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Springback and Longitudinal Bow in Chain-die Forming U and Hat Channels

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Abstract: Chain-die forming is an emerging sheet metal technique for manufacturing advanced high strength steel (AHSS) products. Springback and longitudinal bow are two of the major shape defects in gradual forming. In this study, the springback and longitudinal bow of AHSS in chain-die forming of hat and U profiles are investigated through experiment and finite element simulation. The disparity of springback along the longitudinal direction and disparate longitudinal bow signifies complex deformation processes of chain-die forming. Finite element simulation of the chain-die forming process gives an insight into the formation of non-uniform springback and longitudinal bow. The gradual forming process by one die block after another causes bending and reverse-bending deformation in the web area and the redundant deformation of the sheet metal, which further leads to non-uniform bending moment and accumulated stresses along the longitudinal direction. At the same time, the redundant deformation will also result in the longitudinal strain on the edge, while the

downhill deformation decreases the maximum longitudinal strain at the edge and introduces the longitudinal strain on the web. The different non-uniform longitudinal strain distribution along the transversal direction causes disparate longitudinal bow behaviors for chain-die formed AHSS hat and U profiles, downward bowing and upward bowing respectively. By the established model, the disparate springback and longitudinal bow behavior can be determined, which also contribute to the process design for chain-die formed AHSS products.

Keyword: Chain-die forming; Characteristic deformation; Non-uniform springback; Longitudinal bow; Chain-die forming experiments

1. Introduction

Advanced high-strength steels (AHSS) have been found more extensive usage in automotive manufacturing for weight reduction and crash safety [1]. The development of high-strength steels posed great challenges to stamping, i.e., shear fracture when being draw-bended through a tight radius [2]. Gradual forming techniques have become attractive to AHSS product manufacturing due to their incremental deformation nature that enables the forming of small radius [3]. Roll forming and flexible roll forming progressively deform a steel strip into products with required cross-sectional profiles by a series of rolls installed at the tandems along the longitudinal direction [4,5]. In which process, alloy sheets are gradually formed through incremental bending, and thus a small bend radius could be realized [6]. Chain-die forming was recently proposed to fabricate AHSS products and also falls into gradual forming techniques of sheet metals [7]. In contrast with roll forming, chain-die forming increases the forming length by enlarging the radii of the rolls to tens of meters, which is realized by discrete die blocks attached to a rotational track board, as shown in Fig. 1 [8,9].

Fig. 1. Schematic diagram of the chain-die forming process [9].

Channel products with constant and variable cross-sections can be formed by chain-die forming technique. The quality of sheet metal products is crucial for industrial applications, and springback and longitudinal bow are two of the most typical shape errors in gradual forming processes, especially for manufacturing AHSS products considering their large springback and complex material behaviors [10,11].

Springback, referring to the shape changes after removing forming loads due to elastic recovery, has been always a critical problem in forming AHSS sheets. Springback in stamping and roll forming has been extensively studied in the recent two decades. In stamping, the main characteristics of springback for AHSS products are the sidewall curl and larger springback angle [12]. AHSS sheets present different springback behaviors in roll forming processes. Badr et al. [13] compared the springback of roll-formed channels with V-die-bended ones and found roll forming leads to a lower level accumulated stresses and thus smaller springback. When a channel with a uniform cross-section is roll-formed, non-uniform springback along the longitudinal direction can usually be observed. Halmos [14] concluded that in the roll forming process, the amount of springback at the entry and exit ends of the pre-cut metal sheet is larger than that of the middle area, which is also known as end flare, referring to the outwards curling at the front and tail ends. The non-uniform springback engendered at the front and tail ends of roll-formed products was attributed to lack of constraints at two ends of the strip, i.e., not fully clamped by neighboring rolls. Bui and

Ponthot [15] established a 3D finite element model to simulate a cold roll forming process. Both the experiments and numerical simulation signified that the front end of cold-roll formed precut sheet metal shows flare out deformation. Wiebenga et al. [10] proposed a robust optimization method to compensate for shape error and minimize the sensitivity for variation of material properties in the cold forming process. It was found springback angle varies along the longitudinal direction in roll forming DP780 V-section profile, and end flares were observed in both experiment and simulation. Abvabi et al. [16] studied the influence of residual stress on the longitudinal bow and end flare for the roll-formed DP780 V-section profile. Their experimental and numerical results showed that the non-uniform springback results from the disparate distribution of longitudinal stresses for the roll-formed parts.

Longitudinal bow is defined as the vertical deviation of web area along the longitudinal direction and is also considered as an accompanied deformation of springback [17]. Many efforts have been made to study longitudinal bow in the cold roll forming processes and the researches mainly focused on the relationship between the longitudinal bow and redundant longitudinal strain introduced in the forming processes. Jeong et al. [18] designed an under-rail product and simulated the roll forming process of the design profile. Two types of flower patterns were compared and it was found that the flower pattern which results in a larger longitudinal strain also leads to a severe longitudinal bow. Shirani Bidabadi et al. [19] experimentally and numerically studied the longitudinal bow defects in cold roll-formed U profile. It was found that the difference between longitudinal strain induced in the flange and web causes the longitudinal bow in cold roll formed products. Meanwhile, they proposed that a downhill strategy is an effective method to eliminate the longitudinal bow. Woo et al. [11] studied the characteristics of the longitudinal bow in flexible roll-formed U profiles using three different blank sheets, trapezoid, convex and concave, and the longitudinal bow defects were ascribed to the transversal non-uniformity of the longitudinal strain. Badr et al. [20] studied the influence of two roll forming approaches

(constant bend radius and constant arc-length method) on springback and longitudinal bow of Ti-6Al-4V sheet. The results showed that the constant bend radius forming method leads to less longitudinal bow and less permanent longitudinal deformation in the edge. Park et al. [5] proposed an incremental counter forming (ICF) process to reduce the bowing defect in cold roll forming. The experimental results showed effectiveness of the proposed method.

