A novel incremental sheet metal forming process for long and open section profiles

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Abstract. Complex components from High Strength Steel (HSS) can be formed with Flexible Roll Forming (FRF). However, flange wrinkling limits the part shape complexity that can be achieved and hence limits its application in the automotive industry. A novel forming technology is introduced in this study, Incremental Shape Rolling (ISR), where a pre-cut blank is clamped between a top and bottom die and then a single forming tool incrementally forms the material according to the bottom die’s geometry. It is believed that ISR can significantly reduce the wrinkling issue compared to FRF. In the contrast to the incremental sheet forming process, ISR allows the manufacture of long and open sections from HSS sheets. In this work, the experimental prototyping trials of the ISR process are performed using a 5-axis milling machine and then are used to validate the FEA model which is developed to simulate and analyse the deformation behaviour of the ISR process. The results show a clear development of transverse tensile strain along the flange which can overcome the wrinkling issue when the ISR process is applied to complex profiles.

1. Introduction

High Strength Steel HSS has attracted a large amount of attention for use in the automotive industry for structural and crash components due to the high strength and low weight of parts made from such materials [1, 2]. However, forming of HSS with the conventional Flexible Roll Forming (FRF) comes up with flange wrinkling which occurs when the required longitudinal compressive strain in the flange edge exceeds the buckling limit [3] and this restricts the part shape complexity achievable with FRF [4, 5].

Recently, a prototype flexible roll forming facility has been developed, where the pre-cut blank is fully clamped between two dies. Then, a single forming roll stand incrementally bends up the pre-cut blank around the top die to obtain the required shape. The roll stand is placed on two hexapods on either side of the clamping dies, each hexapod has six degrees of freedom so that the forming tool can follow the part shape contour [6]. However, similar to the conventional FRF process, the results showed high potential for the occurrence of excessive wrinkling which limits the part shape complexity that can be achieved.

In the Incremental Sheet Forming (ISF) process, such as sheet metal spinning, the developed axial tensile stress along the flange balances the compressive hoop stress, hence, wrinkle-free components can be formed [7, 8]. However, warm forming techniques need to be implemented when ISF is used to
form HSS [9]. In addition, due to the limited working range of the milling machines, the forming of long and open sections is not feasible with ISF [10].

In this paper, the ISR process will be introduced and applied to a U-profile to study potential forming issues and material deformation. In ISR, the pre-cut blank is clamped between two dies, and a single forming tool then incrementally forms the sheet to the desired shape. Because the flange is being wrapped around the forming tool in ISR, a tensile transverse strain is introduced along the flange which balances the compressive longitudinal strain similar to ISF, and hence allows the forming of wrinkle-free components with complex cross-sections. In this way, this novel study develops the platform for the understanding and development of ISR to form complex profiles from high strength materials in future work.

2. Material properties and profile geometry

An Instron 5967 with a 30 kN load cell was used to carry out the standard tensile tests. Three tensile specimens were tested at a test speed of 0.025 mm s\(^{-1}\) and the averaged true stress–true strain curve of the stainless steel specimens along the rolling direction is shown in Figure 1-a. The mechanical properties of the tested 0.45 mm ferritic stainless steel strip shown in Table 1 are obtained by fitting the Hollomon’s power law of the tested specimens. The U-profile illustrated in Figure 1-b is selected for this study. The profile has a uniform cross-section along its length (Figure 1-c). Due to the shape symmetry, only one-half of the U-profile was addressed in this investigation.

![Figure 1](image)

Figure 1 Averaged true stress-true strain curve of the stainless steel, (b) 3D view of the required profile and (c) the cross-section of the U-profile – dimensions in mm

| Material | Ferritic stainless steel |
|----------|-------------------------|
| Young’s modulus (GPa) | 202.02 |
| Poisson’s ratio \(\nu\) | 0.3 [11] |
| The angle from the rolling direction | 0° | 45° | 90° |
| Yield Strength (MPa) | 243.03 | 242.68 | 244.33 |
| K (MPa) | 699.56 | 697.67 | 712.92 |
| Strain hardening \(n\) | 0.1868 | 0.1877 | 0.1856 |
| Lankford parameters \(r=\varepsilon_u/\varepsilon_t\) | 1.042 | 1.025 | 1.047 |
| Planer anisotropy \(\Delta R=(\varepsilon_0-2\varepsilon_{45}+\varepsilon_{90})/2\) | 0.0195 |
3. The concept of the ISR process

