Prototyping of Straight Section Components Using Incremental Shape Rolling

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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.

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]. It allows the forming of difficult to form materials to complex geometries with minimum shape defects but is limited to long profiles of constant cross-section [5]. 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 [6-8].

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 [6, 9-13]. Flange wrinkling occurs when the required longitudinal compressive strain in the flange edge exceeds the buckling limit [8] and this restricts the part shape complexity achievable with FRF [14, 15]. 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 [16]. 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 [16].

With incremental sheet forming 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 [17-19]. Jia et al. [17] 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 [20] suggested that compressive hoop stresses in the flange during the conventional spinning process can be balanced by tensile stresses to avoid flange wrinkling.

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 [21], and also 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].

Similar to the newly introduced prototype flexible roll forming process [16], in the new Incremental Sheet Rolling (ISR) process introduced in this study, long and weight-optimised components of variable height and depth are manufactured by clamping a pre-cut blank between two forming dies and a single forming tool then incrementally forms the sheet to the desired shape. In contrast to the flexible roll forming process, the flange is not bent into shape but rolled onto a forming die. Similar to metal spinning, this may allow the control of the stress state to reduce wrinkling issues while at the same time forming long components with optimised shape may be possible from higher strength steels. Only one single forming roll is used which reduces tooling costs and may increase manufacturing speed.

In this paper, the new ISR technique will be applied for the forming of a long and straight U-channel profile to investigate material deformation and potential forming issues and to develop and validate a numerical model of the process. 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 Figure 1.

Standard tensile tests were carried on an Instron 5967 with a 30kN load cell and with a test speed of 0.025mm/s . The bone-shaped specimens were oriented along the rolling direction of the strip. The averaged true stress–true strain curves of the two tested materials are shown in Figure 2 while the strip thickness and the mechanical properties obtained by fitting the Hollomon’s power law are given in Table1.

Table 1 Tensile parameters

Material	Thickness (mm)	Yield Strength (MPa)	Ultimate tensile strength (MPa)	n	K (MPa)	Young’s modulus (GPa)
Aluminium	0.55	103.35	141.36	0.0776	171.6	71.15
Stainless Steel	0.45	243.03	512.57	0.1868	699.56	202.02

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 Z-direction. The 2-D path was repeated until the pre-cut blank was formed to the desired shape, see Figure 3.

4. Experimental Tooling And Forming Sequence

The experimental setup is shown in Figure 4-a. 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 set-up 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 4-b 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. In this study forming trials with 6 and 12 forming steps with an incremental step down of $d_y = 4.7$ and 2.35 mm in each step, respectively were analysed.

The part shape was analysed with a 3D laser scanner after the component had been removed from the tooling. The part shapes obtained from the 3D scanner were imported to the Geomagic Qualify

software [23] for comparison with the desired shape.

For the shape analysis, three X-Y planes were created along the part' 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 Figure 5-a).

The experimental results showed that the outer zone of the flange (the flange edge) is not fully formed to 90° and that there is a deviation from the desired shape that starts close to the middle length of the flange. Figure 5-b illustrates this shape error (the flange edge is not fully formed to 90°). Two parameters were identified to measure this shape error. The first is the maximum deviation from the desired shape in the X-direction ($\max. X_{\text{deviation}}$) 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_{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.

In order to measure the f_{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 (Figure 5-b), and f_{intact} is defined as the vertical length of the flange measured from the end of the profile corner radius to the flange location where $X_{\text{deviation}}$ reaches 0.05 mm.

A two-directional strain gauge was attached to the centre length of the blank and near to the flange edge to measure the longitudinal and transverse strains during the ISR process, Figure 6. 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. The symmetry half of the pre-cut blank is shown in Figure 6.

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 spring-back on the wrinkling 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 Figure 7.

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 was 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 Figure 8-a and four elements through the material thickness were used with an aspect ratio of less than 10. 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. A "frictionless contact"

surface to surface contact interaction algorithm was applied between the forming roll and the sheet surfaces to avoid convergence issues [24]. The “hard contact condition” was used to minimize the penetration of the rigid surfaces into the sheet surfaces at the constraint locations [9].

The 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 [25] and 0.3 for the stainless steel [26]. The plastic part of the true stress-strain curves shown in Figure 2 was used to define the plastic material behaviour. Isotropic hardening and the von Mises yield criteria were assumed for both materials [27, 28].

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 Figures 9 and 10 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_{intact} . In all cases, the maximum deviation ($\text{max. } X_{\text{deviation}}$) occurred at the flange edge.