A few studies have been carried out on simulation and experiments of the chain-die forming process. Sun et al. [21] studied the longitudinal strain development at the edge of the plate during U profiles chain-die forming processes and found that peak longitudinal strain varies inversely with the virtual roll radius. Li et al. [22] compared the chain-die forming and roll forming process of a U profile. The experimental and numerical results show that a smaller longitudinal strain is achieved by chain-die forming, due to a smoother transitional surface, and it was also observed that chain-die forming can alleviate the longitudinal bow defects. Li et al. [8] proposed an analytical model for rapid prediction and compensation of the U profile chain-die forming process. Qian et al. [23] established a finite element model for the multi-stand chain-die forming process of a U channel and investigated the influence of material strength, sheet metal thickness, vertical forming gap, and effective virtual roll radius on springback for chain-die formed AHSS U profiles.

The objective of this work is to further investigate the characteristic deformations and product shape defects in the AHSS chain-die forming, and springback and longitudinal bow are the main focus. The rest of the paper is organized as follows. In section 2, chain-die forming experiments are performed. In section 3, a finite element model is established. In section 4, the non-uniform springback along the longitudinal direction and the disparate longitudinal bow behaviors are analyzed and numerical models are verified with experimental results. In section 5, three characteristic deformations in chain-die forming are discussed. Moreover, the cause of non-uniform springback and longitudinal bow are probed. Section 6 gives conclusions.

2. Experiments

Chain-die forming experiments on the hat and U profiles with different lengths and corner radii are conducted. Fig. 2 shows one case of the hat and U products, with the desired bending angle equal to 90° for both sidewall and flange. The longitudinal length L is set to be 100 mm, 220 mm, and 420 mm, and the corner radius R is set to be 3.6 mm and 5.0 mm, respectively, as listed in Table 1.

Table 1 Geometrical dimensions of the experimental samples.

Design parameters	Hat profile	U profile
L (mm)	100, 220, 420	100, 220, 420
R (mm)	3.6, 5.0	3.6, 5.0

Note: L represents the longitudinal length; R represents the corner radius, as depicted in Fig. 2.

Fig. 2. Basic configurations of the designed test samples (a) hat profile and (b) U profile (Unit: mm).

The material considered in this study is a 1.2 mm thickness QP1180 (QP refers to quenching and partitioning) sheet acquired from Baosteel. The tensile and compression-tension (CT) tests were previously carried on this alloy [22]. The width of the specimen tested in the forming experiments is 132 mm for the hat profiles and 86 mm for the U

profiles.

Fig. 3 shows the lab-scale chain-die forming machine, which mainly consists of track boards, rollers, chains, and die blocks [22]. The radius of the track board R_v is 35 m. The discrete die blocks that are mounted to the chains are driven by the gear [22] and the linear velocity of the die blocks is set to 70 mm/s. Fig. 3 also shows the resistant strain gauge (BX120-5AA), the National Instruments (NI) cDQA-9171 and NI 9237 used to record the longitudinal strain evolution developed at the flange edge of the hat profile (middle position, 210 mm from the lead end for 420 mm-length hat profile). Two strain gauges are firmly attached on both sides of the plate and the average value of the longitudinal strain for the two positions can be therefore obtained. The center of the strain gauge is about 1.5 mm away from the flange edge. A reference test piece is added to improve accuracy. The ATOS Triple Scan non-contact structured blue light 3D scanner is used to acquire the geometry of the formed samples. Chain-die forming experiments are repeated at least three times to ensure repeatability.

Fig. 3. Chain-die forming test machine and the measurement of longitudinal strain

3. Finite element modeling

A finite element model for the chain-die forming process is established by using ABAQUS, as shown in Fig. 4, and a half model is considered due to symmetry. The

plate is assumed to have the same dimensions as in the experiments and discretized by 5 layers of the eight-node linear brick element with reduced integration (C3D8R). A fine mesh with a size of 0.55 mm is evenly assigned for the parts that experience bending and unbending deformation along the transversal direction. The mesh size for other areas is 2.66mm.

Twelve pairs of die blocks with a length of 36 mm are used. The die blocks are modeled as discrete rigid surfaces by 4-node 3-D bilinear rigid quadrilateral (R3D4) elements. The discrete die blocks are assembled on a track board with a radius of 35 m and are assigned with the angular velocity of 0.002 rad/s around the X-axis (opposite in direction for top and bottom die blocks). The Coulomb friction model is employed and the friction coefficient between the sheet and die blocks is set to 0.1 [22].

The von Mises yield criterion and Chaboche nonlinear kinematic hardening model with 3 back stress components are used to describe the hardening behavior of the QP1180 materials. The coefficients from the previous study [22] are adopted and are listed in Table 2. A saturated elastic modulus of 180.5 GPa calculated from the LUL test [8] is used in this study.

