A first step towards an in-line shape compensation for UHSS roll forming

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Abstract. Roll forming is an important sheet metal forming process and is being used increasingly in the automotive industry for the manufacture of structural and crash components from Advanced High Strength Steel (AHSS) and Ultra High Strength Steel (UHSS). In AHSS and UHSS, the material properties can change from coil to coil or within the same coil and this can lead to varying part quality in roll forming. The effect of changes in material properties on part quality depends on the geometry of the part being formed as well as on the process parameters. There is a strong interest in developing in-line shape compensation for roll forming, and this will only be possible if the relationship between part quality, material properties, process- and part shape- parameters is understood.

In this paper, the effect of material properties and both process and geometrical parameters on longitudinal bow is analysed. A new technique is introduced for the identification of variations in the longitudinal bow in a roll formed component based on roll load and torque measurements as well as process parameters and part geometry.

1. Introduction

Roll forming is a well-established process for the forming of long components with uniform cross section from metal sheet. In roll forming, sheet is formed into the desired shape by incremental deformation in consecutive roll stations. The process allows Advanced High Strength Steel (AHSS) and Ultra High Strength Steel (UHSS) materials to be formed into complex shapes and is being used increasingly in automotive manufacturing. The biggest disadvantage in AHSS and UHSS roll forming is that in the steel mill, small changes in processing the sheet may significantly change the properties of the sheet material. The resulting variation in material properties from coil to coil or over the length of a coil can influence final part quality in the roll forming process. To overcome such defects requires time-consuming adjustments of machine setting leading to significant machine downtime. If changes in material properties can be identified in advance, interactive adjustment in the forming process are possible. To achieve this, the sensitivity of forming defects to material properties needs to be known. Abeyrathna B, et al. [1] identified that the variation in material properties can be represented for a selected profile by roll load and torque measurements taken in one roll stand. They further established a link between longitudinal bow and roll load and torque making it possible to predict changes in the longitudinal bow due to changes in material behaviour. Azizitafti R, et al. [2] showed that the degree of longitudinal bow not only depends on material parameters but also on geometrical and process...
parameters, while Bhattacharyya D, et al. [3] have shown that roll load is a function of the bending angle, material thickness, flange length and the yield strength. Later Lindgren M [4] suggested that the roll load and torque are a function of the material yield strength, forming angle and material thickness. This suggests that the combined effect of those process and geometric parameters and changes in material properties on roll load and torque as well as on the part shape needs to be understood to develop a reliable defect compensation routine for interactive control in the roll forming processes.

Longitudinal bow is a common defect in roll forming and trial and error methods are often employed in the industry to control it. Ona H, et al. [5] experimentally investigated a method to eliminate twist, bow and camber of a symmetrical channel section. They used an exit straightener, roll pressure adjustment, transverse shift of the rolls, over-bending of the strip and a twist forming stand as correction methodologies. Groche P, et al. [6] introduced an in-line springback compensation method for high and ultra-high strength steels. In their method, the profile was over-bent by a special tool placed at the end of the roll forming line activated by profile information given by two laser cameras.

In this present paper, a new approach will be introduced to identify the basis of longitudinal bow in a roll forming process by extending the previous studies carried out by the authors [1] and as a further step towards on-line compensation of it. The ultimate goal of this study can be represented by the flow chart given in Figure 1. The roll forming of a trapezoidal section will be simulated using different materials, process parameters and geometries. A regression model is then developed to link the amount of bow with roll load, torque and other relevant parameters. Then a new adaptive roll stand is introduced which is capable of compensating of longitudinal bow based on roll load, torque and other parameters; however this work is not presented in this paper due to space limitation.

In future research, the ability to achieve a complete solution space for compensation under any forming condition, would enable a solution set can be stored in an in-built memory of the controller to give the required corrective signal for the actuator. This is not an easy task as the compensation action itself depends on the material properties as well as geometric and process parameters. This paper will only focus on the development of the prediction model and its experimental validation.