In the ISR process, the pre-cut blank is fully clamped between the top clamp and the bottom die, and one forming roll is initially placed at a distance from the bottom die equal to the blank thickness. The tool is then incrementally fed down in Y-direction (dy) before it moved linearly in the longitudinal (Z) direction. The incremental vertical feed (dy) and the linear longitudinal movement in Z-direction are repeated until the blank is formed to the required shape according to the geometry of the bottom die, see Figure 2. The experimental trials were done on a 5-axis milling machine where the die-set is placed on a milling table that provides the vertical (dy) and linear longitudinal (Z) movements. The blank holding force is provided by five equally distributed bolts. The roll is mounted on a tool holder which is attached to the tilted spindle of the milling machine. Due to the symmetry of the shape, only one transversal half of the U-profile was formed, as shown in Figure 2.

![Figure 2 Schematic drawing of the experimental setup of the incremental shape rolling process](image)

Figure 2 Schematic drawing of the experimental setup of the incremental shape rolling process

Figure 3 shows a schematic drawing for the forming sequence of the ISR process of the U-channel profile, where 12 forming steps are implemented with increment step size dy equal to 2.35 mm. In this forming sequence, the flange is wrapped around the forming tool in each forming pass and incrementally rolled onto a forming die until the blank is formed to the desired shape according to the die’s geometry. Thus, bending and stretching in the transverse direction are the main deformation mechanisms in the ISR process.

A strain gauge was glued to the centre length of the sheet and near to the blank edge to measure the transverse strain during the 1st forming pass.

![Figure 3 Schematic of the forming sequence of ISR](image)

Figure 3 Schematic of the forming sequence of ISR

4. The finite element model

The finite element simulation of the ISR process was performed with Abaqus Implicit. The dies and the forming roll were modelled as rigid bodies, while the pre-cut blank has been discretized with reduced
integration, hexahedral, linear brick elements. Four elements through the blank thickness were used with an aspect ratio of less than 10. Only the transversal half of the profile was modelled due to the symmetry of the shape about the Y-Z plane. A “frictionless contact” was assumed between the forming roll and the blank surfaces to avoid convergence issues [12]. To minimize the penetration of the rigid bodies into the blank surfaces at the constraint locations, the “hard contact condition” was applied [13]. As shown in Table 1, the stainless steel sheet showed isotropic material behaviour, hence, isotropic hardening and the von Mises yield criteria were used to define the plastic material behaviour of the stainless steel sheet [14, 15].

5. Shape analysis

The results illustrated that the formed flange deviates from the desired shape. The flange edge is not fully formed to 90° degrees, and this shape error starts close to the middle length of the flange, see Figure 4-b. Above the starting point of that shape error, no spring-back was observed after the forming tool lost contact with the sheet. Thus, instead, the maximum deviation from the desired shape in the X-direction (max. X deviation) that is generated at the flange edge is used to determine the severity of that shape error. In addition to that f intact defines the length of the well-formed flange length measured to the starting point of X deviation, see Figure 4-b. The ideal shape has the maximum value of f intact which is equal to the flange length, this means that the full flange length follows the required shape.

The formed profiles were scanned with a 3D laser scanner after they were removed from the tooling to be compared with the desired shape and the FEA results. The 2D shape analysis of the formed profiles has been done at three X-Y sections along the part’s length, i.e., the section where the forming started (lead section), the tail section, and the centre of the formed part (middle section), see Figure 4-a.