The simulation of the chain-die forming process consists of two steps. In the forming stage, the sheet metal is assumed to be stationary at the beginning and then is gradually bended by the rotating die blocks; in the subsequent springback stage, top and bottom die blocks are sequentially removed, and the formed sample is released.

Table 2 The fitted coefficients of the Chaboche model for QP1180 [22].

C_1 (MPa)	γ_1	C_2 (MPa)	γ_2	C_3 (MPa)	γ_3	Q (MPa)	b
3490.2	10.4	11407.3	72.5	16187.9	295.8	200.1	291.9

Note: C_i and γ_i ($i=1,2,3$) are kinematic hardening constants; Q is the saturation stress; b is the saturation rate of isotropic hardening stress.

Fig. 4. The finite element model for chain-die forming (hat profile, $L=420\text{mm}$, $R=5.0\text{mm}$).

4. Experimental results and verifications

4.1 Springback in chain-die forming

Chain-die formed hat and U test samples show different non-uniform springback characteristics. In this section, the springback non-uniformity along the longitudinal direction is quantitatively studied.

Fig. 5 illustrates the strategy for springback measurement. Along the longitudinal direction, two, three, and six cross-sections are selected to measure their configurations for 100 mm-length, 220 mm-length, and 420 mm-length profiles, respectively. Section #1 is defined as 5 mm away from the lead end of the part. Section #2 for 100 mm-length parts (Section #3 for 220 mm-length parts, and Section #6 for 420 mm-length parts) is defined at 5 mm away from the tail end. The interval distances between the two neighbor sections are 90 mm, 105 mm, and 82 mm for 100 mm-length, 220 mm-length, and 420 mm-length profiles, respectively.

Fig. 5. Illustration of the analysis strategy for non-uniform springback along the longitudinal direction for the test samples (Unit: mm).

To quantitatively describe the springback characteristics of chain-die formed hat profiles, the following four springback indicators are employed here, as illustrated in Fig. 6(a).

θ_1 - the springback angle between web and sidewall.

θ_2 - the springback angle between sidewall and flange.

ρ_1 - the curvature of web curl.

ρ_2 - the curvature of the sidewall curl.

(a)

(b)

Fig. 6. Indicators for springback evaluation (a) hat profile, and (b) U profiles.

4.1.1 Springback of hat profile

Fig. 7 compares the measured springback configurations of different cross-sections from the lead end to the tail end for the hat profile ($L=420\text{mm}$, $R=5.0\text{mm}$).

Two distinctive features of springback, sidewall curl, and web curl are observed. Web curl is the curvature occurring in the web and also refers to crossbow defects in the roll forming process [14]. As shown in Fig. 7, the sectional springback configuration varies along the longitudinal direction. The lead end exhibits a large springback, and the tail end has a curved web. With the increase of longitudinal length, the sidewall gradually flares inward, and the web area tends to be more curved.

Fig. 7. Measured springback configurations between different cross-sections for the chain-die formed hat profile ($L = 420$ mm, $R = 5.0$ mm).

The measured θ_1 , θ_2 , ρ_1 and ρ_2 with respect to the distance from the lead end for hat profiles of different dimensions are listed in Table 3. The variation of relative springback angle $\Delta\theta_1$ and ρ_1 are shown in Fig. 8, where the relative springback angle $\Delta\theta_1$ are defined as $\theta_1 - 90$, and the longitudinal distance from the lead section is normalized by the distance between the lead end and tail end of the profile. Fig. 8(a) shows that for hat profiles, the springback angle θ_1 decreases with increasing distance

from the lead end, and the web-curl curvature ρ_1 exhibits a different tendency, as shown in Fig. 8(b). By comparing θ_1 and ρ_1 between hat profiles with different lengths, it is found that with the increase of profile length, the deviation of the relative springback angle $\Delta\theta_1$ and web-curl curvature ρ_1 between the lead and the tail end increases, as shown in Fig. 8. The non-uniform springback configurations shown in Fig. 7 are also confirmed by Fig. 8. Fig. 8(a) also shows that the springback of the hat profiles with a 3.6 mm corner radius is smaller than that with a 5.0 mm corner radius, i.e. a tighter die radius generally results in a reduced springback angle [24]. Meanwhile, with the increase of the distance from the lead end, the variation of θ_2 and ρ_2 are not noticeable, in contrast with θ_1 and ρ_1 .

Table 3 Measured springback indicators for the chain-die formed hat profiles.

