Prototyping of straight section components using incremental shape rolling

Abdelrahman Essa1 · Buddhika Abeyrathna1 · Bernard Rolfe2 · Matthias Weiss1

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Abstract
Flexible Roll Forming (FRF) allows the forming of components with a variable cross section along the length of the component. However, the process has only limited application in the automotive industry due to wrinkling in the flange which currently prevents the forming of high strength steels and limits the part shape complexity. This paper presents a new forming technology, Incremental Shape Rolling (ISR), where a pre-cut blank is clamped between two dies, and then a single forming roll is used to incrementally form the material to the desired shape. The new process is similar to some Incremental Sheet Forming (ISF) approaches but with the difference that Incremental Shape Rolling (ISR) allows the manufacture of longitudinal components from high strength metal sheets. In this work, a numerical model of the ISR of a straight section is developed. Experimental prototyping trials are performed and are used to validate the numerical model which is then applied to analyse the new forming process. The results show that in ISR, tensile residual strains are developed in the flange. Flange wrinkling is observed and directly linked to the number of forming passes that are used in the process.

Keywords Incremental shape rolling · Roll forming · Finite element analysis · Flange wrinkling

1 Introduction

Formed components of high strength steel are increasingly used in the automotive industry for structural and crash components [1]. This is attributed to their high strength-to-weight ratio allowing overall weight reduction [2].

Roll forming (RF) is a well-known process for the manufacturing of components with a uniform cross section for applications in the automotive and building industry [3, 4]. In roll forming, the metal strip is fed through consecutive sets of rotating rolls. Each forming roll stand performs an incremental part of the bend, and the flange is therefore incrementally bent to the desired shape and angle. Plane strain bending is the main deformation mechanism in the roll forming process. Roll forming, therefore, allows the room temperature forming of high strength metals with limited ductility [5]. However, the process is limited to long profiles of constant cross section, as the roll stands are stationary [6].

To enable the roll forming of structurally optimised profiles that vary in width and depth over the length of the part, Flexible Roll Forming (FRF) has been developed. In FRF, the pre-cut blank is fed through several roll stands, where some rolls stay stationary similar to the conventional roll forming process while others rotate and translate axially to achieve variability in the cross-section shape [7–9].

Web-warping and flange wrinkling are the two major shape defects in FRF; previous studies mostly focused on understanding the causes of web-warping and proposed some practical solutions [7, 10–14]. Flange wrinkling occurs when the required longitudinal compressive strain in the flange edge exceeds the buckling limit [9], and this restricts the part shape complexity achievable with FRF [15, 16]. To further investigate flange wrinkling and to enable the flexible roll forming of components with variable depth, a recent study introduced a prototype flexible roll forming facility where the pre-cut blank is clamped between two forming dies and formed into shape by one forming roll stand that is mounted on a robotic arm on either side of the die [17]. Similar to the conventional flexible roll forming process, the forming roll follows the part shape contour and...
incrementally bends the flange into shape. Different forming roll profiles are needed between forming passes which reduce the efficiency of the process. However, similar to the conventional flexible roll forming process, excessive wrinkling can occur which limits the part shape complexity that can be achieved [17].

With Incremental Sheet Forming (ISF), a wrinkle-free component can often be formed by controlling the state of stress in the processes. For example, the state of stress in metal spinning may depend on the tool path. During a forward forming path, a combination of tensile radial stress and compressive hoop stress is generated in the flange, while during a backward forming path, both hoop and radial stresses are compressive; this can lead to wrinkling [18–20]. Jia et al. [18] investigated two tool path strategies, one with and the other without a backwards forming path to form a 304 stainless steel cylinder using metal spinning. The spun part that was produced without backwards forming showed no wrinkling which suggests that excessive wrinkling can be eliminated by applying a suitable forming approach that reduces the circumferential compressive stress. Music et al. [21] suggested that compressive hoop stresses in the flange during the conventional spinning process can be balanced by tensile stresses to avoid flange wrinkling.

However, ISF does not allow the forming of long and open sections that are required in the automotive industry for structural and crash components, as the size of such components is longer than the working range of the ISF milling machines [22]. Also, cold forming of high strength materials still is a major challenge in the incremental sheet forming processes, and thus different warm forming techniques are implemented to form such materials [23].

