Analysis of material behaviour and shape defect compensation in the flexible roll forming of advanced high strength steel

S Ghanei1, B Abeyrathna1, B Rolfe2 and M Weiss1

1 Institute for Frontier Materials, Deakin University, Geelong, VIC 3216, Australia
2 School of Engineering, Deakin University, Geelong, VIC 3216, Australia
*Corresponding author e-mail: sghanei@deakin.edu.au

Abstract. Roll forming is a fast and low-cost forming process with the ability to form a wide range of materials, especially advanced high-strength steels (AHSS) that have limited ductility. However, roll forming is only able to form constant cross-sections along the longitudinal direction of the component, while many automotive components are more complex in shape. Flexible Roll Forming (FRF) uses rolls that have the ability to translate or rotate during production, enabling the manufacture of a part that has a variable cross-section potentially useful for the automotive industry. Deakin University is equipped with a flexible forming facility that can prototype parts with variable cross-sections. The machine has been developed, patented and manufactured by dataM Sheet Metal Solutions GmbH. Deakin’s Flexible Forming Facility (DFFF) consists of a single forming stand with two opposing robotic arms connected to forming rolls. The flexibly controlled arms form the clamped sheet along a CNC defined bend line while the sheet remains clamped. This facility is capable of creating changes in the cross-section in both width and depth along the part. Moreover, the Deakin facility can form the part in both forwards and backwards directions along the longitudinal dimension of the part. In contrast, conventional FRF facilities use multiple stands of forming rolls, and the forming sequence occurs in a single direction along the part.

The first part of this study compares material deformation in the DFFF in contrast to that of the conventional FRF setup. This study will determine the similarities and differences in the final formed part between DFFF and the forming conditions in conventional FRF. The second step of the study is to investigate the forming properties of the final part when the part has variable depth. An experimental part formed on DFFF was compared to a numerical analysis using COPRA RF FEA to investigate the material flow and the forming defects. The results show that the major shape error is wrinkling. A new forming concept using a blank holder tool was analysed, and it shows promising results in regard to wrinkling reduction.

Keywords: Flexible roll forming; High-strength steel; Simulation; Strain; Wrinkling

1. Introduction

There is pressure on the automotive industry to reduce the weight of vehicles leading to a corresponding reduction in harmful emissions of greenhouse gases [1]. Advanced High Strength Steels (AHSS) have attracted a large amount of attention for use in the vehicle Body-in-White (BIW) because they provide high strength and safety as well as weight reduction [2]. The limited formability of AHSS is a challenge for vehicle manufacturers to achieve the desired part shapes for modern BIW structures [3, 4]. In recent decades, the hot stamping process has been increasingly used for the manufacture of automotive
components from AHSS [5]. However, hot stamping is prone to high costs including: high tool wear, complex tooling designs, and large infrastructure costs.

Roll forming is a fast and low-cost forming process with high material utilisation. Roll forming has the ability to form the AHSSs that have limited ductility to tighter radii and with less springback than conventional stamping processes [6-9]. However, roll forming is unable to produce many automotive parts because they have varying cross-sections along the part, while roll forming is restricted to parts with constant cross-sections [10]. To overcome this drawback, new generation roll forming machines, Flexible Roll Forming (FRF), have been developed. FRF utilises forming rolls that have the ability to translate or rotate to produce a part profile with a variable cross-section (Fig. 1-a) [11-13]. A wide range of components can be produced without the need to change the tooling, which makes it a cost-effective substitute to conventional stamping. Also, due to the incremental nature of the forming concept, it may enable the forming of AHSS parts.

There are some common shape errors that occur during FRF. Web warping is the deviation of height in web area from the desired profile, and wrinkling is where there are buckles or wrinkles in the side wall flange. Both these errors increase as the strength of the blank material increases [12]. Web warping has attracted the attention of many researchers and there are methods to reduce the warping in a web area. However, an applicable concept to solve the wrinkling issue in the flange during the FRF is still unavailable.

In this paper, a new prototyping flexible roll forming facility will be introduced (Deakin’s Flexible Forming Facility (DFFF)) and its production is compared with conventional FRF. The comparison is then followed by an extensive flange wrinkling study using DFFF. A new blank holder concept will be introduced to reduce the severity of wrinkling in the flange of the component.