The experimentally measured values of the $\text{max. } X_{\text{deviation}}$ and the f_{intact} are determined from Figures 9 and 10 and compared with the FEA results in Figures 11 and 12 for the aluminium and the stainless steel profiles, respectively using the procedure explained earlier and shown in Figure 5.

The experimental and the FEA results show the same trend in regard to $\text{max. } X_{\text{deviation}}$ and the f_{intact} for both the aluminium and stainless steel forming case. In both cases, the lowest “ $\text{max. } X_{\text{deviation}}$ ” occurred at the middle section, while its maximum value was generated at the tail section. The highest value of f_{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 but accurately represents the trends observed. It is therefore used in the following part of this study to further investigate the ISR process.

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 $d_y = 4.7$ mm and 2.35mm, respectively. Figures 13 and 14 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 seconds 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_y of 4.7mm show a deviation after the longitudinal strain shifts from tensile into compression (at the location of the attached strain gauge after 125 seconds of forming time) as shown in Figure 13-b and Figure 13-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. For this reason, the measurements for longitudinal and transverse strain are highlighted in red 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 seconds) 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 (Figure 13).

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 Figure 13-c and Figure 13-d).

In the transverse direction, the material is first compressed in front of the forming roll and then stretched when the forming roll has passed (Figure 14). In the Aluminium profile, this results in a small level of permanent transverse stretch in the strip edge (Figure 14 a and 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 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 (Figure 14 b and c).

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 16 and 17 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 Figures 16-b and 17-b 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 Figures 16-a and 17-a, 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.

7. Discussion

7.1 Material flow in the transverse direction

The results demonstrated in Figures 9 and 10 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 Figure 17-a). To further illustrate this, the transverse plastic strain was numerically analysed in the forming zone under the roll (Figure 17-b) 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 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 Figure 14 which show 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 (Figure 17-b), the transverse deformation that is measured by

the strain gauge is also close to zero (Figure 14). However, closer to the profile radius, there is a plastic transverse strain.

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 [16]. Here previous studies have shown that if transverse stretch can be introduced into the flange wrinkling is significantly reduced [17]. This suggests that the new method of incremental shape rolling presented here may represent a solution for overcoming wrinkling defects and may therefore 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 Figure 13 showed that during forming the flange edge is first under tensile deformation followed by longitudinal compression. In Figure 18 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 [29, 30].

After the forming roll has passed, the strip edge needs to be re-straighten and its length has to be equal to the roll contact line (Figure 18). 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 18-b 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_y), 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 Figures 15 and 16).

Figure 18-c shows the FEA results of the stainless steel profile with different values of d_y for the roll position indicated in Figure 18-b. In order 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 in the 12 steps forming condition is compared with that of the 2nd forming pass in the 6 steps forming condition. Note that the stainless steel profile showed a buckle after the 2nd forming pass in the 6 steps condition. The comparison illustrates that for the same total step down there is higher

longitudinal membrane strain when a higher increment step-size is used (Figure 18-c). This suggests that a larger step-down size (d_y) leads to higher tensile and compressive membrane strains and stresses. If the compressive stress 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 initiated). 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 19-a 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 Figure 19 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 steps condition shows a small drop in the compressive stress. This small stress drop is due to the formation of a small buckle. Figure 19-b 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 Figure 19-b). 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 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. 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-degree 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 spring-back.
- 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_y).

