Finite Element Study on Chain-Die Forming of an AHSS Channel with Variable Depth

F F M BENE,1,a Z Y Liang1,b, H Yang1, D Y Li1,c,* and S C Ding2,d

1State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai 200240, China
2School of Mechanical and Mining Engineering, University of Queensland, St Lucia, QLD 4072, Australia

Corresponding author: *franckbene@sjtu.edu.cn; bliangzhenye@sjtu.edu.cn; cdyli@sjtu.edu.cn; ds.ding@uq.edu.au

Abstract. A novel manufacturing technology called chain-die forming was in recent years proposed by Dr. Ding as an alternative to conventional roll forming. Mainly applied in the automotive industry, its prolonged deformation range enables the forming of advanced high strength steels (AHSS) with considerably reduced residual strain, which enables an adequate response to the increasing market requirements of this industry. In this paper, the finite element simulation of chain-die forming an AHSS channel with variable depth is performed. For more accurate predictions, the Bauschinger effect is well considered through the Chaboche hardening model implemented. The residual plastic strain and thickness distributions of the U shaped variable-depth profile are numerically evaluated. The forming limit at a critical zone is analyzed and the predicted magnitude of springback after forming is also calculated. The results portray the forming feasibility and strength of the chain-die forming technology as a valid alternative solution to stamping and roll forming, which are commonly used methods to manufacture such products. In one pass, a complete profile is achieved as opposed to roll forming, with no product defect such as wrinkling or cracking with limited springback development.

Keywords: Chain-die Forming, Advanced high strength steel, Variable-depth profile, residual plastic strain, springback

1. Introduction
Variable-depth products are commonly used in the automotive industry, some of which include frame rails, bumpers and door beams [1]. In order to meet the rising light weight, quality and safety demands of the automotive market, advanced high strength steels(AHSS) have become very popular in recent years in manufacturing companies. Constant profile products may be easily formed through roll forming or stamping, but as regards more complex shapes with variable width or depth, additional technique needs to be included. For example stamping AHSS products requires a servo-driven press, which with the help of a pressure sensor controls the slide speed all through the stroke in order to ensure the shape of the formed product[2]. It is a complex control process which sometimes produces defects such as wrinkling and cracking. AHSS high strength will also require a high press load which most often results in high springback due to reverse loading on the product. Conventional roll forming
also has the limitation of only forming products with a regular cross section. In recent years flexible roll forming has been a feasible response to the limitations of traditional roll forming by introducing transversely moveable forming rolls [3]. The rolls can move along a desired path of bending to form products of variable cross-sections[4]. A numerical control system is used to command the rotational and translational displacements of the rolls. This is as well a complex forming process which usually has web-warping, end flaring and wrinkling as common defects[5].

(a)

(b)

Figure 1. (a) Schematic diagram of the Chain-die former [6]; (b) quarter section feature definition.

In the above mentioned forming methods just like in most metal forming processes, product defect is as a result of redundant plastic strain development and residual stress producing springback. Chain-die forming(CDF) was first proposed by Ding et al [5] in 2008 as an alternative to roll forming. This forming technology boasts the advantages of low residual stress on the end product (due to an increased virtual rotation radius), insignificant redundant plastic strain, simplified control unit and cheaper tooling cost. In comparison to roll forming, the chain-die former increases the forming length to more than 10 meters [7] with a ratio of 1:100 [8, 9]. CDF is a combination of bending and stamping. Discrete die blocks are mounted on two track boards each having a large radius. The die blocks are held together by chain links and mounted as to rotate round the track board as shown in figure 1(a). The blank is fed incrementally in between the die blocks at a quasi-static rate in one pass to form the product.

Various studies have been carried out on forming variable width products by flexible roll forming and chain-die forming but forming variable depth products by CDF remains unexplored. This study seeks to investigate the feasibility of chain-die forming, to a variable depth product. For that, it is necessary to investigate the residual plastic strain after forming, the thickness distribution of the product as well as the springback. Two tooling corner radii are considered for this study.

2. Material and Product Dimensions
AHSS have proved to exhibit a high level of bauschinger effect when used in forming processes which involve loading and reloading[10]. The Chaboche hardening model has been proved to better describe the AHSS material behaviors during numerical simulations, especially springback[6]. Following previous work [11], the Chaboche hardening model is used to predict the residual plastic strain and springback. The Mises yield criterion is employed here as:

\[ f = \| \sigma - x \| - \varphi = \left( \frac{3}{2} \left( \sigma' - x' \right) : \left( \sigma' - x' \right) \right)^{\frac{1}{2}} - \varphi = 0 \] (1)

where \( \varphi = \sigma_0 + \sigma_{ISO} \), \( \varphi \) is the yield surface size in stress space, \( \sigma_0 \) is the initial yield stress, \( \sigma_{ISO} \) is the isotropic hardening stress, \( \sigma' \) and \( x' \) are deviatoric parts of stress \( \sigma \) and back stress \( x \) respectively. The back stress and isotropic hardening parameters implemented as benchmark were obtained from Y. Li et al [10]. The Bauschinger ratio for the material is 0.811.
Table 1. Mechanical properties of the material (tested by a Zwick/Roell Z020 machine at SJTU)

| Property                        | Value  |
|--------------------------------|--------|
| Thickness (\(t\))              | 1.2mm  |
| Young’s modulus (\(E_h\))       | 204 GPa|
| 0.2% Offset yielding stress (\(\sigma_y\)) | 884 MPa|
| Ultimate tensile strength (\(\sigma_{UTS}\)) | 1403 MPa|
| Uniform elongation (\(\varepsilon_u\)) | 16.2% |
| Total elongation (\(\varepsilon_t\)) | 18.2% |

