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Prototyping of automotive components with variable width and depth

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Abstract. Roll forming enables the manufacturing of longitudinal components from materials that combine high strength with limited formability and is increasingly used in the automotive industry for the manufacture of structural and crash components. An extension of conventional roll forming is the Flexible Roll Forming (FRF) process where the rolls are no longer fixed in space but are free to move which enables the forming of components with variable cross section over the length of the part. Even though FRF components have high weight saving potential the technology has found only limited application in the automotive industry.

A new flexible forming facility has recently been developed that enables proof of concept studies and the production of FRF prototypes before a full FRF line is built; this may lead to a wider uptake of the FRF technology in the automotive industry. In this process, the pre-cut blank is placed between two clamps and the whole set up moves back and forth; a forming roll that is mounted on a servo-controlled platform with six degrees of freedom forms the pre-cut blank to the desired shape.

In this study an initial forming concept for the flexible roll forming of an automotive component with variable height is developed using COPRA® FEA RF. This is followed by performing experimental prototyping studies on the new concept forming facility. Using the optical strain measurement system Autogrid Compact, material deformation, part shape and wrinkling severity are analysed for some forming passes and compared with the numerical results.

The results show that the numerical model gives a good representation of material behaviour and that with increasing forming severity wrinkling issues need to be overcome in the process.

1. Introduction

Roll forming is a well-known process for the manufacturing of components with uniform cross section for applications in the building and automotive industry [1]. It allows the forming of hard to form materials to complex geometries with minimum shape defects. As a result roll formed sections from Ultra High Strength Steel (UHSS) and Advanced High Strength Steel (AHSS) are increasingly used in automotive industry for structural and crash components [2]. While roll forming is limited to long profiles of continuous cross section the recently developed Flexible Roll Forming (FRF) technology...
enables forming of profiles with variability in width and depth over the length of the part [3-6]. In FRF some rolls stay stationary similar to the conventional roll forming process while others provide a translational and rotational movement to achieve variability in cross section shape.

The two major shape defects in FRF are web warping and wrinkling in the flange [7]. Web warping has been extensively studied by Ona [8] who showed that a lack of permanent deformation in the transition zones of FRF profiles of variable width led to increased web warping. Jiao et al. [9] developed an analytical model to predict web warping defects in FRF profiles of variable width. Larranaga [7] introduced a local heating system while Abee et al. [10] developed a blank holder system to minimise web warping defects. Only a few studies investigated wrinkling in FRF [10-12]. So far the wrinkling defect has only been studied for profiles of variable width and has been related to an excessive stretching of the strip edge before it enters the compression zone[12]. However the cause for wrinkling may differ depending on the part shape and currently there are no guidelines for minimising wrinkling defects in FRF.

The existing FRF technology is still limited in regard to the geometries that can be formed and wrinkling was found to be a critical defect. It is believed that wrinkling in FRF can be minimised by an advanced tool and process design. In this paper, a new prototyping FRF equipment will be introduced together with a new tool concept. This promises production of profiles with both variable width and depth at low tooling cost.

2. Profile geometry and materials
The profile considered for this investigation is shown in Figure 1(a). The profile height varies along the length and the cross sectional dimensions across sections A-A and D-D in Figure 1 are illustrated in Figure 1(b) and (c) respectively. The thickness of the material is 2mm and a dual phase steel (DP780) was used in the experiments and the finite element analysis.

![Figure 1](image_url)

Figure 1. (a) Isometric view of the profile (b) cross sectional dimension through section A-A (c) cross sectional dimension through section D-D

Standard tensile tests were carried out according to ASTM E8/E8M [13] with bone shaped samples oriented along the rolling direction of the strip. An Instron 5967 with a 30kN load cell was used for the tests and the test speed was 0.025ms⁻¹ giving a strain rate of 0.001s⁻¹. The true stress–true strain curve of the DP780 is given in Figure 2.
Figure 2. Averaged true stress strain curve of DP 780 tested along the rolling direction

Table 1 presents the material parameters which were obtained by fitting the Hollomon’s power law to the true stress- effective plastic strain curve of the material.