Declarations

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References

1. Baluch N, Udin ZM and Abdullah CS (2014) Advanced High Strength Steel in Auto Industry: an Overview. *Engineering, Technology & Applied Science Research*. 4 (4): 686-690.
2. Sun G, Deng M, Zheng G, et al (2019) Design for cost performance of crashworthy structures made of high strength steel. *Thin-Walled Structures*. 138: 458-472. <https://doi.org/10.1016/j.tws.2018.07.014>
3. 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 (1-4): 743-754. <https://doi.org/10.1007/s00170-017-0164-x>
4. Paralikas J, Salonitis K and Chryssolouris G (2008) Investigation of the effects of main roll-forming process parameters on quality for a V-section profile from AHSS. *The International Journal of Advanced Manufacturing Technology*. 44 (3-4): 223-237. <https://doi.org/10.1007/s00170-008-1822-9>
5. Jiao-Jiao C, Jian-Guo C, Qiu-Fang Z, et al (2020) A novel approach to springback control of high-strength steel in cold roll forming. *The International Journal of Advanced Manufacturing Technology*. 107 (3-4): 1793-1804. <https://doi.org/10.1007/s00170-020-05154-8>
6. Jiao J, Rolfe B, Mendiguren J, et al (2016) An analytical model for web-warping in variable width flexible roll forming. *The International Journal of Advanced Manufacturing Technology*. 86 (5-8): 1541-1555. <https://doi.org/10.1007/s00170-015-8191-y>
7. Yan Y, Wang H, Li Q, et al (2014) Simulation and experimental verification of flexible roll forming of steel sheets. *The International Journal of Advanced Manufacturing Technology*. 72 (1-4): 209-220. <https://doi.org/10.1007/s00170-014-5667-0>
8. Kasaei MM, Naeini HM, Abbaszadeh B, et al (2014) Flange Wrinkling in Flexible Roll Forming Process. *Procedia Engineering*. 81: 245-250. <https://doi.org/10.1016/j.proeng.2014.09.158>
9. Woo YY, Han SW, Oh IY, et al (2019) Shape Defects in The Flexible Roll Forming of Automotive Parts. *International Journal of Automotive Technology*. 20 (2): 227-236. <https://doi.org/10.1007/s12239-019-0022-y>
10. Jiao JS, Rolfe B, Mendiguren J, et al (2015) An analytical approach to predict web-warping and longitudinal strain in flexible roll formed sections of variable width. *International Journal of Mechanical Sciences*. 90: 228-238. <https://doi.org/10.1016/j.ijmecsci.2014.11.010>
11. Woo YY, Han SW, Hwang TW, et al (2018) Characterization of the longitudinal bow during flexible roll forming of steel sheets. *Journal of Materials Processing Technology*. 252: 782-

794. <https://doi.org/10.1016/j.jmatprotec.2017.10.048>
12. Kim JH, Woo YY, Hwang TW, et al (2016) Effect of loading pattern on longitudinal bowing in flexible roll forming. *Journal of Mechanical Science and Technology*. 30 (12): 5633-5639. <https://doi.org/10.1007/s12206-016-1132-3>
 13. Rezaei R, Moslemi Naeini H, Tafti RA, et al (2017) Effect of bend curve on web warping in flexible roll formed profiles. *The International Journal of Advanced Manufacturing Technology*. 93 (9-12): 3625-3636. <https://doi.org/10.1007/s00170-017-0784-1>
 14. Kasaei MM, Naeini HM, Liaghat GH, et al (2015) Revisiting the wrinkling limits in flexible roll forming. *The Journal of Strain Analysis for Engineering Design*. 50 (7): 528-541. <https://doi.org/10.1177/0309324715590956>
 15. Groche P, Zettler A, Berner S, et al (2010) Development and verification of a one-step-model for the design of flexible roll formed parts. *International Journal of Material Forming*. 4 (4): 371-377. <https://doi.org/10.1007/s12289-010-0998-3>
 16. Abeyrathna B, Ghanei S, Rolfe B, et al (2021) Optimising part quality in the flexible roll forming of an automotive component. *The International Journal of Advanced Manufacturing Technology*. <https://doi.org/10.1007/s00170-021-08176-y>
 17. Jia Z, Li L, Han ZR, et al (2018) Experimental study on wrinkle suppressing in multi-pass drawing spinning of 304 stainless steel cylinder. *The International Journal of Advanced Manufacturing Technology*. 100 (1-4): 111-116. <https://doi.org/10.1007/s00170-018-2712-4>
 18. Wong CC, Dean TA and Lin J (2003) A review of spinning, shear forming and flow forming processes. *International Journal of Machine Tools and Manufacture*. 43 (14): 1419-1435. [https://doi.org/10.1016/s0890-6955\(03\)00172-x](https://doi.org/10.1016/s0890-6955(03)00172-x)
 19. Wang L and Long H (2011) Investigation of material deformation in multi-pass conventional metal spinning. *Materials & Design*. 32 (5): 2891-2899. <https://doi.org/10.1016/j.matdes.2010.12.021>
 20. Music O, Allwood JM and Kawai K (2010) A review of the mechanics of metal spinning. *Journal of Materials Processing Technology*. 210 (1): 3-23. <https://doi.org/10.1016/j.jmatprotec.2009.08.021>
 21. Kumar A, Gulati V, Kumar P, et al (2019) Forming force in incremental sheet forming: a comparative analysis of the state of the art. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*. 41 (6). <https://doi.org/10.1007/s40430-019-1755-2>
 22. Behera AK, de Sousa RA, Ingarao G, et al (2017) Single point incremental forming: An assessment of the progress and technology trends from 2005 to 2015. *Journal of Manufacturing Processes*. 27: 37-62. <https://doi.org/10.1016/j.jmapro.2017.03.014>
 23. Qualify G (June 2014) Available: <http://www.geomagic.com/en/>. Accessed
 24. Weiss M, Abeyrathna B, Gangoda DS, et al (2017) Bending behaviour and oil canning in roll forming a steel channel. *The International Journal of Advanced Manufacturing Technology*. 91 (5-8): 2875-2884. <https://doi.org/10.1007/s00170-016-9892-6>
 25. Murugesana M, Sajjad M and Jung DW (2020) Experimental and numerical investigation of cold roll forming process. *Materials Science and Engineering*. 758. <https://doi.org/10.1088/1757->