Configurations		Indicators	Section1	Section2	Section3	Section4	Section5	Section6
R=5.0mm	L=420mm	θ_1 (degree)	99.54	96.89	95.04	93.58	92.61	91.34
		θ_2 (degree)	87.28	87.42	87.25	87.17	87.34	87.93
		ρ_1 (mm ⁻¹)	0.0033	0.0028	0.0033	0.0047	0.0056	0.0097
		ρ_2 (mm ⁻¹)	0.0132	0.0151	0.0142	0.0142	0.0141	0.0145
	L=220mm	θ_1 (degree)	98.57	95.46	93.76	-	-	-
		θ_2 (degree)	88.10	88.94	89.07	-	-	-
		ρ_1 (mm ⁻¹)	0.0032	0.0031	0.0064	-	-	-
		ρ_2 (mm ⁻¹)	0.0118	0.0151	0.0131	-	-	-
	L=100mm	θ_1 (degree)	98.53	96.79	-	-	-	-
		θ_2 (degree)	89.54	88.72	-	-	-	-
		ρ_1 (mm ⁻¹)	0.0033	0.0037	-	-	-	-
		ρ_2 (mm ⁻¹)	0.0115	0.0152	-	-	-	-
R=3.6mm	L=420mm	θ_1 (degree)	98.30	97.29	94.87	92.50	91.10	89.61
		θ_2 (degree)	88.17	87.74	87.61	88.17	88.59	87.99
		ρ_1 (mm ⁻¹)	0.0040	0.0033	0.0036	0.0050	0.0059	0.0091

	ρ_2 (mm ⁻¹)	0.0109	0.0138	0.0135	0.0130	0.0125	0.0115
$L=220\text{mm}$	θ_1 (degree)	98.01	94.30	91.43	-	-	-
	θ_2 (degree)	89.18	88.52	87.97	-	-	-
	ρ_1 (mm ⁻¹)	0.0032	0.0026	0.0066	-	-	-
$L=100\text{mm}$	ρ_2 (mm ⁻¹)	0.0119	0.0136	0.0122	-	-	-
	θ_1 (degree)	99.09	96.68	-	-	-	-
	θ_2 (degree)	88.96	87.13	-	-	-	-
	ρ_1 (mm ⁻¹)	0.0029	0.0032	-	-	-	-
	ρ_2 (mm ⁻¹)	0.0119	0.0144	-	-	-	-

Note: θ_1 , θ_2 , ρ_1 , and ρ_2 are depicted in Fig. 6(a).

(a)

(b)

Fig. 8. The variation of springback indicators with longitudinal distance for hat profiles (a) relative springback angle $\Delta\theta_1$ and (b) web-curl curvature ρ_1 .

4.1.2 Springback of U profile

Fig. 9 compares the measured springback configurations of the cross-sections of interest for chain-die formed U profile ($L = 420$ mm, $R = 3.6$ mm). Similar to the hat profile, discrepancies are found between the springback angle for different cross-sections. However, the web is much flatter than the hat profile and does not show obvious variation along the longitudinal direction. Two springback indicators, θ_1 and ρ_1 , are adopted, and the measurements for different sections are shown in Fig. 10 and listed in Table 4. Fig. 10(a) shows a downward trend for $\Delta\theta_1$. Meanwhile, the springback angles at the tail end for the 420 mm-length U profiles are relatively larger, which indicates an end flare. Fig. 10(a) also shows that $\Delta\theta_1$ decreases with increasing longitudinal distance from the lead end for U profiles with a length of 100 mm or 220

mm. For the U profile of 420 mm length, θ_1 decreases firstly and then increase, signifying a different non-uniform springback behavior compared with the hat profiles. Besides, the web-curl curvature ρ_1 and its variation for U profiles shows significant difference from the hat profiles, with no obvious discrepancies being found between the cross-sections measured, as shown in Fig. 9 and Fig. 10(b).

Fig. 9. Comparison of the measured springback configurations for different cross-sections with varying distance from the lead end of the chain-die formed U profile ($L = 420$ mm, $R = 3.6$ mm).

Table 4 Measured springback indicators for chain-die formed U profiles.

Configurations			indicators	Section1	Section2	Section3	Section4	Section5	Section6
$R=5.0\text{mm}$	$L=420\text{mm}$	θ_1 (degree)		93.18	90.95	90.05	89.00	88.13	88.73
		ρ_1 (mm^{-1})		0.0024	0.0030	0.0029	0.0033	0.0033	0.0026
	$L=220\text{mm}$	θ_1 (degree)		92.72	90.36	89.47	-	-	-
		ρ_1 (mm^{-1})		0.0024	0.0032	0.0022	-	-	-

$R=3.6\text{mm}$	$L=100\text{mm}$	θ_1 (degree)	92.59	91.30	-	-	-	-
		ρ_1 (mm^{-1})	0.0025	0.0015	-	-	-	-
	$L=420\text{mm}$	θ_1 (degree)	92.41	89.52	88.72	87.87	87.89	88.65
		ρ_1 (mm^{-1})	0.0023	0.0017	0.0021	0.0027	0.0025	0.0012
	$L=220\text{mm}$	θ_1 (degree)	92.40	88.66	87.91	-	-	-
		ρ_1 (mm^{-1})	0.0024	0.0019	0.0010	-	-	-
	$L=100\text{mm}$	θ_1 (degree)	91.23	88.93	-	-	-	-
		ρ_1 (mm^{-1})	0.0025	0.0009	-	-	-	-

Note: θ_1 and ρ_1 are demonstrated in Fig. 6(b).

(a)

(b)

Fig. 10. The variation of (a) relative springback angle $\Delta\theta_1$ and (b) web-curl curvature ρ_1 with regard to the distance from the lead end for U profiles.

4.1.3 Experimental verification

Fig. 11 compares the calculated springback configurations with experimental measurement of the 420 mm-length profiles, which exhibit the largest non-uniformity. Fig. 11 shows that the calculated configurations of lead end and tail end are consistent with the measured springback configuration for both the hat and U profiles. The disparities between the lead end and tail end are well captured. The variation of relative springback angle $\Delta\theta_1$ with respect to longitudinal distance from the lead end is presented to illustrate the non-uniform springback characteristics. The coordinates for the cross-sections of interest are extracted and the relative springback angles are obtained following Fig. 6.