Table 1. DP780 material data

| Material | Yield Strength (MPa) | Ultimate tensile strength (MPa) | Elastic limit | n     | K (MPa) |
|----------|----------------------|---------------------------------|---------------|-------|---------|
| DP780    | 594                  | 960                             | 0.003         | 0.12  | 1228    |

3. Forming strategy
A schematic of the new 3D roll forming prototyping equipment is shown in Figure 3. The pre-cut blank is placed between two clamps where the top clamp has the features of the inner surface of the part to be formed such as the corner radius, the profile length and width. The clamping force is provided by a set of hydraulic cylinders attached to the main frame which is called “sled”. The sled which carries the blank sheet and clamps can be moved back and forth on the mill bed by a lead screw attached to a servo controlled motor. The forming tool is mounted on two hexapods that consist of six leadscrews which are driven by six separate servo motors. The tool holder which carries the forming tool is placed on the hexapod plate providing a six degrees of freedom tool motion. According to this new machine concept, the same tool set can be used for several roll forming steps which enables an infinitely selection of bending angles and significantly reduces tooling cost.

Figure 3. Schematic of the new 3D roll forming prototyping equipment
The part shown in Figure 1(a) has a uniform width and a variable height. Therefore the pre-cut blank has a non-uniform width which can be obtained by unfolding the 3D model given in Figure 1(a). The symmetry half of the pre-cut blank is shown in Figure 4 and the same blank was used for the finite element analysis. The profile web has three different curvatures that are followed by the forming tool to form the flange (Figure 5).

![Figure 4. Symmetric half of the pre-cut blank](image)

Figure 4. Symmetric half of the pre-cut blank

**4. Forming sequence and tooling**

The flower pattern shown in Figure 6(a) shows the forming sequence while Figure 6(b) gives a schematic of the tool used in the first four forming passes. This consists of three bottom rolls (B1, B2 and B3) and two top rolls (T1 and T2). The two top rolls are called finger rolls due to their shape and the part will be formed in FEA with and without finger rolls to understand their effect on the material flow. The centres of roll B1, B2 and T1 are located in one plane and the right part of Figure 6(a) indicates their position on the flange during forming. The tool has to follow a path given by the web of the profile as shown in Figure 5 to generate the component geometry.

![Figure 6. (a) Flower pattern (b) schematic of the forming roll cluster](image)

Figure 6. (a) Flower pattern (b) schematic of the forming roll cluster
5. Finite element model
In reality, the sled which carries the clamps and the pre-cut blanks moves back and forth while the tool changes its position and angle to form the flange according to the forming sequence. However in the finite element model, the pre-cut blank is fixed in space and the forming tool moves in sequence over the blank to form the strip to the desired shape as shown in Figure 7(a).

The numerical analysis was performed using the commercial software package COPRA® FEA RF [14] which is based on MSC Marc and uses an implicit solver. The rolls and clamps were modelled as solid bodies while the strip was discretised with full integration, hexahedral, type 7 arbitrarily distorted brick elements. Only the transversal half of the strip was modelled due to symmetry as shown in Figure 4 and one element through the thickness was used to save computational time. A refined mesh was used in the bending region and frictionless contact was assumed. Material data for the model was obtained from the tensile test. The elastic material behaviour was defined assuming a Poisson’s ratio of 0.3 and a Young’s modulus of 200GPa. Isotropic hardening and von Mises yield criterion were used in combination with the plastic component of the trues tress strain curve given in Figure 2 to define plastic material behaviour [15-17].

The boundary conditions applied on the pre-cut blank are shown in Figure 7(b). An X lock boundary condition was applied on the nodes along the symmetric centre which fixes the material in X direction to represent the transversal symmetry of the pre-cut blank. A Y lock boundary condition was applied on nine bottom nodes along the symmetric centre at three different locations; this was to hold the pre-cut blank in the vertical plane while forming. The longitudinal movement of the strip is restricted by the Z lock boundary condition which is applied on four nodes at the end of the strip, towards the symmetric centre (see Figure 7). In addition to that, to define the tool movement a tool path was introduced in the finite element model which has same contour as the web of the profile shown in

![Finite element model (a) Concept of forming in FEA (b) boundary conditions on the pre-cut blank](image)

6. Experimental analysis
The flexible roll forming experiments were carried out with the newly developed 3D Rollforming Center at dataM Sheet Metal Solutions. The final part shape and the strain distribution after four forming passes was experimentally investigated using a 3D laser scanner and the Vialux Autogrid Compact [18] strain measuring system respectively.