2. Experimental procedures
The FRF trials were carried out using DFFF (Fig. 1-b). The facility was developed, patented and manufactured by DataM Sheet Metal Solutions GmbH and is fully programmable to form various profiles with different cross-sections. DFFF consists of a single forming stand with two opposing robotic arms connected to forming rolls; the blank is held in place between the top and bottom dies. The pre-cut sheet is fully clamped by the top and bottom dies, which simulate a moving blank-holder. The flexible forming facility forms the part simulating a CNC controlled forming line; the dies (making up the blank holder) can move back and forth allowing forming in two directions. This arrangement permits comparison with a conventional flexible roll forming.

A variable depth automotive profile was selected for the FRF experiments. The final part shape and dimensions are shown in Fig. 2-a. The pre-cut sheets used in FRF experimental trials were produced from two dual-phase steels (DP600 and DP1000) each having a thickness of 2mm. Two different flange lengths were studied during the experimental FRF trials (Table 1).
Table 1. Different used samples made from different dual-phase steels.

| Material | Sample 1 | Sample 2 | Sample 3 |
|----------|----------|----------|----------|
| Flange length (mm) | DP1000 | DP600 | DP600 |
| 100 | 80 | 100 |

Fig. 2. a) The geometry of the investigated variable depth component, and b) the true stress-strain curves of the used materials.

Fig. 2-b represents the mechanical properties of the materials as obtained from standard tensile tests (according to ASTM E8/E8M standard) using an Instron 5967-30kN at a strain rate of 0.001s⁻¹.

The profile was formed in four passes starting from a bend angle of 15° bending angle and ending with 40°. The flower pattern and roll set that were used in the experiments are shown in Fig. 3. The AutoGrid strain analysis system [14] was used to study the deformation and the corresponding strains in the experiments. Before the FRF trials, a 2mm×2mm grid was etched on the sample surface by electrochemical etching.

3. Numerical analysis

The flower pattern and tool designs were carried out using the commercial software package COPRA® RF 2017 and those designs were imported into COPRA® FEA RF 2017 to simulate the FRF process. COPRA® FEA RF is specifically for roll forming process design and optimisation, with a built-in MSC Marc solver [15].

3.1. Comparison between conventional FRF and DFFF

To study the differences and similarities between the conventional FRF and DFFF, a variable width component (Fig. 4-a) was chosen based on the literature [16]. The sheet was modelled as a deformable meshed part while the die and the roll sets were defined as rigid surfaces. In order to reduce the computational time, only half of the pre-cut sheet was modelled due to the symmetry. The sheet material properties were defined using isotropic material behaviour in combination with the tensile curve of DP600 and the Von Mises yield criteria was applied to model the plastic behaviour. The Poisson’s ration and Young’s modulus were 0.33 and 210GPa, respectively.

Fig. 3. a) The flower pattern used to form the variable depth component, and b) original roll set using two finger rolls.
DFFF approach was compared with the conventional FRF using a frictionless FEA model consisting of two solid elements through the thickness, with different tool sets and spacing between the forming stations (Fig. 4-b). Fixing the web for both approaches, directs all the deformation towards the flange and allows the study of comparable conditions.

3.2. Wrinkling study using DFFF

Mirroring the experimental set-up, the dies, the rolls set and the pre-cut sheet were reproduced in the simulation model of the variable depth component (Fig. 5-a). The coordinate system used and the boundary conditions are shown in Fig. 5-a. In order to define the geometric properties of the materials during the FRF modelling, two element types were used for the sheet: structural 3D solid (Hex element type 7) and structural 3D solid shell (Hex element type 185). There were 10 meshes along the longitudinal direction in the critical compressive and tensile areas (length of $z=6.3$ mm). The width of the elements in the critical areas was as follows: $x=2.37$ mm in bending region, $x=2.09$ in the edge region and for the flat region in between the bending and edge regions it was in the range of 3.52 to 6.56 mm. After constructing an accurate FEA model capable of predicting the wrinkling for samples No. 1 and 2, a blank holder concept was implemented to reduce the severity of wrinkling. In this, sample No. 3 was formed in the FEA model up to a bend angle of $40^\circ$ using the original roll set shown in Fig. 3-b, then, a new roll set, blank-holder roll set (Fig. 5-b), was used to compensate the formed wrinkle at the same bending angle. In this new roll set, two line contacts provided by two finger rolls were replaced by a surface contact over 100 mm × 85 mm area.
4. Results and discussions
There are several differences between the conventional FRF and DFFF approaches, but the most important one is the reduction of the multiple active roll stands in conventional FRF to one hexapod on each side in DFFF. The FEA model was used to prove whether DFFF leads to a forming response that is the same as that found in conventional FRF. The comparison is only made on the finished samples (after the 3rd forming station). The variable width components were examined by these two approaches and both results were compared in Fig. 6. In addition, the results were compared with the analytical strain calculations.