The new Incremental Sheet Rolling (ISR) process introduced in this paper has the potential for the manufacture of long and weight-optimised components with variable height and depth cross sections. In contrast to the incremental roll forming process, the flange is not incrementally bent into shape but is wrapped around the forming tool and incrementally rolled onto a forming die until the blank is formed to the desired shape which is given by the die geometry. Thus, bending and stretching in the transverse direction are the main deformation mechanisms in the new ISR process. Similar to metal spinning, a tensile transverse strain is developed in the transverse direction, and this may balance compressive longitudinal strain when ISR is applied to complex profiles. In contrast to incremental roll forming, only one single forming roll is used which reduces tooling costs. Previous studies reported on the incremental roll forming process for the manufacture of doubly curved sections. This process is very different to the presented ISR process regarding both material deformation and application fields [24, 25].

ISR is a new forming technique, and this work aims at providing the first proof of concept via experimental prototype trials. In addition, the material and forming behaviour in the new ISR is analysed by extensive experimental trials and numerical analysis performed on two different sheet metal alloys. In this way, this work develops the platform for the development and application of ISR to form high strength and complex profiles in future work.

### 2 Profile geometry and materials

Figure 1 shows the U-profile considered for this investigation. Only one-half of the profile was formed due to the symmetry of the shape. The profile has a constant cross section along its length, and the dimensions are illustrated in Fig. 1. The material thicknesses are given in Table 1.

![Isometric view and the cross-section dimensions of the U-profile](image)

#### Table 1 Elastic parameters along the rolling direction

| Material          | Thickness (mm) | Poisson’s ratio ν | Young’s modulus (GPa) |
|-------------------|----------------|------------------|-----------------------|
| Aluminium 1100-H14| 0.55           | 0.33             | 71.2                  |
| Stainless steel 430| 0.45           | 0.3              | 202                   |
Due to the limited force capacity of the CNC machine utilised in this study, sheets with lower yield strength and thickness were selected to provide the first proof of concept for the new incremental shape rolling technique and to identify material behaviour and potential forming issues. Standard tensile tests were performed on an Instron 5967 with a 30-kN load cell and with a test speed of 0.025 mm/s, according to ASTM E8/E8M [26]. The bone-shaped specimens were oriented along the rolling direction, 45° and 90° from the rolling direction of the strip. The averaged true stress–true strain curves of the two tested materials (aluminium 1100-H14 and stainless steel 430) along the rolling direction are shown in Fig. 2, while the strip thickness and the elastic properties are given in Table 1.

The mechanical properties 0°, 45° and 90° from the rolling direction have been determined by fitting the Hollomon’s power law and are shown in Table 2. The Lankford parameters that describe anisotropy have been determined according to ASTM-E517 [29] and are shown in Table 2. The results showed near isotropic material behaviour for the stainless steel, while a small level of anisotropy was observed for the aluminium.

### Table 2 Anisotropy parameters

| The angle from the rolling direction | Aluminium 1100-H14 | Stainless steel 430 |
|-------------------------------------|---------------------|---------------------|
|                                     | 0°  | 45° | 90° | 0°  | 45° | 90° |
| Plastic-strain ratio (Lankford parameters) $r = \varepsilon_t / \varepsilon_r$ | 0.78 | 0.70 | 0.81 | 1.04 | 1.03 | 1.05 |
| Averaged normal anisotropy $R_m = (r_0 + r_{45} + r_{90})/4$ | 0.75 | 1.04 |
| Averaged planar anisotropy $\Delta R = (r_0 + r_{90} - 2r_{45})/2$ | 0.09 | 0.02 |
| Yield strength (MPa) | 103 | 110 | 110 | 243 | 243 | 244 |
| $K$ (MPa) | 172 | 172 | 172 | 700 | 698 | 713 |
| $n$ | 0.08 | 0.07 | 0.07 | 0.19 | 0.19 | 0.19 |

3 Concept of the incremental shape rolling (ISR) process

In the ISR process, the pre-cut blank is clamped between two dies, and a single forming roll is initially located at a clearance from the die that represents the sheet thickness. The forming roll is then fed down incrementally in Y-direction ($d_y$) followed by a longitudinal movement along the part length to follow the part contour. Given that in this particular case, the part contour was a straight line, the roll was simply moved in the Z-direction. The 2-D path was repeated until the pre-cut blank was formed to the desired shape, see Fig. 3.