First a grid of 2mm x 2mm was etched on critical areas of the pre-cut blank to enable analysing the strain distribution after forming. Then the Autogrid Compact captured the grid after deformation (while the pre-cut blank was still located within the clamps) to determine major and minor strains for comparison with the FEA. Part shape measurement was carried out with a 3D laser scanner which has been developed by dataM Sheet Metal Solutions and uses the laser light-section principle.
Part shape was analysed after the fourth forming step. For this the output .IGES files from the 3D scanner and the FEA were imported to the Geomagic Qualify software [19]. To determine the wrinkling pattern the cross section perpendicular to the part edge was considered. For this the “Height” from a reference line, as shown in Figure 8(a) to the strip edge was considered. To further understand the material flow in the flange, strain in the strip edge was measured after the fourth forming pass using the Autogrid Compact system. Over the section length shown in Figure 8(b) and in the first half of the blank the minimum principal strain in the strip edge was determined.

![Reference line considered for wrinkling measurement](image1.png) ![Arc length considered for strain measurements](image2.png)

Figure 8. (a) Reference line considered for wrinkling measurement (b) arc length considered for strain measurements

7. Results

The final strip height measured in the experiments and predicted by FEA after the 4th forming station is compared in Figure 9(a). The overall height of the strip edge is similar in magnitude between the experiments and the FEA. However while the experiments show three local peaks the FEA only predicts two.

Given that in the process the strip edge mostly undergoes compressive deformation only the minimum principal strains evaluated in both the experiments and FEA are presented in Figure 9(b). According to Figure 9(b) the FEA shows slightly higher compressive strains compared to the experiments in most parts of the flange region. This suggests that in the FEA the material holds the compressive deformation, i.e., a higher magnitude of compressive strain is permanent. In the experiments the material releases the compression most likely in form of wrinkling of the flange which may explain the higher wrinkling tendency observed in the experiments compared to the numerical model (Figure 9(a)).

![Wrinkling pattern](image3.png) ![Compressive strain comparison between experiments and FEA](image4.png)

Figure 9. (a) Wrinkling pattern (b) compressive strain comparison between experiments and FEA

The numerical results for the wrinkling pattern in the edge after the fourth forming step and the minimum principal strain is compared between the forming with and without the use of finger rolls in Figure 10(a) and (b) respectively. Figure 10(a) clearly indicates that the finger rolls play a major role in postponing the initiation of wrinkles and lead to less wrinkling defect. In Figure 10(b) it can be observed
that even though the part is symmetric in longitudinal direction there is a non-symmetric distribution of minimum principal strain. The minimum principal strain is higher if finger rolls are used which indicates that the finger rolls increase the level of permanent compressive strain in the material; this leads to reduced wrinkling. Without the finger rolls the material tends to release more compressive strain by developing more wrinkles. This suggest that wrinkling issues in flexible roll forming may be minimised by a smart tool design and by optimising the forming sequence.

Figure 10. (a) Wrinkling pattern with and without finger rolls (b) distribution of the minimum principal strain after each pass

8. Conclusion
A new prototyping facility for roll forming variable width and depth components was introduced and was successfully simulated with COPRA® FEA RF. The high strength steel that was formed showed a high tendency for wrinkling and a newly introduced roll cluster showed good potential to postpone the initiation of wrinkles. Higher magnitude of compressive strain attributed to the less sever wrinkling and vice versa. Introduction of the finger rolls reduced the number wrinkling peaks from 6 to 2. In addition the numerical control of the roll movement can be used to increase the accuracy of the part by changing the tool path or bending angle.

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