![Figure 1: Methodology for bow compensation](image)

**2. Materials**

Two dual phase and one martensitic grade of steel, namely DP600, DP1000 and MS900, were used in this investigation. Tensile tests were conducted in an Instron 5967 machine on all three materials according to ASTM E8/E8M [7]. A 30kN load cell was used and a test speed of 0.025 mm s\(^{-1}\) chosen giving a strain rate of 0.001 s\(^{-1}\). The averaged true stress strain relationship for all samples along the rolling direction is shown in Figure 2. The material property constants were obtained by fitting
Hollomon’s power equation to the true stress - effective plastic strain curves derived from Figure 2. The values are given in Table 1. Experimental roll forming trials will be performed with these 3 materials to test the accuracy of the derived regression equation for the longitudinal bow prediction based on roll load and torque.

![Figure 2: Averaged true stress strain curve along the rolling direction for three steels](image)

Table 1: Material properties calculated for DP600, DP1000 and MS900

| Material | Yield Strength (MPa) | Young’s Modulus (GPa) | Ultimate tensile strength (MPa) | Elastic limit | n | K (MPa) |
|----------|----------------------|-----------------------|--------------------------------|---------------|---|---------|
| DP600    | 446.5                | 200                   | 767.7                          | 0.0022        | 0.117 | 926.3   |
| DP1000   | 764.1                | 200                   | 1194.3                         | 0.0038        | 0.122 | 1632.8  |
| MS900    | 931.9                | 205                   | 1102.7                         | 0.0045        | 0.058 | 1337.8  |

3. Roll forming experiment

The roll forming experiments were carried out in a laboratory roll former and two stations were used to form the trapezoidal section. The first station fed the material using two flat cylindrical rolls and the strip is formed to the desired shape in the second station (see Figure 3(a)). Each bottom shaft is driven by identical AC motors giving a line speed of 17.3 mms⁻¹.

The roll load was measured using a BCM Model 1311 shear web compression load cell positioned between the bearing housing of the top roll shaft and the arch of the frame (Figure 3(b)). The roll torque was measured using a LORENZ DR-2 slip-ring type rotational torque transducer that was attached between the bottom roll shaft and the AC motor shaft through a set of shaft-to-shaft jaw couplings as shown in Figure 3(b).

All the experiments were carried out without lubrications and the length, width and thickness of the blank strip were 2000mm, 150mm (or 125mm) and 2mm respectively. The forming sequence was 0 - 20° free and the corresponding flower pattern for a 150mm wide part is given Figure 3(c).

The roll gap was set be same as the material thickness in station 1 and it was 0.1mm higher than the material thickness in station 2 where the roll load and torque were measured; this avoided excessive loads being applied on the top roll due to material thickness variations [4]. To measure longitudinal bow the outer surface of the roll formed part was scanned and compared with the ideal shape as explained in [1]. The longitudinal bow is the maximum height deviation of the web of the part compared with the ideal shape.
Figure 3: (a) Schematic of the roll forming setup used for the experiments (b) schematic of the 2nd station with the roll load and torque measuring facility (c) flower pattern diagram for a 150mm wide part

4. Finite element analysis

For the numerical model development, the commercial software package Copra RF/FEA [8] was used. An implicit numerical model of the process, experimentally validated in [1], was used for the analysis (Figure 4(a)). In this model the friction coefficient was 0.1 while the element type was a full integration, hexahedral, type 7, arbitrarily distorted brick. In addition, the stiffness of the roll stand components and of the roll shafts were taken into account in the numerical model [1]. To account for changes in material properties, artificial material models were developed using the procedure explained in [1]. For this in a first step the Hollomon’s power equation was fitted to the experimental tensile data of the DP780 steel. Then the values for yield strength and hardening exponent were varied to generate an extensive material input data set for the numerical regression analysis.

A number of simulations was carried out with different combinations of process, geometric and material parameters (input parameters). The input parameters were chosen based on the literature and on experience and some are shown in (Figure 4(b)). Other variables such as material yield strength, hardening exponent, inter station distance and friction coefficient between the strip and the rollers were considered as input parameters.
5. Determination of the number of numerical models
For this analysis, three levels from each input parameter above were analysed to account for non-linearity. The list of input parameters and their different levels are given in Table 2. The parameter levels chosen were based on the general roll forming conditions and the capacity of the machine.