Figs. 12 and 13 compare the variation of calculated and measured relative

springback angle $\Delta\theta_1$ about longitudinal length for the hat and U profiles respectively. Fig. 12 shows that the calculated $\Delta\theta_1$ for hat profiles are generally smaller than experimental values. The deviation between experimental results and numerical results is denoted with $< \Delta\theta_1 >$, which is defined as:

$$< \Delta\theta_1 > = \frac{1}{6} \sum_{i=1}^{i=6} \Delta\theta_{1i} - \Delta\theta'_{1i} \quad (1)$$

where $\Delta\theta_{1i}$ and $\Delta\theta'_{1i}$ are measured and calculated $\Delta\theta_1$, respectively, for section i , $i=1, 2, \dots, 6$. The numerical model underestimates the springback angle by 1.39° and 2.07° for the 420 mm-length hat profiles with a corner radius of 5.0 mm and 3.6 mm, respectively. Fig. 12 also shows that the variation trend of the relative springback angle with longitudinal distance agrees well with experimental results for both profiles. $\Delta\theta_1$ decreases with longitudinal length.

Fig. 13 shows that the deviation between calculated $\Delta\theta_1$ and experimental results for chain-die formed U profiles are smaller than hat products, and the average deviations are 1.87° and 0.19° for the U profiles with a corner radius of 5.0 mm and 3.6 mm, respectively. Meanwhile, a similar variation of θ_1 with respect to longitudinal length is observed in both experimental and numerical results. $\Delta\theta_1$ decreases firstly and then increases, resulting in a concave curve.

(a)

(b)

Fig. 11. Comparison of the experimental and calculated springback configurations between the lead end (Section #1) and tail end (Section #6) for (a) hat profile ($L = 420$

mm, $R = 5.0$ mm), and (b) U profile ($L = 420$ mm, $R = 3.6$ mm).

(a)

(b)

Fig. 12. Comparison of the experimental and calculated variation of relative

springback angle $\Delta\theta_1$ concerning the normalized distance for hat profiles (a) $L = 420$ mm, $R = 5.0$ mm, and (b) $L = 420$ mm, $R = 3.6$ mm.

(a)

(b)

Fig. 13. Comparison of the experimental and calculated variation of relative springback angle $\Delta\theta_1$ about the normalized distance for U profiles (a) $L = 420$ mm, $R = 5.0$ mm, (b) $L = 420$ mm, $R = 3.6$ mm.

4.2 Longitudinal bow in chain-die forming

Chain-die formed hat and U test samples show disparate longitudinal bow behaviors. In this section, the experimental results of longitudinal bow are presented and the numerical model is verified.

4.2.1 Disparate longitudinal bow behavior

Fig. 14 shows the measured longitudinal bows for chain-die formed 420 mm-length U and hat profiles. The extracted curves are rotated to make two ends of the profiles be aligned with each other. Fig. 14 shows that chain-die formed U profiles show an upward longitudinal bow, while hat profiles have a downward longitudinal bow.

Fig. 14. Illustration of the disparate longitudinal bow for hat and U profiles.

4.2.2 Experimental verification

Fig. 15 compares the measured and calculated longitudinal membrane strain developed on the edges for the middle part of the plate. The variation of the calculated longitudinal strain agrees well with the experimental result.

Fig. 16 compares the measured and calculated maximum deviation of the longitudinal bow (ΔH in Fig. 14) for the hat and U profiles with different longitudinal lengths and corner radius and specific values are listed in Table 5. The calculated ΔH matches well with the experimental result for both trends and values, and for the 420 mm-length profiles, the maximum relative error is 16.21%. It can also be found that the maximum deviations of longitudinal bow always increase with the increase of profile length and decrease of corner radius, although the influence of the corner radius is limited.

Fig. 15. Verification of calculated longitudinal strain evolution (hat profile, $L = 420$ mm, $R = 5.0$ mm).

(a)

(b)

Fig. 16. Comparison of measured and calculated maximum longitudinal bow for (a) hat profiles, and (b) U profiles with different longitudinal length and corner radius.

Table 5. Experimental and calculated maximum longitudinal bow ΔH for the hat and

U profiles with varying dimensions.

		100		220		420	
		L (mm)		R (mm)			
		5.0	3.6	5.0	3.6	5.0	3.6
Hat	Exp.(mm)	-0.077	-0.096	-0.197	-0.221	-1.135	-1.215
	FE (mm)	-0.144	-0.121	-0.126	-0.17	-0.966	-1.018
	σ (%)	87.01	26.04	36.04	23.08	14.89	16.21
U	Exp.(mm)	0.118	0.147	0.141	0.215	0.903	1.011
	FE (mm)	0.062	0.042	0.162	0.193	0.802	0.923
	σ (%)	47.46	71.43	14.89	10.23	11.18	8.70

Note: σ (%)—relative deviation between calculated and experimental results.

