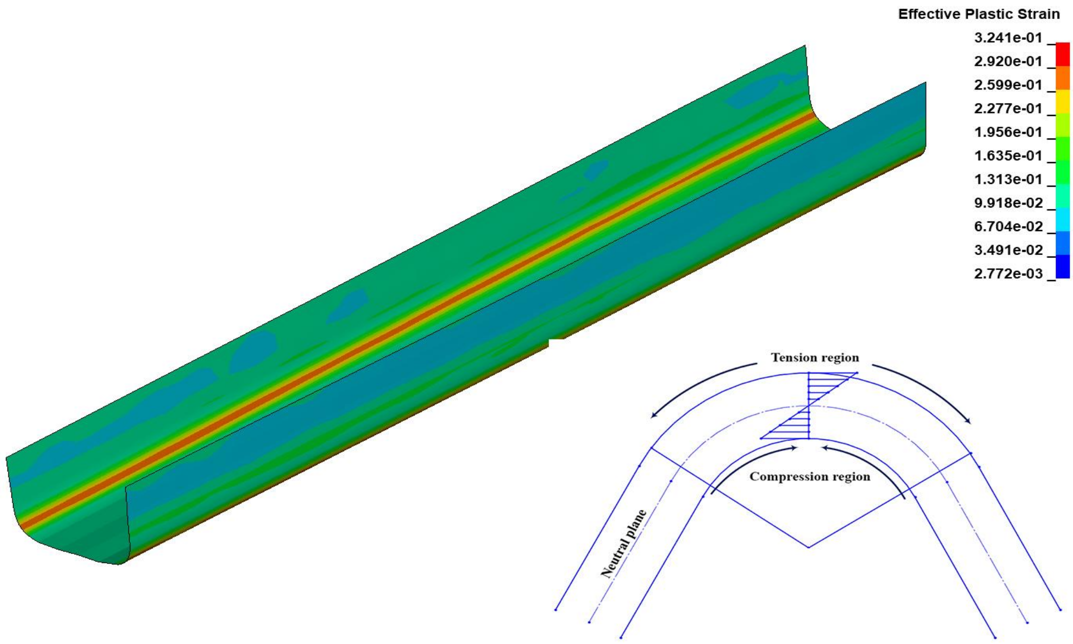
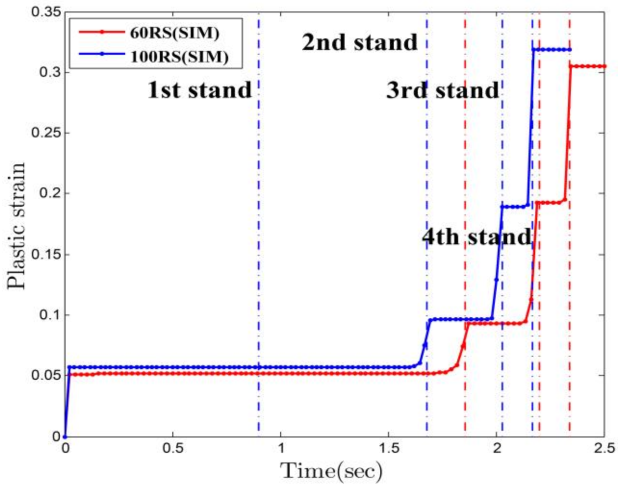
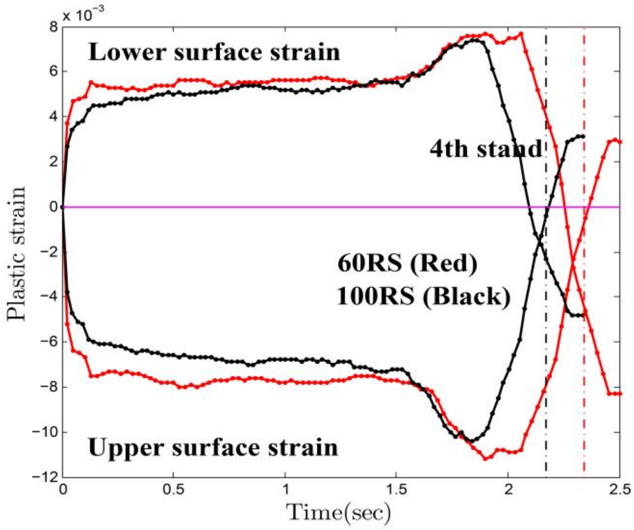
The effective strain distributions were measured at front bending section along the rolling direction and the maximum effective plastic strains were found to be occurred at the bending section as shown in Fig.4(a). Furthermore, the effective plastic strain at each stand exit, Fig.4(b), is increasing whenever the material is actively reaches every roll stand and also noticed to be constant when it stays at roll contact of particular stand and this behavior is same at each and every stand. When the forming speed is high the strain also tends to be increasing but showed the same behavior as low forming speed as illustrated in Fig.4(b). In addition, plastic strains at lower and upper sides of the formed part is measured and depicted in Fig.4(c). Fig.4(c) explains that as lower surface experiences tension force, the strains at that region found to be positive and steady till the second roll stand and showed exponential growth at the last two roll stand. In a similar way, upper surface experiences compressive force and results in compressive strains in terms of negative sign and the behavior found to be symmetric.

Overall the parts can be manufactured to the desired shape with superior quality by means of proper FE modeling techniques, on the contrary it needs more computational time effort.



(a) Effective plastic strain at 100RS in U-channel formed part (post cut)





(b) Longitudinal strain at formed part **(c) Strain at upper and lower surface**

Figure 4 Numerical results about plastic strains in formed part at different speeds

3. Conclusions

The cold roll forming process using both experiment and numerical simulations were carried out to evaluate the forming process.

- Flower pattern for four stages of roll forming was developed considering U-channel section and further the dimensions were utilized to design the rollers.
- More than two samples were tested in the roll forming machine until get the high quality product and on the other hand, error in the roll positions and the roll gaps were rectified during the forming process.
- The tensile test at room temperature was conducted to obtain the mechanical properties and later incorporated into FE tool to define the material plastic region.
- The geometry of the U-channel roll formed product was predicted successfully using FEM simulation.
- Good results correlation in terms of longitudinal bow measurements was achieved between numerical simulation and experimental observations.
- Moreover, it was found that the longitudinal bow can be minimized at high roll speed and it was proved using the experimental measurements eventually.
- The presence of longitudinal strains in terms of each stand, lower and upper surfaces were discussed here.
- Overall, for numerical simulation, mesh should be finer at bend zones and can be coarse in the straight parts, where there will be no deformation, and shell elements are recommend.
- Further studies will be concentrating on investigating the formability in terms of the modified bending sequence to check the model improvement, springback and failure analysis in order to decrease the formability effects such as bow, edge waves and flange camber to increase the parts quality for the industrial applications.

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