To form the ideal shape component without any shape defects, control of the geometrically necessary compressive and tensile strains at the edge of the variable width component is needed. Both the compressive strain ($\varepsilon_c$) and tensile strain ($\varepsilon_t$) can be calculated using [16]:

$$\varepsilon_c = \ln \left( \frac{R_t}{R_c} \right)$$

$$\varepsilon_t = \ln \left( \frac{R_c}{R_t} \right)$$

where, $R_t$ and $R_c$, are respectively the measured radii of tensile and compressive sections after forming at the edge of the flange.

As can be seen in Fig. 6, the formed components are similar in shape and there is no visible difference between using DFFF and the conventional approach. The strain data from both approaches are similar (RMS=5.40E-04). In addition, both values of the strains are close to the necessary values of compressive and tensile strains, especially in compression zone. Thus, the forming conditions in conventional FRF and DFFF can be considered to be similar.

The mesh sensitivity study was carried out to determine the correct level of mesh type and density for the FEA model to accurately predict the wrinkling shape error. Yoon et al. [17] compared element types in FRF simulation; they concluded that the model with the solid shell elements is able to predict the experimental trend in FRF better than other elements. Here, to choose the best element type and density through the thickness, the experimental data was compared with the FEA models including: one solid element through the thickness; two solid elements through the thickness; and two solid shell elements through the thickness of the pre-cut sheets. Fig 7 compares the modelled values of longitudinal strains (measured at the edge of the flange) with the experimental results.

![Comparison of Deakin 3D forming and Conventional FRF](image)

Fig. 6. The 3D shapes, sections and strains results comparing conventional FRF vs. DFFF.
Fig. 7. Modelled values of the longitudinal strains (at the flange edge) for sample No.1 after the 4th forming station in comparison with the experimental data provided by Autogrid measurements.

The FEA model with two solid elements through the thickness led to higher model accuracy compared to the other two approaches. This finding is in contrast with the results of Yoon et al. [17], which stated that the solid shell elements have a better performance compared to the solid elements when modelling the FRF process. The FEA results of the model using one solid element significantly overestimate the negative strain peak.

To further validate the proposed model, another series of experimental and numerical results were compared in Fig. 8 for sample 2 made from DP600. All results in this figure show the improved performance of the FEA model with solid elements in predicting the material behaviour during the FRF process. This model will be used for the remaining part of this study.

Wrinkling in the flange is a common shape defect occurring during the FRF of high and ultra-high strength steels and finding an applicable concept to solve the wrinkling issue is still an open issue. As can be seen in Fig. 8-d, there is wrinkling in the compression section of the variable depth component.

Fig. 8. a-c) The strain, and b) shape comparisons for sample No. 2 obtained from the experiments and the FEA using two solid elements through the thickness.
To reduce this, it was thought that surface contact could constrain excessive sheet movement during wrinkle formation. Fig. 9 shows two formed components, before and after using the blank holder roll arrangement, Fig. 5-b), which clearly shows an improvement in the shape quality of the component; strain results are compared in Fig. 10. As can be seen, using the blank holder results in increased strain values compared with the values measured from the original roll set. When the original roll set was used, the flange bulged out due to the formation of a wrinkle which reduces the compressive strain in the flange area. The surface contact of the blank holder roll set resulted in an additional constraint and kept the material at a strain value closer to that analytically required. It should be noted that the blank-holder concept is still in its preliminary stages and needs further development.