In general, the finite element model captures the experimentally observed non-uniform springback along the longitudinal direction and the springback configuration for single cross-sections. Meanwhile, the calculated longitudinal strain and disparate longitudinal bow behaviors match well with the experiments. The characteristic deformations of the chain-die forming process which lead to the non-uniform springback and different bowing behavior will be elaborately discussed in the following section.

5. Deformation analysis

Chain-die formed hat and U test samples show different non-uniform springback characteristics and disparate longitudinal bow behaviors. In this section, the characteristic forming mechanisms leading to the non-uniform springback and longitudinal bow are probed by using the above established FE model.

5.1 Deformation in chain-die forming

5.1.1 Bending and reverse-bending deformation

The deformation of sheet metal in chain-die forming is characterized as a gradual

forming process. Two representative cross-sections, corresponding to sections #1 and #6 in Fig. 5, are selected to illustrate the discrepant deformation process for different cross-sections along the longitudinal direction in the hat profile chain-die forming process, as shown in Fig. 17. Three sequential forming states are plotted and compared in terms of section configuration, where R_{L1} represents the web curl radius of the lead end at the forming state I, and R_{T2} denotes the radius of web curl for the tail end at the forming state II. R_{L1} is much larger than R_{T1} , indicating a curved web at the tail end. With the proceeding of forming, the curved web is gradually deformed into the desired geometry. Fig. 17 shows that the web area near the lead end barely experiences redundant deformation, while the web of the tail web is subjected to bending and reverse-bending deformation.

Fig. 18 schematically depicts the bending and reverse-bending deformation process. Due to the gradual forming nature and the less-constrained boundary condition in the chain-die forming process, the tail end is firstly deformed into a curved geometry with a radius of R_1 under the action of a bending moment $M^{\infty \rightarrow R_1}$ at the early stage of the forming process. Then the curved web is reversely bended into the desired geometry, i.e., a flat web, by taking advantage of a reverse-bending moment $M^{R_1 \rightarrow \infty}$. Finally, the formed part is released and a bending moment $M^{\infty \rightarrow R_2}$ is engendered to balance the reverse bending moment $M^{R_1 \rightarrow \infty}$, and the bending moment $M^{\infty \rightarrow R_2}$ results in an additional inward springback. Due to the bending, reverse-bending, and subsequent inward springback, the web area near the tail end for hat profile is deformed complicatedly into a flare-in geometry with an obvious curvature, which often refers to the crossbow defect that occurs in roll forming processes.

Figs. 17 and 18 show that the bending and reverse-bending deformations at the web are responsible for small $\Delta\theta_1$ and large ρ_1 at the tail end of the hat profiles observed in the experiment, especially in the case of channels with 420 mm length, where the reverse-bending effect is enhanced compared with 220 mm length and 100 mm length ones. A similar conclusion was drawn by Phanitwong and Thipprakmas [25] in their

study on the springback of a U-bending process. The deformation for a single cross-section in the chain-die forming process shown in Fig. 18 is similar to a U-bending process, e.g., the inward springback is caused by the bending and reverse-bending deformation at the web area.

Fig. 17. Discrepant deformation process for two representative cross-sections in the hat profile chain-die forming process, representing the lead end and tail end, respectively.

Fig. 18. Schematic illustration of (a) bending and (b) reverse-bending deformation engendered at web area in chain-die forming.

To quantitatively illustrate the discrepant bending process along forming direction, seven points located on the symmetrical line of the web (on the outer surface), P1 to P7, are selected and the logarithmic transversal strain evolutions are traced and presented in Fig. 19. With the increase of longitudinal distance, the maximum value of transversal strain increases, and the maximum transversal strain at P7 is three times as large as that at P1, indicating an enhanced bending deformation and a larger bending moment $M^{\infty \rightarrow R_2}$ depicted in Fig. 18. Therefore, the main reason for the non-uniform springback of the chain-die formed hat profile is the bending and reverse-bending deformation at web area in the gradual forming process. Besides, there is also a discrepancy in the time at which the transversal strain reaches the maximum for different points. The maximum transversal strain turns to be delayed with the increase of longitudinal length, characterizing the gradual nature of chain-die forming.

Fig. 19. Comparison of the transversal strain evolution for the selected points in the hat profile chain-die forming process. (The distance of the points from the lead end is normalized by dividing with the profile's length.)

5.1.2 Redundant deformation

The curvature of web curl for the chain-die formed U profiles shows no obvious discrepancies with respect to longitudinal length, as shown in Fig. 9. Meanwhile, the variation of springback angle θ_1 is different from that of hat profiles, and both ends of the chain-die formed U profiles of 420 mm length show a flare out deformation, indicated by a large springback angle θ_1 .

Fig. 20 shows the U profile chain-die forming process, where redundant deformation engenders because the edge of the plate is geometrically necessary to travel a longer distance compared with the central line [21]. The redundant deformation basically consists of four forming stages, represented by four dashed lines AB, CD, EF,

and GH, respectively, where A, C, E, and G are points located at the edge of the plate, and B, D, F, and H are points located at the corner. The plate is bended concavely at line AB and then experiences convex deformation at line CD. Finally, the deformed area is reversely bended through the line EF, due to geometry continuity, to the desired geometry represented by line GH. During these processes, longitudinal stress and in-plane shear stresses are introduced, and the redundant deformation is similar to the cold roll forming process described by [26].

Fig. 20. Redundant deformation in the U profile chain-die forming.