4 Experimental tooling and forming sequence

The experimental setup is shown in Fig. 4a. The metal blank is placed between two clamps where the bottom clamp has the features of the inner surface of the desired part shape including the corner radius, the profile length and the width. The clamping force is provided by five blank holder bolts. The whole setup is placed on a milling table that can be moved back and forth to provide the linear longitudinal movement, in addition to the incremental feed down ($d_y$) of the roll. The roll holder is attached to the milling spindle, while the whole milling head can be tilted to reduce the contact area between the metal strip and the forming roll. In this way, the same forming roll can be used for the full forming process. Figure 4b shows the forming roll used in this study, and its geometrical parameters are given in Table 3.

Figure 5 shows schematically the ISR forming sequences used to form the U-channel profile. The tool is placed at a clearance from the die that equals the sheet thickness. Then, it is incrementally fed down ($d_y$) and moved in the longitudinal direction. In this way, the sheet wraps around the tool radius in each forming stage with bending and stretching being the main deformation modes in the transverse direction, see Fig. 5. In contrast to conventional incremental
sheet forming processes, ISR allows the forming of long and weight-optimised components with variable height and depth cross sections, which are relevant to the automotive industry. The developed tensile transverse strain will help to balance compressive longitudinal stresses when ISR is applied to such complex profiles and hence promises the production of wrinkle-free components. In ISR, a single forming roll is used to form the sheet over a forming die, hence, the only controllable process parameter is the increment step-down size \( (d_y) \). The roll diameter and the tool nose radius are considered geometrical parameters (see Table 3). In this study, the influence of the process parameter \( (d_y) \) on the forming result was investigated. For this, forming trials with 6 and 12 forming steps and an incremental step-down of \( d_y = 4.7 \) and \( 2.35 \) mm in each step, respectively, were performed to provide the first proof of concept of the forming technology and to identify potential forming issues.

The part shape was analysed with a hand-held 3D laser scanner “CreaForm HandyScan 700” after the component had been removed from the tooling. The part shapes obtained from the 3D scanner were imported to the Geomagic Qualify software [30] for comparison with the desired shape.

For the shape analysis, three X–Y planes were created along the part’s length, and the x–y coordinates of the intersected 2D profile with each plane were exported in the form of x–y coordinate data to determine the 2D profile shape. The three chosen X–Y cross sections were the lead section where the forming started, the tail section where forming ended and the middle section which represents the centre of the formed profile (see Fig. 6a).

The forming results show that in the outer zone of the flange (near the flange edge) there is a deviation from the desired shape that starts close to the middle length of the flange. This can be considered to be due to springback. Near the profile radius, there was only a small springback which led to a well-formed flange length. To represent the formed part shape characteristics, two parameters were introduced. Those are illustrated in Fig. 6b. The first is the maximum deviation from the desired shape in the X-direction \( (d_x) \) that generates at the flange edge. The second is the length of the well-formed flange length before the deviation from the ideal shape starts \( (f_{\text{intact}}) \). A larger value of this parameter illustrates a better shape, as it means that a larger length of the flange follows the ideal shape and shows less springback.

In order to measure the \( f_{\text{intact}} \), a vertical line that represents the ideal flange shape is drawn from the zero X–Y coordinates to the end of the flange length (Fig. 6b), and \( f_{\text{intact}} \) is defined as the vertical length of the flange measured from the end of the profile corner radius to the flange location where X deviation reaches \( 0.05 \) mm.

A two-directional strain gauge was attached to the centre length of the blank and close to the flange edge to measure the longitudinal and transverse strains during the ISR process, Fig. 7. The change in voltage was measured using a data logger and transferred into strain values. Given that the part that was formed had a uniform cross section, the pre-cut blank was of uniform width of 52 mm and length of 250 mm.

To determine the severity of flange wrinkling, first, the formed profile was rotated about the Z-axis to orientate the flange edge perpendicular to the X–Z plane. This was done to exclude the effect of springback on the wrinkling.

| Parameter          | Value   |
|--------------------|---------|
| Roll diameter \( (D) \) | 98.76 mm |
| Roll nose radius \( (r_n) \) | 3.00 mm  |
| Roll width \( (R_w) \) | 25.00 mm |
| Roll face angle \( (\theta) \) | 80°      |
measurement. Then, an ideal line was constructed along the profile length, and the wrinkling height was measured as the deviation of the shape from that reference line in the X-direction along the length of the part as shown in Fig. 8.

