Numerical analysis of the flexible roll forming of an automotive component from high strength steel

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Abstract. Conventional roll forming is limited to components with uniform cross-section; the recently developed flexible roll forming (FRF) process can be used to form components which vary in both width and depth. It has been suggested that this process can be used to manufacture automotive components from Ultra High Strength Steel (UHSS) which has limited tensile elongation. In the flexible roll forming process, the pre-cut blank is fed through a set of rolls; some rolls are computer-numerically controlled (CNC) to follow the 3D contours of the part and hence parts with a variable cross-section can be produced. This paper introduces a new flexible roll forming technique which can be used to form a complex shape with the minimum tooling requirements. In this method, the pre-cut blank is held between two dies and the whole system moves back and forth past CNC forming rolls. The forming roll changes its angle and position in each pass to incrementally form the part. In this work, the process is simulated using the commercial software package Copra FEA. The distribution of total strain and final part quality are investigated as well as related shape defects observed in the process. Different tooling concepts are used to improve the strain distribution and hence the part quality.

1. Introduction
Roll forming is an incremental sheet forming process which was introduced more than one hundred years ago. The process has generally been used for manufacturing longitudinal profiles for different applications such as structural, household and automotive components with uniform cross-sections until early 2000. Since then the conventional roll forming technology has been advanced to produce parts with variability in width and depth. This process is called “flexible or 3D roll forming” and as this technology is fairly new, there have been some recent research papers published \[1, 2\]. The main advantage of the process is the ability to form high strength and low ductility materials and it is attractive for manufacturing automotive parts from Ultra High Strength Steel (UHSS) and Advanced High Strength Steel (AHSS). The use of 3D roll forming presents an opportunity to reduce tooling cost and global tooling footprint by simplifying tool designs and potentially re-using tooling for multiple components and derivatives. Whilst this has been well documented for traditional roll forming (linear constant cross section components), the opportunity to roll from components with variable geometry significantly broadens the application and hence potential benefits.
In the flexible roll forming operation some rolls are kept stationary with an axial rotation while the others have both axial rotation and translational movement to generate the variable width or depth of the parts. Several researchers have investigated flexible roll forming \[1, 3, 4\] and the first validated flexible roll forming line for automotive parts manufacturing was developed by the European R&D project PROFORM \[2, 5\]. Accuracy of the final shape is critical in flexible roll forming of automotive components. The main defects in flexible roll formed products are wrinkling and web warping \[6\]. Excessive compressive stresses in the flange at the transition region cause wrinkling \[7\] while web warping is caused by the lack of longitudinal plastic strains in the flanges of the transition region \[6\]. Larranaga \[6\] introduced heat-assisted flexible roll forming to minimise the web warping. Later Sedlmaier et al. \[8\] introduced a blankholder system which helped to eliminate the occurrence of web warping by applying some pressure on the web region while flange forming. Groche et al. \[9\] introduced an analytical model to predict the critical stress level at the flange which causes wrinkles in variable width flexible roll forming. Park et al. \[10\] introduced an analytical model to predict the longitudinal strain in flexible roll forming and discovered that it can be controlled by changing the forming parameters. Jiao et al. \[11\] developed an analytical model to predict the amount of web warping in flexible roll forming and extended this study to obtain an analysis to predict the longitudinal strain in this process. Yu et al. \[12\] showed that the finite element model of the flexible roll forming process can be improved by supplemented material input based on the Swift’s law.

Even though a number of investigations have been carried out on flexible roll forming, careful process design is needed to achieve precise profiles. The main challenge is to obtain the best profile with the minimum tooling cost. In this paper, a new variable width flexible roll forming technique is introduced similar to variable depth forming of the type presented in \[13\]. This process allows significant cost reduction through tooling optimisation. Several forming concepts are introduced and material behaviour under each forming condition is discussed.

2. Part dimensions and materials
The CAD part of an automotive component was provided by the Ford Motor Company, Australia and its simplified isometric view is shown in Figure 1(a); the cross-sectional dimensions are shown in Figure 1(b). It can be seen that this profile has a uniform cross-section, but is curved.