The plate is gradually bended into the desired profiles in the chain-die forming process, and the accumulated longitudinal stress and shear stress will be released once the top and bottom die blocks are removed. Since the die blocks are engaged one pair after another, the accumulated stress is also released sequentially. Therefore, stresses at the lead end are released while the tail end can be still fully constrained, leading to the fact that the accumulated stress varies from lead end to tail end before removing corresponding die block pairs. Fig. 21 illustrates the stress releasing process at the lead and tail ends for the U profile of 420 mm length, where the die blocks are removed in sequence. As shown in Fig. 21(a), at the lead end, the accumulated longitudinal stress is negative on the inner surface and positive outside before removing the die blocks,

accompanied by a bending moment M_z around the y-axis. The part subjected to tension at the end of the forming process tends to shrink after unloading, while the part subjected to compression tends to be expanded [27]. After removing the die blocks, the release of bending moment M_z will introduce an opposite bending moment M'_z , resulting in flaring out deformation. In contrast, at the tail end, as depicted in Fig. 21(b), the accumulated longitudinal stress is positive inside and negative outside, and the stress releasing leads to flaring in deformation.

(a)

(b)

Fig. 21. Illustration of the flaring out and flaring in resulted from the release of accumulated non-uniform longitudinal stress, (a) release of the lead end and (b) release of the tail end.

In addition to the longitudinal stress, the in-plane shear stress also contributes to the non-uniform springback for chain-die formed U products. As depicted in Fig. 20, bending and reverse bending, which is dominant in the area of CDEF, will introduce in-plane shear stress in the transversal-longitudinal direction, while the shear stress along the thickness-longitudinal direction is almost zero considering the small metal sheet thickness [26]. The in-plane shear stress in transversal-longitudinal direction will lead to the twisting moments M_{zy} and M_{yz} [26], as depicted in Fig. 22(a). When removing the die blocks gradually, opposite twisting moments are introduced, resulting in flaring in deformation at the lead end and flaring out deformation at the tail end, as illustrated in Fig. 22(b).

In summary, redundant deformation causes the accumulated non-uniform longitudinal stress and in-plane shear stress, and release of the accumulated non-uniform longitudinal stress leads to flare out at the lead end and flare in at the tail end, while the release of the accumulated in-plane shear stress has an opposite effect. Their combined action determines the overall springback configuration.

(a)

(b)

Fig. 22. Illustration of the flaring out and flaring in resulted from the release of the accumulated non-uniform in-plane shear stress, (a) before releasing, and (b) after releasing.

5.1.3 Downhills deformation

In the chain-die forming process, the redundant deformation will result in the longitudinal strain on the edges, as shown in Fig. 20. However, the longitudinal strain developed on the web is less investigated. In this section, downhills in the single-pass

chain-die forming process are discussed.

Downhill is usually used in roll forming of electric-resistance-welded pipes [14] and U channels [28] to eliminate the non-uniform longitudinal strain, where the descent of the pass line-height is optimized to minimize the edge stretch. In the downhill roll forming lines, the bottom of the section does not travel in a straight plane, and at the same time, the edge of the plate travel a short deformation distance compared to the regular forming line, which therefore engenders a least amount of redundant strain and stress [14]. The downhill strategy is one of the most important factors that affect the longitudinal bow in cold roll forming [19]. Qian et al. [23] studied the downhill in a multi-stand chain-die forming process, and it can also be classified as the downhills between forming passes, which is similar to the downhills in roll forming processes, usually achieved by elevation of forming stands. The downhill discussed in this study refers to the unique deformation in one single pass and is one of the inherent characteristics for chain-die forming.

Fig. 23 depicts a random forming posture in U profile chain-die forming process. Fig. 23(a) shows that the numerical model is consistent with the fact that the virtual rolls of chain-die forming consists of multiple discrete die blocks, and the gaps between the top and bottom die blocks are gradually reduced with synchronous motions of the dies [21]. It was proved that the strain paths of the points located at the edge of the plate are similar from the initial engaged position to the exit end in the gradual forming process [29]. Thus, the material flow of sheet metal in chain-die forming is similar to those in roll forming. The deformed configurations for different cross-sections along the longitudinal direction can be taken as those at successive roll-stands in roll forming. As such, a smoother deformation surface can be achieved [22]. Comparing the deformed configuration of sections 1 to 4, it is found that the sheet metal is gradually bended through multiple roll-stands. The four extracted cross-sections in Fig. 23(b) indicates that a downhill phenomenon is naturally existing in the single-pass chain-die forming process.

Fig. 23(c) is depicted as a comparison, where the web of the extracted cross-sections shown in Fig. 23(b) are aligned vertically with each other. It is shown that the edge of the plate travels a vertical distance of ΔH_1 in Fig. 23(c). However, in the chain-die forming process, as shown in Fig. 23(b), a downhill of ΔH_3 engenders, leading to a shorter increment of ΔH_2 . The study of Paralikas et al. [28] proved that maximum longitudinal strain on the edges decreases with increasing downhill displacement. Thus, the existence of downhill has two significant effects. On the one hand, the longitudinal strains developed on the edges caused by redundant deformation are reduced, and on the other hand, longitudinal strains on the web are introduced.

(a)

(b)

Fig. 23. Downhills in single-pass chain-die forming: (a) an overview of the deformation posture, (b) comparison of deformed configurations for the selected sections, and (c) comparison of deformed configurations without downhill.