A LEXT 3D measuring laser microscope OLS4100 was used to measure the average surface roughness ($Ra$). This represents the integral of the height of the surface roughness [31]. For this, a square sample piece was cut from the flange region (Fig. 9). Measurements were taken at three positions along the profile length and averaged (10 mm from both ends and at the centre length of the profile). A 5× magnification lens was used, and a non-cut-off wavelength was specified; this allowed the measurement of the surface roughness of the superimposed surface waviness.

5 The finite element model

Abaqus Implicit was used to simulate the ISR process. The die, the blank holder and the forming roll were modelled as rigid bodies, while the sheet has meshed with reduced integration, hexahedral, linear brick elements. Only one-half of the profile was detailed using a symmetry boundary condition about the Y–Z plane as shown in Fig. 10a. A mesh sensitivity analysis was performed, and the predicted values for forming strain, cross-section error and wrinkling converged at a mesh size of $1.1 \times 0.8 \text{ mm}$ along the sheet length and width, respectively. Four elements through the material thickness were used. Symmetry was applied to the blank with an X-lock boundary on all nodes along the symmetric line of the sheet to restrict material movement in the X-direction. Surface to surface contact was applied between the forming roll and the sheet surfaces assuming a coefficient of friction of 0.1 [32]. The “hard contact condition” was used to minimise the penetration of the rigid surfaces into the sheet surfaces at the constraint locations [10].

Young’s modulus was calculated from the slope of the elastic part of the stress–strain curves and is shown in Table 1, while the Poisson’s ratio was assumed to be 0.33 for the aluminium sheet [27] and 0.3 for the stainless steel [28]. The plastic part of the true stress–strain curves shown in Fig. 2 was used to define the plastic material behaviour. As shown in Table 2, the average planar anisotropy $\Delta R$ for the aluminium and the stainless steel sheets is 0.0195 and 0.0935, respectively. Hence, the stainless steel showed isotropic material behaviour, while a small level of anisotropy was observed for the aluminium. A comparison of results achieved with an anisotropic and a simple isotropic material model did not show any major differences in results. Therefore, isotropic hardening and the von Mises yield criteria were assumed for both materials in this study [33, 34].

In the experimental setup, five holes were cut in the web zone to hold the blank between the bottom die and the blank holder with bolts. In the FEA, a boundary condition was applied to all nodes along the symmetric line of the sheet to restrict the material movement in the X–Z plane. Given that the web zone is fully clamped by the top and bottom dies during the forming process, this simplification will not affect the accuracy of the FEA model.

In order to validate the FEA model with the experimental results, the numerically formed U-shapes were exported as obj files and then imported to the Geomagic software, where the same procedure as previously applied for the experimental shape analysis was used. For the validation of strains, four elements were selected in a location that matched that of the strain gauge in the experiments. The longitudinal and transverse strains of the 4 elements were averaged and compared with the experimentally measured strains.
6 Results

6.1 The shape quality in the transverse direction

The experimental results were compared with the FEA for the forming condition involving 12 forming stages. The part shape at the three cross-section locations (lead, middle and tail) is compared with the ideal shape in Figs. 11 and 12 for the aluminium and the stainless steel profiles, respectively. Both, the experimental and the FEA results show that the flange edge is not fully formed to 90° and that there is a deviation from the ideal shape in the X-direction that starts from different values of $f_{\text{intact}}$. In all cases, the maximum deviation (max. X deviation) occurred at the flange edge.

The experimentally measured values of the max. X deviation and the $f_{\text{intact}}$ are determined from Figs. 11 and 12 and compared with the FEA results in Figs. 13 and 14 for

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**Fig. 7** Schematic of the actual ISR trials platform showing the location of the attached 2-directional strain gauge and the strain measurement procedure

**Fig. 8** Schematic drawing illustrating how flange wrinkling was determined

**Fig. 9** Schematic drawing illustrating how the roughness measurement was performed
the aluminium and the stainless steel profiles, respectively, using the procedure explained earlier and shown in Fig. 6.