Table 2: Input parameters and their levels

| Input parameter                  | Parameter level |
|----------------------------------|-----------------|
| Frictional coefficient (FC)      | 0.1 0.15 0.2    |
| Yield strength (YS)/MPa          | 590 740 890     |
| Hardening exponent (n)           | 0.15 0.25 0.35  |
| Flange length (FL)/mm            | 36 48.5 61      |
| Material thickness (t)/mm        | 1 2 3           |
| Web length (WL)/mm               | 50 70 90       |
| Bottom roll diameter (BRD)/mm    | 101.6 121.6 141.6 |
| Forming angle (FA)/degrees       | 10 20 30       |
| Bending radius (BR)/mm           | 4.8 8.8 12.8   |

In the regression analysis, different models can be approximated to represent the relationship between the input and the output parameters such as first order, second order and so on. In this analysis, a full quadratic model was employed where the complete second order and the two factor interactions of the input parameters were considered as given by Equation (1).

After this an analysis of variance (ANOVA) study was carried out to determine the significance of the model parameters.

\[ y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 \]  

(1)

where \( x_i \) and \( x_j \) are input parameters, \( \beta_i \), \( \beta_{ij} \) and \( \beta_{ii} \) are the regression coefficient of linear, interaction and square terms respectively.

To generate a suitable number of simulation models for the analysis, the Box-Behnken response surface design [9] was employed which is especially developed for second order model generation. In this method, three levels from each parameter are considered for the analysis. The standard Box-Behnken design for nine input parameters consists of 130 different combinations of input parameters. Therefore 130 numerical models were developed as proposed by the MINITAB software package [10] and analysed to obtain a regression equation for the longitudinal bow.
6. Results and discussion

6.1. Prediction of longitudinal bow

To represent changes of material properties in terms of roll load and torque, the process and geometry factors that have an effect on roll load and torque need to be considered separately. The regression analysis for longitudinal bow needs to consider all input parameters given in Table 2 including their square terms and the two-factor interactions. The yield strength and hardening exponent can be replaced by roll load and torque given that Abeyrathna et al.[1] have shown previously that there is a direct relationship between roll load and torque and the material properties. In addition, the square root terms of roll load and torque are taken into account as they are significant parameters in this investigation; this may help to obtain a robust regression model to represent longitudinal bow. The regression equation obtained this way is given by Equation (2) and the corresponding ANOVA analysis results are shown in Table 3. The P value (calculated probability) and F value were used to confirm the significance of the regression model; if the P value < α (α was taken as 0.001), then the parameter is significant. The F value has to be greater than F (6, 123) which is 4.04 (this value is taken from the standard F statistic table) to be the regression model a good predictive model. The high values determined for $R^2$, $R^2_{adj}$ and $R^2_{prediction}$ of 88.5%, 87.9% and 86.91% respectively confirm the significance the relationship developed and its ability to predict bow.

$$\text{Bow} = \frac{1 + 6.1t - 0.102 \text{FL} \times t + 0.449 t \times \text{FA} - 0.00204 \text{FA} \times \text{Torque} - 7.28 \sqrt{\text{Load}} + 0.321 \sqrt{\text{Load} \times \text{Torque}}}{2.3}$$

where t is material thickness in mm, FL is flange length in mm, FA is forming angle in degrees, Load is roll load in kN and Torque is roll torque in Nm.

Table 3: ANOVA table for longitudinal bow

| Parameter | Source | DoF | Sum of squares | Mean squares | F      | P     |
|-----------|--------|-----|----------------|--------------|--------|-------|
| Bow       | Model  | 6   | 2169           | 361.5        | 157.3  | 0     |
|           | Residual error | 123 | 283            | 2.3          |        |       |
|           | Total  | 129 | 2452           |              |        |       |

As given in Equation (2), bow is affected by the material thickness (t), the forming angle FA, the flange length FL and the material properties (yield strength (YS) and material hardening (n)); however, material behaviour can be represented by roll load and torque. The coefficient of friction, web length, bottom roll diameter (BRD) and bending radius (BR) are not significant factors in defining longitudinal bow. Equation (2) can be used with any given trapezoidal section to determine the amount of longitudinal bow in the part based on the measured values of roll load and torque. It is important to note that precise load and torque measurements are needed to predict accurately the longitudinal bow as they are the only variables measured during the roll forming process.