![Figure 1. (a) Isometric view of the profile (b) Cross sectional dimension of the profile](image)

The strip thickness is 1mm and a Dual Phase steel (DP1000) was used as the material in the finite element models. The tensile test was carried out from the bone shaped samples oriented along the rolling direction of the strip and the standard given by ASTM E8/E8M \[14\] was followed. An Instron 5967 with a 30kN load cell was used for the test and the test speed was 0.025\(\text{mms}^{-1}\) giving a strain rate of 0.001\(\text{s}^{-1}\). The true stress–true strain curve of the material is given in Figure 2.
Figure 2. Average true stress strain curve for the samples tested along the rolling direction

Other material parameters were obtained from the Hollomon’s power law fitted to the true stress-plastic strain curve of the material and are given in Table 1.

Table 1. DP1000 material data

| Material | Yield Strength (MPa) | Ultimate tensile strength (MPa) | Elastic limit | n | K (MPa) |
|----------|----------------------|--------------------------------|---------------|---|---------|
| DP1000   | 764                  | 1194                           | 0.004         | 0.12 | 1633    |

3. Forming strategy

The part shown in Figure 1 is of uniform section, but because of the curved shape in the plan view, the deformation is similar to that of a part of varying width. The proposed forming method employs a die to hold the blank and the whole die set is driven back and forth by a lead screw. A tool holder carries the tooling which is CNC controlled; so that rotational and translational movement can be introduced to the rolls to form the sides as shown in Figure 3. The blank is pre-cut to a shape obtained by unfolding the profile in a CAD system. The forming rolls follow a selected path to form both sides and flanges. The forming sequence is designed to have the minimum number of tooling changes to keep tooling cost and tool changing time to a minimum. In this paper two different tooling concepts will be discussed and the strain distribution under each condition indicated.

Figure 3. Flexible roll forming methodology
4. Flower pattern and tooling
The forming sequence used in this investigation is given by the flower pattern shown in Figure 4. Two tooling sets were used for the forming sequence.

![Figure 4. Flower pattern](image)

The dimensions of the pre-cut blank were obtained by unfolding the simplified CAD profile given in Figure 1(a) and are shown in Figure 5.

![Figure 5. Symmetric half of the pre-cut blank](image)

In this investigation, two different tooling concepts were used to form the left-hand side of the part shown in Figure 4 and a single tooling concept for the right side of the profile (here we mainly focused on the left-hand side of the part since it introduces the complexity to the profile). However the same tooling configuration was used in both concepts from 1st - 11th stations and is shown in Figure 6.
Two different tooling configurations were used for forming from the 12th to the 15th station as shown in figure 6. In the first tooling concept only one cylindrical bottom roll was used to form the flange to the final angle as shown in Figure 7 (a). In concept 2, top and bottom rolls were used to form the flange as shown in Figure 7 (b).

Figure 6. Tooling configuration used in both concepts for (a) 1st - 5th stations (b) 6th - 11th stations

Figure 7. Tooling configuration used in 12th - 15th station for (a) tooling concept 1 and (b) tooling concept 2

5. Finite element model

Unlike in the traditional roll forming process, in the variable width flexible roll forming process, tooling is moving in a 3D space to generate the required part geometry. In this work, a new concept of variable width flexible roll forming is introduced and is similar to the variable depth roll forming process introduced in [13]. In the finite element model, first the pre-cut blank is held between the clamping dies and the forming tools pass a certain contour to form the blank incrementally to the desired shape. The die set then opens and the finished product can be removed.

The tool design and numerical simulation were carried out with the commercial software package COPRA® FEA RF [15] which uses built-in MSC.Marc and an implicit solver. Half of the length of the part was modelled due to the symmetry and full integration, hexahedral, type 7 arbitrarily distorted brick elements available in the software package were used to model the pre-cut blank. Only one element through the thickness was used and a refined mesh was introduced at the bending regions. The effect of friction was neglected in the FEA model. Material input for the FEA model was taken from the tensile test data given in Figure 2 while the Poisson’s ratio was taken as 0.3. Given that several previous studies have shown that in conventional and flexible roll forming a first adequate representation of material behaviour can be made using a simple isotropic hardening model [16, 17] the von Mises Criterion was used to define plastic material behaviour.