The experimental and the FEA results show the same trend in regard to max. $X_{\text{deviation}}$ and the $f_{\text{intact}}$ for both the aluminium and stainless steel forming case. In both cases, the lowest “max. $X_{\text{deviation}}$” occurred at the middle section, while its maximum value was generated at the tail section. The highest value of $f_{\text{intact}}$ was observed at the middle section, while it was the smallest at the tail region. The experimental and the FEA results of the stainless steel profile show higher magnitudes of shape deviation compared to the aluminium profile.

The FEA underestimates the generated shape deviations, especially for the stainless steel profile. This deviation between the FEA and the experimental results is possibly due to tool deflection. This would lead to less deformation and a larger shape error in the experiments but not in the FEA where the effect of tool deflection was not considered. However, the FEA accurately represents the trends observed in the experimental results. The FEA is therefore used in the following part of this study to further investigate the material deformation in the longitudinal and the transverse direction and to correlate the generated shape errors to that deformation behaviour.

6.2 Longitudinal and transverse strain in the sheet edge

The strain measurements were performed during the 1st forming step of the 6 and 12 forming steps condition, i.e. at $d_i = 4.7$ mm and 2.35 mm, respectively. Figures 15 and 16 show the longitudinal and transverse strain measured on the strain gauge over time while the roll is moving along the strip length. Note that it takes the forming roll 125 s to reach the position of the strain gauge which is located on the edge in the centre length of the strip. There is a good agreement...
between the FEA and experiment regarding both the longitudinal and the transverse strain for both the aluminium and the stainless steel profiles during the first forming step.

The strain measurements for the 6-step forming condition which represents a $d_s$ of 4.7 mm show a deviation after the longitudinal strain shifts from tensile into compression (at the location of the attached strain gauge after 125 s of forming time) as shown in Fig. 15b, d. This was related to the strain gauge de-attaching from the sheet due to the occurrence of wrinkling in the flange and therefore cannot be considered a successful measurement. The experimental strain measurements for the 12-step forming condition showed a good correlation with the FEA results, as shown in Fig. 15a, c. Here, no buckling or de-attachment of the strain gauge was observed. For this reason, the measurements for longitudinal and transverse strain for the 6-step forming condition are highlighted in red after the buckling has occurred, and only the FEA results are considered for further analysis of the 6-step condition.

The strain results suggest that there is a tensile longitudinal strain in front of the forming roll. The longitudinal strain that is measured on the strain gauge increases by reducing the distance to the forming roll. When the forming roll passes the strain gauge (after 125 s), material deformation reverses to longitudinal compression. It therefore can be concluded that in front of the forming roll material is first stretched, while after the forming roll it is under longitudinal compression (Fig. 15).

The FEA results for the 6-step forming condition show a clear increase in the longitudinal compressive strain, especially for the stainless steel profile compared to the 12 forming steps condition (see Fig. 15).

In the transverse direction, the material is first compressed in front of the forming roll and then stretched...
when the forming roll has passed (Fig. 16). In the aluminium profile, this results in a small level of permanent transverse stretch in the strip edge (Fig. 16a, b), while in the stainless steel, the transverse strain that measured with the strain gauge, which is located close to the strip edge, is near zero. Similar to longitudinal strain, there is a good

![Graphs showing experimental and FEA values](image)

**Fig. 14** The experimental and FEA values of (a) max. X deviation and (b) f intact for the stainless steel profile determined in the three cross sections after the 12th forming step.

![Graphs showing longitudinal strain](image)

**Fig. 15** Longitudinal strain history of the ISR process during (a) the 1st step out of 12 steps ($d_f = 2.35$ mm) for the aluminium profile, (b) 1st step out of 6 steps ($d_f = 4.7$ mm) for the aluminium profile, (c) the 1st step out of 12 steps for the stainless steel profile and (d) the 1st step out of 6 steps for the stainless steel profile.
The correlation between the FEA and the experimental strain measurements until the strain gauge de-attaches from the strip edge when it is passed by the forming roll in the more severe 6-step forming condition due to the occurrence of wrinkling (Fig. 16b, d).

6.3 Effect of the increment step-down ($d_y$) on the shape quality

Experimental forming trials were performed with 6 and 12 forming steps. The shape quality of the flange formed with 6 forming stages ($d_y = 4.7$ mm) is compared to the flange formed with 12 steps ($d_y = 2.35$ mm) after the formed part was removed from the dies. Figures 17 and 18 show the aluminium and the stainless steel flanges formed with the two different forming conditions, respectively.