6. Results and discussion

6.1. The shape quality in the longitudinal and transverse directions

All the ISR trials in this study were done with increment size \( d_y = 2.35 \) mm i.e., 12 forming steps. Figure 5 shows the top view of the FEA and the experimental results of the formed profile which prove that the ISR process is capable to produce straight U-profiles with a high flange quality. Nevertheless, the experimental result shows a shape error in the longitudinal direction that the FEA cannot capture. Moreover, both the experimental and the FEA results demonstrate that there is a deviation between the formed flange and the ideal shape in the X-direction (the flange edge is not fully formed to 90° degree) and that shape error starts from different values of \( f_{\text{intact}} \). The experimentally measured values and FEA results of the \( f_{\text{intact}} \) and the max. X deviation are shown in Figure 6. FEA appears to accurately represent...
trends observed in the experimental data, however, it underestimates the magnitude of the generated shape deviations.

Figure 5 Top view of the FEA and experimental results show the formed profile after the final pass

Figure 6 The values of (a) max. X deviation and (b) f intact measured after the last forming pass

6.2. State of strain in the sheet edge

Figure 7 shows the transverse strain (PE11) measured versus time during the 1st forming step. Note that the transverse strain component, PE11, is measured with respect to the local coordinate system which follows the deformed flange as shown in Figure 8-a, while X, Y, Z represent the global coordinate system. The experimental strain measurements are obtained using a strain gauge. Figure 7 shows that there is a compression transverse strain in front of the forming roll and this decreases as the forming roll gets closer to the attached strain gauge (at the middle of the strip). When the forming tool passes the location of the attached strain gauge (approximately 150 seconds) transverse strain reverses to transversal tension. It therefore can be concluded that the flange is first compressed in front of the roll and stretched behind the forming roll. However, the result shows near-zero permanent transverse strain, given that this strain reading was measured at the sheet edge (where the strain gauge is located).

In conclusion, even though the FEA model underestimates the cross-sectional shape error measurements, it reproduces the experimental trends in regard to the effect of material and process parameters on the final shape. This suggests that the FEA model is valid to be used for further investigation of the ISR process in this study.
6.3. The reason for the shape error in the transverse direction

The results demonstrate that the flange edge is not fully formed to 90° and that there is a deviation from the ideal shape in the X-direction. This may be related to the level of the flange wrapping over the tool radius (see Figure 8-a). To prove this hypothesis, the transverse plastic strain is numerically analysed along the three cross-sections after the final forming pass (Figure 8-b). This shows that the maximum transverse strain occurred just under the profile corner which is formed in the earlier forming passes where a higher level of sheet wrapping over the tool is developed. The transverse strain reduces towards the flange edge and reached near-zero transverse strain at the flange edge; this is due to the low level of sheet deformation by the tool in the later forming steps. This suggests that the plastic transverse strain that is formed into the flange decreases in the later stages of the forming passes, and that this results in X deviation. The small level of transverse plastic strain at the flange edge shown in Figure 8-b is confirmed with the experimental transverse strain result shown in Figure 7 which shows near-zero permanent transverse deformation, given that the strain gauge was located at the strip edge.

Figure 7 The history of the transverse strain during the 1st step

Figure 8 (a) Schematic shows the level of sheet wrapping over the tool during different forming passes (b) FEA results of the transverse plastic strain along the three cross-sections after the 12th forming step
It is believed that the permanent stretching in the transverse direction can overcome the wrinkling issues when ISR is applied to complex profiles. This argument is based on previous studies that have shown that flange wrinkling is significantly reduced when a transverse stretch is introduced into the flange [8]. Therefore, we can say that ISR may provide an alternative forming process that can form wrinkle-free complex components that would be wrinkled if produced with the FRF process [6].

7. Conclusion

- A simplified straight profile was successfully formed with the incremental shape rolling process.
- The result shows a clear development of permanent transverse stretching along the flange.
- It is believed that the transverse stretching will overcome the wrinkling issue when the ISR process is applied to complex profiles with variable cross-sections over the part length.
- The smaller level of flange wrapping over the tool in the later forming passes leads to a lower permanent transverse deformation, hence, the $X_{\text{deviation}}$ increases towards the flange edge with a decrease in the transverse deformation, and reaches its maximum value “max. $X_{\text{deviation}}$” at the flange edge where the transverse deformation is almost zero.

Acknowledgements
The authors would like to thank Deakin University Postgraduate Research Scholarships (DUPRS) for the provided scholarship and financial support and acknowledge data M Sheet Metal Solutions GmbH for the developed 3D Rollforming Center.

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