26. Ellobody E and Young B (2005) Structural performance of cold-formed high strength stainless steel columns. Journal of Constructional Steel Research. 61 (12): 1631-1649. <https://doi.org/10.1016/j.jcsr.2005.05.001>
27. Abeyrathna B, Rolfe B, Pan L, et al (2016) Flexible roll forming of an automotive component with variable depth. Advances in Materials and Processing Technologies. 2 (4): 527-538. <https://doi.org/10.1080/2374068x.2016.1247234>
28. Abeyrathna B, Rolfe B, Harrasser J, et al (2017) Prototyping of automotive components with variable width and depth. Materials Modelling and Testing for Sheet Metal Forming. <https://doi.org/10.1088/1742-6596/896/1/012092>
29. Abeyrathna B, Rolfe B, Hodgson P, et al (2016) Local deformation in roll forming. The International Journal of Advanced Manufacturing Technology. 88 (9-12): 2405-2415. <https://doi.org/10.1007/s00170-016-8962-0>
30. Mohammadi Najafabadi H, Moslemi Naeini H, Safdarian R, et al (2018) Effect of forming parameters on edge wrinkling in cold roll forming of wide profiles. The International Journal of Advanced Manufacturing Technology. 101 (1-4): 181-194. <https://doi.org/10.1007/s00170-018-2885-x>

Figures

Figure 1

Isometric view and the cross-section dimensions of the U-profile

Figure 2

averaged true stress-true strain curves tested along the rolling direction

Figure 3

Schematic drawing of incremental shape rolling of a straight u-channel profile

Figure 4

(a) the experimental set up of the incremental shape rolling process, and (b) schematic of the ISR forming sequence

Figure 5

schematic drawings showing (a) the location of the X-Y sections cuts along the profile length and (b) the transverse shape errors that were determined

Figure 6

Schematic of the pre-cut blank with the main dimensions and the location of the attached 2-directional strain gauge indicated (dimensions in mm)

Figure 7

schematic drawing illustrating how flange wrinkling was determined

Figure 8

(a) the FE model of the ISR process (b) mesh size and boundary conditions applied to the blank

Figure 9

Comparison of the desired 2D shape with the three different cross-sections formed with the 12 forming step condition for the aluminium profile, (a) experimentally and (b) FEA

Figure 10

Comparison of the desired 2D shape with the three different cross-sections formed with the 12 forming step condition for the stainless steel profile, (a) experimentally and (b) FEA

Figure 11

the experimental and FEA values of (a) $\max. X_{\text{deviation}}$ and (b) f_{intact} for the aluminium profile determined in the three cross-sections after the 12th forming step

Figure 12

the experimental and FEA values of (a) $\max. X_{\text{deviation}}$ and (b) f_{intact} for the stainless steel profile determined in the three cross-sections after the 12th forming step

Figure 13

longitudinal strain history of the ISR process during (a) the 1st step out of 12 steps ($d_y=2.35$ mm) for the aluminium profile, (b) 1st step out of 6 steps ($d_y=4.7$ 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

Figure 14

transverse strain history of the ISR process during (a) the 1st step out of 12 steps ($d_y=2.35$ mm) for the aluminium profile, (b) 1st step out of 6 steps ($d_y=4.7$ 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

Figure 15

Wrinkling severity in the flange for Aluminium with (a) 12 forming steps and (b) 6 forming steps.

Figure 16

Wrinkling severity in the flange for stainless steel with (a) 12 forming steps and (b) 6 forming steps

Figure 17

FEA results of the stainless steel profile (a) Level of sheet wrapping around the forming roll during different stages of forming (b) level of transverse plastic strain generated in the flange at the different forming stages.

Figure 18

front view of the ISR process showing the longitudinal bending curvatures which follow a concave and a convex shape (a) experimental results, (b) FEA results and (c) plastic membrane longitudinal strain at the flange edge along the stainless steel profile's length during the 2nd step in the 6 steps condition and the 4th step in the 12 steps condition

Figure 19

membrane longitudinal stresses at the flange edge along the stainless steel profile's length after (a) the 2nd step out of 6 and the 4th step out of 12 and (b) the 3rd step out of 6 and the 6th step out of 12