The wrinkling height in the X-direction along the profile length is shown in Figs. 17b and 18b for the aluminium and stainless steel parts formed with 6 forming steps, respectively. The aluminium and stainless steel parts formed with 12 forming steps are presented in Figs. 17a and 18a, respectively.

Both the FEA and the experimental results correlate well with each other and show that the flange edge of the aluminium profile formed with 12 steps leads to a good quality with a straighter edge compared to the 6-step condition. The experimental stainless steel profile shows a small shape error in the longitudinal direction that is not captured by the FEA model. When using only 6 forming steps, severe flange wrinkling is observed for both the aluminium and stainless steel profiles. While the experimental results of both the aluminium and the stainless steel profiles show the formation of 2 wrinkles in the flange edge for the 6-step condition, the
FEA only predicts one wrinkle. This suggests that the FEA accurately reproduces the effect of the number of forming steps on the occurrence of wrinkling but that it underestimates its severity. In both the FEA and the experimental results, wrinkling initiated in the 1st and the 3rd forming step in the 6-step forming condition for the aluminium and stainless steel parts, respectively.

The surface roughness of the undeformed aluminium and stainless steel strips was measured. This showed an average $Ra$ of 10.22 μm and 5.30 μm for the aluminium and the stainless steel, respectively. The surface roughness of the flange region after ISR was then determined. Figure 19a shows a microscope image of the analysed flange length with the profile corner and the flange edge located on the left and right, respectively, for the stainless steel case. The grooves produced by the forming roller can be clearly seen by the black lines. Figure 19b shows the roughness profile measurement. It becomes clear that the surface grooves near the profile radius are more severe compared to the flange edge. This is indicated by the waved surface roughness profile on the left and the only slight curving on the right (Fig. 19b). The same trend can be
observed for the aluminium case (Fig. 20a, b). This visual observation is confirmed by the determined average roughness $Ra$ values which for both materials are the highest near the profile radius and the lowest near the flange edge (Figs. 19a and 20a). This may be due to a less severe wrapping of the sheet around the roll radius in the later forming passes which leads to less severe material deformation and roll contact conditions.

7 Discussion

7.1 Material flow in the transverse direction

Since the results of both materials showed the same trend in terms of the strain distribution, transverse shape error and wrinkling severity, the discussion section will be limited to the higher strength stainless steel, where shape
errors were more severe. The results demonstrated in Figs. 11 and 12 indicate that the $X_{\text{deviation}}$ for both the aluminium and stainless steel profiles starts approximately from the middle of the flange length. This may be related to the sheet wrapping over the roll radius to a smaller extent in the later forming stages (i.e. starting from step 6 of the 12-step forming condition) (see Fig. 21a). To further illustrate this, the transverse plastic strain was numerically analysed in the forming zone under the roll (Fig. 21b) for the 12-step forming condition for forming steps 2, 6 and 10. This illustrates that in the first forming steps, the transverse strain introduced by the sheet wrapping over the forming roll is high and then reduces to near zero transverse strain in the later forming passes. This suggests that

Fig. 19  (a) Microscope image of the analysed stainless steel flange length (b) the roughness profile measurement

Fig. 20  (a) Microscope image of the analysed aluminium flange length. (b) The roughness profile measurement
the permanent deformation that is formed into the flange reduces after forming stage 6 and that this leads to a higher value for $X_{\text{deviation}}$.

The above results also indicate that the flange is permanently stretched in the transverse direction and that this deformation is high in the flange region closer to the profile radius which is formed in the earlier stages of forming where there is a higher level of sheet wrapping over the forming roll. In the flange region that is closer to the strip edge which is formed in the later forming steps, the transverse deformation is near zero. This is confirmed with the experimental strain results presented in Fig. 16 which shows a reversal from compressive to tensile transverse deformation when the roll passes the strain gauge location. Given that near the strip edge where the strain gauge is located the level of permanent transverse deformation is low (Fig. 21b), the transverse deformation that is measured by the strain gauge is also close to zero (Fig. 16). However, closer to the profile radius, there is a plastic transverse strain. The higher tension in the region formed in the earlier stages of forming (Fig. 21b) confirms why only a small springback was observed in this zone when the part was released from the forming tool.