The material used in this analysis is QP1180 provided by Baosteel. The mechanical properties of the material is as shown in table 1. Local features are defined on a quarter section of the product as shown in figure 1(b). The stress/strain curve is presented in figure 2.

![Figure 2](image-url) (a) Absolute true stress vs accumulated absolute true strain curve of QP1180[10]; (b) Part section and dimensions in mm.

3. Finite Element Modelling

ABAQUS/Standard is employed to carry out the chain-die forming simulations. Due to the symmetry, only a half section is considered for the simulation to save computing time. The dies are computed as rigid body parts and the blank as a deformable part. Both the top and bottom dies are split into 9 fragments in conformity with the chain-die forming machine. The blank is attributed a section of type solid-homogeneous. A large virtual radius of 35m is assigned to the top and bottom die pairs using reference points [10]. A surface to surface contact type is employed between the die and the blank. A penalty friction formulation is used with a friction coefficient of 0.15. A fit exponential curve is used as a pressure-overclosure to compute the normal behaviour during contact. The blank is given a very fine mesh for convergence purposes. The critical zones as previously defined in figure 1(b) are attributed an even more refined mesh to improve accuracy as shown in figure 3. The blank is meshed with 77056 linear hexahedral elements of type C3D8R. The dies fragments having a coarser mesh totally, are made up of 4446 linear quadrilateral elements of type R3D4. A symmetry boundary condition is applied on the blank as shown in figure 3.

![Figure 3](image-url) Assembly diagram of the meshed chain-die former with workpiece.
At the start of the simulation process, in order to avoid a blank distortion at the first contact between the blank and the die blocks, the blank is slightly stamped at a minimal level between the first block-pair of the chain-die former. This enables a tight grip for the incremental forming process to continue smoothly. During the forming process, the top die punches and bends the workpiece gradually upon the bottom die till the middle of the chain-die former. After the middle is crossed, the unloading process begins until both dies separate as the chain-die former rotates.

4. Results
The effective plastic strain, the forming limit at a critical zone, the thickness distribution along longitudinal paths and springback on a quarter section of the product are discussed in this section. In figure 4, Lines 1, 2 and 3 are used to represent section cuts performed to study the effective plastic strain at three regions on a quarter section of the product while paths 1, 2, 3 and 4 represent longitudinal nodes whose coordinates are extracted to evaluate the thickness distribution on the web, corner and sidewall of the same quarter section. Overall, the results portray good forming feasibility, the material properties are preserved as evidenced by negligible redundant plastic strain and limited springback. Further details are described below.

![Figure 4](image)

**Figure 4.** Transverse lines and longitudinal paths used to study the plastic strain development.

4.1. Effective plastic strain
The effective plastic strain across the thickness at the head, middle and tail zones are observed through section cuts along lines 1, 2 and 3. Figure 5 primarily reveals that the strain concentrates are all found in the corner region of the blank. The highest strain concentrations are on the inner surface and outer surface of the blank corner. The maximum effective plastic strain developed at the outer corner surface of the head zone is 0.1444 whereas a maximum value of about 0.0642 is observed on the inner surface. Overall, the middle zone exhibits the maximum strain of 0.1925 on its inner region and 0.1765 on the outer region. This is normal as bending is simultaneous in the longitudinal and transverse directions in the concave region. Along the tail zone a maximum effective plastic strain of 0.1604 is also developed on its outer surface while its inner surface reveals a maximum value of about 0.0802. All three zones have a neutral middle corner layer which portrays no plastic strain. There is a negligible amount of plastic strain in the web and sidewall of the middle zone, and almost no redundant plastic strain in that of the head and tail zones except for the deformation region (the corner). This therefore shows that no product defect such as wrinkling or cracking should be expected.

![Figure 5](image)

**Figure 5.** Effective plastic strain display in cross-section cut along lines 1, 2 and 3 respectively.

4.2. Forming limit check at one critical region
One critical consideration for variable depth profiles which makes forming difficult for other forming methods is that the concave zone of the corner experiences both transverse and longitudinal loading simultaneously. A special attention is therefore given to that region. The major and minor strains of a group of elements in the concave corner as shown in figure 6(a) are extracted. By curve fitting, their
relationship is compared in a forming limit diagram to that of the work-piece. Two bending corner radii are considered, as shown in figure 6(b). The result shows that both bend corners radii of 1.2mm and 5mm can be formed by chain die forming without cracking.