6.2. Regression model validation

To apply the equation obtained above to a real roll forming application, three materials were experimentally tested, a DP600, a DP1000 and a MS900; their true stress strain curves are given in Figure 2 and the corresponding material constants in Table 1. Strips, 1m in length, 125mm in width and 2mm in thickness were roll formed in two stations in the laboratory roll former as explained above. The strips were formed to 20 degrees and the flange length was 36mm while roll load and torque were measured during the process as explained above. Longitudinal bow in the final part was also measured (see Table 4).
Table 4: Experimentally measured roll load, torque and bow for DP600, DP1000 and MS900

| Material | DP600 | DP1000 | MS900 |
|----------|-------|--------|-------|
| Load (kN) | 5.1   | 6.9    | 7.64  |
| Torque (Nm) | 44.9  | 65.12  | 71.24 |
| Bow (mm)- Measured | 9.34  | 8.06   | 6.63  |

The comparison between the measured bow and the predicted bow given by Equation (2) is shown in Figure 5. As shown in Figure 5, the best agreement between the predicted and actual bow is for DP1000, while the greatest error was observed for MS900. The regression model given by Equation (2) over-estimates bow for all three material grades tested. There may be several reasons for this. The accuracy of bow prediction depends on the numerical model and on the regression model which, itself, is based on numerical simulation. It can be seen in [1] that the accuracy of the numerical model for roll load, torque and bow was approximately 71%, 84% and 90% respectively and therefore some error in the value for bow predicted by Equation (2) can be expected. In addition, the $R^2_{\text{prediction}}$ value of the regression model is only 86.9% which suggests that a maximum error of 13.1% can be expected from the regression model itself. For the MS900 the lowest accuracy was achieved. This is most likely due to the numerical models where artificial material properties were based on material properties derived from a dual phase steel (DP780) having significantly higher hardening than a martensitic steel, such as the MS900 steel. This suggests that for developing an equation that generates the relationship between bow and roll load and torque while taking into account the effect of process and geometric parameters, material input as close as possible to that of the actual material that is formed needs to be used.

![Figure 5: Comparison of measured bow and the predicted value given by Equation (2)](image)

7. Conclusion
Extensive finite element analysis was carried out to develop a longitudinal bow prediction model for the roll forming of a trapezoidal section. For that, 130 numerical models were created and analysed with different combinations of nine parameters consisting of material properties, geometric and process parameters. A model of trapezoidal section roll forming with different levels of frictional coefficient, yield strength, hardening exponent, flange length, material thickness, web length, bottom roll diameter, forming angle and bending radius was considered for the investigation.

A full quadratic model was used to determine the relationship between the longitudinal bow and the material, process and geometric parameters. The linear, square and two-factor interactions of all the input parameters were considered, except that the yield strength and the hardening exponent were replaced by roll load and torque. This was possible given that there is a direct relationship between roll load and torque and the material properties. The square-root terms of roll load and torque were considered to obtain a robust regression model. It was found that friction, web length, bottom roll diameter and bending radius had no effect on the amount of bow predicted while roll load, torque, flange...
length, material thickness and the forming angle were found to be significant factors. The model developed was compared with experimental results obtained for three AHSS and UHSS grades and an accuracy of between 75% and 90% was achieved. The error of the regression equation observed may be related to inaccuracies in the numerical model that was used to determine it. The regression model given by Equation (2) can be applied to any trapezoidal section that is roll formed in two stations with the tooling arrangement used here and the model for predicting bow on the basis of roll load and torque which are measured during the operation. The next step of this work is to introduce a special roll stand which can be controlled by an actuator to adjust the tooling to compensate for the predicted longitudinal bow. In this way, an in-line bow compensation system can be introduced for conventional roll forming processes.

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