The permanent transverse stretch in the lower part of the flange may assist in overcoming wrinkling defects when forming components with variable shapes over the component length as those currently produced with the flexible roll forming process [17]. Here, previous studies have shown that if transverse stretch can be introduced into the flange wrinkling is significantly reduced [18]. This suggests that the new method of incremental shape rolling may represent a solution for overcoming wrinkling defects and therefore may allow the manufacture of components with higher shape complexity than currently achievable with flexible roll forming.

### 7.2 Material flow in the longitudinal direction and its relation to wrinkling initiation

The experimental longitudinal strain distribution in Fig. 15 showed that during forming the flange edge is first under tensile deformation followed by longitudinal compression. In Fig. 22, the shape of the stainless steel flange during the 1st pass of the 12 stage forming condition is shown for both the experiment and the FEA. When the roll gets in contact with the sheet, the sheet edge first has a concave shape. After
the forming roll has passed, the concave shape changes into a convex shape which leads to longitudinal tensile stress in front of the forming roll and longitudinal compression behind the roll, respectively. This is similar to longitudinal material deformation observed in conventional roll forming [35, 36].

After the forming roll has passed, the strip edge needs to be re-straightened, and its length has to be equal to the roll contact line (Fig. 22b). This means that the concave zone that is longitudinally stretched in front of the roll has to be compressed after the roll has passed (when the concave curve is shifted to a convex curve). If the longitudinal stretch of the sheet edge is permanent and high, then the compressive longitudinal stress required to contract the sheet after the forming roll has passed may exceed the critical buckling stress of the flange, and, as a result, edge wrinkling occurs.

Figure 22b shows the concave and the convex zones with the longitudinal tension and compression strain, respectively. The magnitude of the longitudinal membrane strain depends on the size of the increment step-down ($d_x$), i.e. the number of forming steps that are used. The experimental and FEA
results show that wrinkling can be reduced by increasing the number of forming steps, i.e. when the step-down size ($d_y$) is reduced (see Figs. 17 and 18).

Figure 22c shows the FEA results of the stainless steel profile for different values of $d_y$ for the roll position indicated in Fig. 22b. To compare the longitudinal membrane strain of the different forming conditions at the same forming level, the longitudinal membrane strain during the 4th forming pass of the 12-step forming condition is compared with that of the 2nd forming pass of the 6-step forming condition. The longitudinal membrane strain was measured with respect to the local cartesian coordinate system which follows the deformed flange (see Fig. 22a, b). Note that the stainless steel profile showed a buckle after the 2nd forming pass in the 6-step condition. The comparison illustrates that for the same total step-down there is a higher longitudinal membrane strain when a higher increment step-size is used, i.e. for the 6-step forming condition (Fig. 22c). This suggests that a larger step-down size ($d_y$) leads to higher longitudinal tensile and compressive membrane strains in front of the roll and behind the roll, respectively. If the longitudinal compressive strain exceeds the critical buckling limit, wrinkling initiates.

The FEA results of the stainless steel profile showed that wrinkling initiated in the 3rd forming pass for the 6-step forming condition. The stress distribution is therefore investigated for the 2nd and 3rd forming steps (before and after wrinkles initiation). In the 12-step condition, no wrinkling was observed. The longitudinal membrane stresses in the 2nd and 3rd forming passes of the 6-step model are compared with the 4th and 6th steps of the 12-step model; this is for the same overall step value $d_y$. In this way, stresses are compared for the same forming levels.

Figure 23a shows the FEA result of the longitudinal membrane stress in the flange edge along the flange length for the stainless steel and before wrinkling is initiated. Note that the stress distribution shown in Fig. 23 is for a point in time when the roll has passed the full sheet length, i.e. it shows the residual longitudinal membrane stress. It can be seen that in the 6-step condition there is a higher level of compressive stress compared to the 12-step condition. The 12-step condition has a uniform distribution of compressive stress, while the 6-step condition shows a small drop in the compressive stress. This small stress drop is due to the formation of a small buckle. Figure 23b shows the longitudinal membrane stress after the 3rd forming pass in the 6-step conditions and the 6th forming pass in the 12-step condition. At this point of forming, wrinkling was observed in the 6-step forming condition while the flange remained wrinkle-free in the 12-step condition. It can be seen that the compressive stress in the 6-step forming condition is approximately 30% higher compared to the 12-step forming condition. This is for the same overall level of deformation. While for the 12-step condition the stress stays uniform, there is a drop in the stress of approximately 85 MPa in the 6-step condition close to the location where the wrinkle developed (see Fig. 23b). This suggests that wrinkling in the 6-step forming condition is due to the compressive longitudinal stress in the flange exceeding the buckling stress. This leads to a wrinkle and the subsequent reduction of the load-bearing capability of the edge in the form of a stress drop. If the number of forming passes is increased, as in the case of the 12-step forming condition, the level for longitudinal compressive stress is maintained below the critical buckling stress.
This leads to a wrinkle-free component when using 12 forming passes with a smaller step-down size while the 6-step forming condition results in the initiation of wrinkling.