![Figure 6](image)

**Figure 6.** (a) Selected region for element strain data extraction; (b) Forming limit diagram.

4.3. Thickness distribution along longitudinal paths

After the springback simulation, the displacement coordinates of nodes along longitudinal paths 1,2,3,4 are examined to investigate the thickness distribution of the blank after forming (see figure 7). For the head region, the results show a small thickness variation with the maximum difference being only about 0.17mm along path 3 at the middle surface of the web. The middle zone also shows even less variation with 0.13mm in the corner zone. This is normal since there is a high strain concentration found in the concave zone (see figure 6(a)) resulting in the thinning of that area. The tail region towards its end along path 3 shows the greatest variation of 0.23mm, though still within an acceptable range. This is reasonable as it represents the middle convex part of the web, which experiences the highest load during forming. Greater springback is also expected from this area as shown in figure 8(a).

![Figure 7](image)

**Figure 7.** Plastic strain development along longitudinal paths in the head, middle and tail zones.

4.4. Springback development

One other product defect which needs to be studied is the springback which occurs during the unloading process mostly due to residual stresses in the product. The coordinates of longitudinal nodes along the middle section of the web bow and that of transverse nodes along line 2 are extracted. For the convex bow as seen in figure 8(a), a springback of about 2mm is observed in the convex web of the 1.2mm corner radius part as opposed to about 2.5mm on the 5mm corner radius part. This reveals a direct relationship between the corner radius and the web bow. The larger the corner radius the greater the web springback. A similar relationship is observed in the concave corner(see figure 8(b)). There is a larger springback of only about 0.7mm which occurs in the R5 corner in contrast to about 0.5mm in the R1.2 corner. Overall this low springback level could easily be compensated for by redesigning the die blocks in the future.

![Figure 8](image)

**Figure 8.** (a) Springback comparison of entire convex zone; (b) Springback comparison at concave zone.
5. Conclusion and Remarks
A finite element study on chain-die forming a variable-depth product with emphasis on possible product defects which can be caused by residual plastic strain after forming and springback development is covered in this paper. The forming limit check at a critical area on the product as well as the thickness distribution on the formed product after springback is also discussed. The following conclusions can be drawn from this analysis:

- A variable depth product can be manufactured by chain-die forming in a single pass.
- The effective plastic strain and residual strains as well as the forming limit check, show that no obvious product defects, such as wrinkling, twisting and cracking, are to be expected on the product.
- There is a low amount of springback in the corner region but a more noticeable amount in the web of the chain-die formed variable depth product.

Due to the accuracy of the springback predictions through the bauschinger effect included in the material’s strain hardening behaviour, further springback compensation studies will also produce a more accurate product. Further studies are currently being carried out and an experimental validation will also be conducted to verify the residual plastic strain predictions and product quality.

Acknowledgments
The authors acknowledge the financial support by NSFC [Grant number U1860110]. The authors express their thankfulness to Baosteel who provided the material used in this work. The valuable inputs and comments from the colleagues in SJTU is also recognized.

References
[1] Joo B D, Han S W, Shin S G R and Moon Y H 2015 Flexible roll forming process design for variable cross-section profile International Journal of Automotive Technology 16 83-88
[2] Abeyrathna B, Rolfe B, Pan L, Ge R and Weiss M 2016 Flexible roll forming of an automotive component with variable depth Advances in Materials and Processing Technologies 2 527-538
[3] Kasaei M M, Naeini H M, Abbaszadeh B, Silva M B and Martins P A F 2015 Flexible roll forming, Materials Forming and Machining 51-71
[4] Larranaga J 2011 Geometrical accuracy improvement in flexible roll forming process by means of local heating, PhD Thesis (Department of Mechanical and Industrial Production, Mondragon University)
[5] Ding S, Daniel W, Yuan J and Zhang Y 2008 Making roll forming flexible-introduction to Chain forming Yokohama Tube and Pipe 2011 Joint Symposium-Innovative Tube and Pipe Manufacturing and Forming: proceedings 335-340
[6] Li Y, Sun Y, Xiao H, Bong H J, Shi L, Li S, Li D Y, Ding S C and Wagonere R H 2018 A numerical study on chain-die forming of the AHSS U-channel and contrast with roll forming International Journal of Mechanical Sciences 135 279-293
[7] Li Y G, Huang H L, Li D Y, Sun Y and Ding S C 2017 Finite Element Simulation of Chain-die Forming U Profiles with Variable Cross-Section Materials Science Forum 898 1177-1182
[8] Lindgren M 2007 Cold roll forming of a U-channel made of high strength steel Journal of Materials Processing Technology 186 77-81
[9] Bidabadi B S, Naeini H M, Tehrani M S and Barghikar H 2016 Experimental and numerical study of bowing defects in cold roll-formed U-channel sections Journal of Constructional Steel Research 118 243-253
[10] Zang S, Sun L and Niu C 2013 Measurements of Bauschinger effect and transient behavior of a quenched and partitioned advanced high strength steel Materials Science & Engineering A 586 31-37
[11] Chaboche J and Rousselier G 1983 On the plastic and viscoplastic constitutive equations - part I: rules developed with internal variable concept. Journal of Pressure Vessel Technology 105 153-158.