Three boundary conditions are applied on the pre-cut blank as shown in Figure 8. An X lock is introduced on the nodes along the transverse centre of the blank which restricts the transverse movement of the part during the forming operation. A Y lock is applied on three nodes of the bottom of the pre-cut
blank (see Figure 8) which limits the vertical movement of the strip when it is not supported by the die set. The longitudinal movement of the strip is avoided by a Z lock boundary condition which is applied on some nodes at the front edge and mid-section of the pre-cut blank (see Figure 8).

6. Results
Different views of the final part simulation with the two tooling concepts are shown in Figure 9. There is some distortion in the horizontal flange at the ends of the both parts. Significant longitudinal stretching takes place in that region when the pre-cut is formed to the final geometry; since this stretching is irreversible, the additional material generates some waviness in the flange; however the waviness generated by the tooling concept 2 is significantly smaller than that of tooling concept 1 (see side view in Figure 9).

Figure 8. Boundary conditions on the pre-cut blank

Figure 9. Final part quality
To understand the material deformation in the process further, the strain history was analysed and for this a node in the critical region of deformation was taken as shown in Figure 10(a). The longitudinal and transverse strain during the process for both tooling concepts are shown in Figure 10(b). Between station 1 and 11, the processes are identical and as this is an edge node the deformation is uniaxial. The peak membrane strains lie between approximately +5% and -2.5% and this is much greater than strains encountered in conventional roll forming. During forming of the side, stations 1 – 5, and forming the flange, 6- 11, the edge is stretched plastically to residual strain of about 3%. During the reforming of the side, stations 12 – 15, the residual longitudinal strain is reduced, i.e. it is compressed to 2 and 1% residual longitudinal strain in tooling concept 1 and 2 respectively. In practical metal forming parlance it would be said that the metal is “crowded” and hence buckling occurs. To illustrate this more clearly, the longitudinal strains in stations 12 – 15 are shown to a larger scale in Figure 10(c). It is seen that the compression is higher in tooling concept 1 (2%) than in tooling concept 2 (1%). The lower longitudinal compressive strain in tooling concept 2 can be attributed to the additional support provided by the top roll as this suppresses material movement.

Figure 10. (a) Location of the node which considers for the strain plot (b) Different strain components (c) Different strain components from S12 to S15
The strain distribution of the whole part along the inside edge is shown in Figure 11; the strain in Figure 11(b) is not the peak strain, but that after forming the complete section. It may be seen that most of the areas do not undergo severe deformation, but between an arc length of 100mm and 200mm there is significant residual strain in the final part. The tooling concept 2 shows higher longitudinal residual strain than that of the tooling concept 1. This comes about because in concept 1 the reduction in edge length is achieved by buckling, which is undesirable, while in concept 2 the reduction is achieved by plastic compression of the metal. Further, it may be seen from Figure 10(b) that concept 2 shows less reduction of longitudinal strain compared to tooling concept 1, because, as mentioned, the top supporting roll suppresses the material movement. As a result tooling concept 2 shows higher longitudinal residual strain in the flange edge (see Figure 11(b)) and improved part quality compared to tooling concept 1.

Figure 11. (a) Node path considered for the strain plot (b) Different strain components

7. Conclusion
A new flexible roll forming technique for a curved channel is introduced and was successfully simulated with the COPRA® FEA RF software package. Two tooling concepts are studied and the final part quality investigated. Improved quality was indicated with a tooling concept which provided additional support for the flange during final side forming. In both tool designs, buckling of the flange occurred where the curvature of the part in the plan view is greatest; buckling was less in the preferred design even though higher final strains due to the suppression of material where found. The work indicated a direct relationship between flange distortion and curvature of the part in the plan view and suggests that this distortion can be minimised by wise part and tooling design.

Acknowledgment
The authors would like to thank Emeritus Professor J.L. Duncan for his assistance in writing this paper and acknowledge the financial support made by the Ford Global - University Research Program – “2012-5089R Flexible roll forming of automotive structures” as well as the technical and software support provided by data M Sheet Metal Solutions GmbH.

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