8 Conclusion

Conventional roll forming of automotive components from UHSS is limited to long components with a continuous profile. The new flexible roll forming process allows the roll forming of more complex and weight-optimised shapes but is limited by wrinkling defects in the flange.

This study presents a new manufacturing process where the sheet is rolled with one single forming roll over a forming die, Incremental Shape Rolling (ISR). The process is similar to previous Incremental Sheet Forming (ISF) methods but allows the forming of long profiles that are relevant to the automotive industry. In this study, the new ISR concept is proven by small-scale forming trials performed on stainless steel and aluminium strip with a 5-axis milling machine. The final component shape and forming strains are analysed by 3D profile scanning and strain gauges, respectively. The experimental work is supported by the numerical analysis of forming strains and stresses.

The major outcomes from this study are given below:

- The experimental and numerical results show a clear development of transverse tensile strain in the flange even for the simple component shape that was tested. It is believed that such strain would facilitate plastic deformation in the flange when forming complex part shapes such as those that currently lead to wrinkling issues in the flexible roll forming process. The presented new ISR process therefore may present an alternative method to flexible roll forming for the flexible and cost-effective manufacture of wrinkle-free and weight-optimised, long automotive components from higher strength steels.
- Some forming issues were observed, including the flange edge deviating from the 90° angle and the wrinkling of the flange.
- The deviation of the flange angle was related to the flange warping less over the forming roll towards the edge. This resulted in a lower level of permanent transverse deformation formed into the edge and a higher springback.
- Wrinkling is due to the flange developing a concave and convex shape in front and behind the point contact with the forming roll, respectively. This leads to longitudinal tensile and compressive stresses similar to those observed in conventional roll forming. If the compressive stress exceeds the buckling limit of the sheet, wrinkling occurs. The longitudinal compression in the flange was reduced, and wrinkling was eliminated by the use of a higher number of forming steps (a smaller increment step-down $d_i$).

Appendix

Mesh sensitivity analysis has been done, where the flange has been modelled with four sizes of the mesh element. That is, 1: $1.5 \times 1$, 2: $1.1 \times 1$, 3: $1.1 \times 0.8$ and 4: $1 \times 0.8$ mm along the Z-direction and X-direction, respectively, see Fig. 10b. Figures 24 and 25 show the FEA results of the stainless steel profile after the final forming pass of the 12-step forming condition. The max $X_{\text{deviation}}$ has been chosen for the mesh sensitivity analysis investigation as it is an independent parameter, while $f_{\text{intact}}$ depends on the magnitude of max $X_{\text{deviation}}$. That is, the higher $X_{\text{deviation}}$ the smaller would be $f_{\text{intact}}$. The FEA result of the max. $X_{\text{deviation}}$ has converged at a mesh size of 3: $1.1 \times 0.8$ mm along the blank length and width, respectively, see Fig. 24.

To determine the extent of the plastic deformation along the flange, the equivalent plastic strain PEEQ has been investigated at the outer surface of the stainless steel profile. A PEEQ value higher than zero in the flange zone means that the flange has been exposed to plastic deformation. Figure 25a, b shows the PEEQ distribution for the two extreme mesh sizes. This clearly shows that the distribution of the equivalent plastic strain is almost similar with the max PEEQ occurring just under the profile radius and reducing to zero at the flange edge. As shown in Fig. 25c, the max PEEQ increases with decreasing mesh size and converges at a mesh size of 3: $1.1 \times 0.8$ mm along the blank length and width, respectively.

![Fig. 24](image-url) The FEA results of the predicted max. X deviation for the different element sizes.
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Declarations

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