![Fig. 9. 3D shape comparison, before and after implementing blank-holder concept.](image)

5. Conclusions
FRF is the next area of development in roll forming. Most of the current studies have focused on the FRF of variable width profiles, but automotive components require variation in height. Wrinkling also requires attention, especially for the forming of advanced high strength steels. This study addresses these areas both experimentally and numerically. The main conclusions are as follows:

1. An accurate FEA model capable of predicting forming strain and wrinkling in FRF has been developed. It was found that the model using two solid elements through the thickness is able to accurately predict material behaviour and validation with experimental trials on different part shapes has been provided.

2. Implementing a blank holder concept, the observed wrinkle can be reduced. Compared with the original roll set using two finger rolls, the blank holder roll set constrained wrinkle formation. The measured compressive strain for the blank holder concept is closer to that analytically required to achieve the part shape.

3. Modelling a variable width component, it was found that the forming behaviour in the conventional FRF is similar to that observed in DFFF.

![Fig. 10. The strain comparison, before and after implementing blank holder concept.](image)
Acknowledgements
The authors acknowledge data M sheet metal solutions for their technical support and for providing several licences of Copra RF/FEA. The authors also would like to thank Emeritus Professor John Duncan for his comments on editing the manuscript.

References
[1] Cazuc P 2016 Driving new lightweight and high strength solutions for the automotive industry Reinforced Plastics 60 376-9
[2] Kaluza A, Kleemann S, Fröhlich T, Herrmann C and Vietor T 2017 Concurrent Design & Life Cycle Engineering in Automotive Lightweight Component Development Procedia CIRP 66 16-21
[3] Hu P, Ma N, Liu L and Zhu Y 2012 Theories, Methods and Numerical Technology of Sheet Metal Cold and Hot Forming: Analysis, Simulation and Engineering Applications: Springer London
[4] Groche P and Christiany M 2013 Evaluation of the potential of tool materials for the cold forming of advanced high strength steels Wear 302 1279-85
[5] Hu P, Ying L and He B 2016 Hot Stamping Advanced Manufacturing Technology of Lightweight Car Body: Springer Singapore
[6] Altan T and Tekkaya A E 2012 Sheet Metal Forming: Processes and Applications: ASM International
[7] Abeyrathna B, Rolfe B and Weiss M 2017 The effect of process and geometric parameters on longitudinal edge strain and product defects in cold roll forming The International Journal of Advanced Manufacturing Technology 92 743-54
[8] Weiss M, Abeyrathna B, Rolfe B, Abeé A and Wolfkamp H 2017 Effect of coil set on shape defects in roll forming steel strip Journal of Manufacturing Processes 25 8-15
[9] Abeyrathna B, Rolfe B, Hodgson P and Weiss M 2016 A first step towards a simple in-line shape compensation routine for the roll forming of high strength steel International Journal of Material Forming 9 423-34
[10] Gülçeken E, Abeé A, Sedlmaier A and Livatally H 2007 Finite Element Simulation of Flexible Roll Forming: A Case Study on Variable Width U Channel. In: 4th International Conference and Exhibition on Design and Production of MACHINES and DIES/MOLDS, (Cesme, TURKEY
[11] Yan Y, Wang H, Li Q and Guan Y 2016 Finite element simulation of flexible roll forming with supplemented material data and the experimental verification Chinese Journal of Mechanical Engineering 29 342-50
[12] Abeyrathna B, Rolfe B, Pan L, Ge R and Weiss M 2016 Flexible roll forming of an automotive component with variable depth Advances in Materials and Processing Technologies 2 527-38
[13] Abeyrathna B, Abvabi A, Rolfe B, Taube R and Weiss M 2016 Numerical analysis of the flexible roll forming of an automotive component from high strength steel IOP Conference Series: Materials Science and Engineering 159 012005
[14] GmbH V 2012 AutoGrid Release 5.0 operator manual.
[15] GmbH d S M S 2015 COPRA FEA RF user Manual.
[16] Kasaei M M, Naeini H M, Abbaszadeh B, Mohammadi M, Ghodsi M, Kiuchi M, Zolghadr R, Liaghat G, Tafi R A and Tehrani M S 2014 Flange Wrinkling in Flexible Roll Forming Process Procedia Engineering 81 245-50
[17] Yoon D H, Kim D H, Zhang Y and Jung D W 2016 Compare of shell element and solid element in roll forming simulation. In: Advanced Materials, Mechanical and Structural Engineering, ed S M Hong (London: Taylor & Francis Group) pp 261-4