Figs. 23 indicates that downhills are naturally existing in chain-die forming processes and results in longitudinal strain on the web. Chain-die forming machine consists of a pair of track boards which usually have a very large radius R_v , as shown in Fig. 1. To give an insight to the influence of virtual roll radius on the maximum longitudinal strain on the web, the downhill in chain-die forming is furthermore discussed here. The virtual roll radii of 35000 mm shown in Fig. 4 is set to vary from 10000 mm to 45000 mm, with an interval of 5000 mm. The maximum longitudinal strain developed on the web for different virtual roll radius are compared in Fig. 24. It shows that for both hat and U profiles, the peak longitudinal strain on the web decreases slowly with the increase of virtual roll radius.

Fig. 24. Maximum longitudinal strain developed on the web for (a) U and (b) hat profiles chain-die forming process with different virtual roll radii ($L = 800$ mm, $R = 5.0$ mm).

Fig. 25 schematically depicts the downhill in single-pass chain-die forming process, where S is the stroke of tools. Once R_v and S are given, a downhill displacement of DH is therefore determined:

$$DH = \frac{S}{2} \quad (2)$$

The angle between the trajectory of the plate and the horizontal line is defined as the downhill angle in the chain-die forming, and can be calculated as:

$$\tan\theta = \frac{DH}{L_n} \quad (3)$$

where L_n is the nominal deformation distance and can be calculated as:

$$L_n = \sqrt{(R_v + S)^2 - \left(R_v + S - \frac{S}{2}\right)^2} \quad (4)$$

Fig. 25. Schematic diagram of the downhill in single-pass chain-die forming.

By substituting Eq. (2) and Eq. (4) to Eq. (3), the downhill angle θ can be calculated:

$$\theta = \tan^{-1} \left(\frac{\frac{S}{2}}{\sqrt{R_v S + \frac{3}{4} S^2}} \right) \quad (5)$$

The maximum longitudinal strain developed on the web can be reflected by the downhill angle θ . Eq. (5) shows that θ increases with the decreasing of virtual roll radius R_v . An increased θ signifies an enhanced downhill deformation, and will further lead to an increased maximum longitudinal strain on the web for both U and hat profiles, which is also confirmed by numerical results, as shown in Fig. 24. Therefore, downhill deformation is closely related to the longitudinal strain developed on the web in chain-die forming.

It has been proved that chain-die forming can achieve a smaller redundant longitudinal strain on edge compared with cold roll forming processes, owing to the longer deformation length [21] and smoother transitional surfaces [22]. This study

further clarifies that another factor that contributes to the reduction of longitudinal strain is the downhill nature in chain-die forming, and a sound product could be expected.

5.2 Contrast between the hat and U profile

Three characteristic deformations in chain-die forming are discussed in previous section. In this part, the deformations of hat and U profiles are compared to investigate the effect of the flange on the chain-die forming process.

5.2.1 Non-uniform springback configuration

Fig. 8 shows that for hat profiles, $\Delta\theta_1$ increases with length, and synchronous increase of ρ_1 indicates a strong reverse-bending effect. In contrast, for the U profiles, as shown in Fig. 10, ρ_1 does not remarkably vary with channel length. Thus, the reverse-bending effect is very limited for U profiles.

Fig. 26 compares the chain-die forming processes of the hat and U profiles. In the hat profile chain-die forming process, the top die blocks prevent the plate from bending upward, while the sidewalls of U profiles can move freely when bending the corners. Thus, for the hat profile chain-die forming process, redundant deformation is depressed due to the constraints of top die blocks, which at the same time lead to an enhanced bending and reverse-bending deformation at the web area.

Fig. 27(a) compares the evolution of longitudinal stress developed at the edge points A_1 and A_2 (inner side) shown in Fig. 26 for hat and U profiles, respectively. The maximum accumulated stresses prior to springback developed at the edge of the hat profile are much less than those at the edge of the U profile, even though the sidewall of the hat profile is 10 mm larger than the U profile. Fig. 27(b) shows the evolution of in-plane shear stress developed at points B_1 , B_2 , at the inner, outer surfaces of the sidewall for the hat profile, and the counterparts, points B'_1 and B'_2 , on the U profile. Fig. 27(b) shows that the difference of shear stress magnitude between the inner and outer surfaces of the U profile is obviously much larger than those of the hat profile. In

general, Fig. 27 signifies that the influence of redundant deformation is very limited for hat profiles compared with U profiles, and the non-uniform springback along longitudinal direction for hat profiles should be ascribed to the bending and reverse-bending deformation at web. However, for the U profiles, redundant deformation is the major cause of non-uniform springback.

Fig. 26. Comparison of the chain-die forming process between (a) hat profile (where top die blocks prevent the sheet metal from bending upward), and (b) U profile.

(a)

(b)

Fig. 27. Illustration of the limited redundant deformation in hat profile chain-die forming, (a) longitudinal stresses evolution and (b) in-plane shear stresses evolution

during ($L = 420$ mm, $R = 3.6$ mm; A_1 , A_2 , B_1 , B_2 , B'_1 , and B'_2 are shown in Fig. 26).

5.2.2 Disparate longitudinal bow

Fig. 28 compares the non-uniformity of longitudinal strain distribution for path A'-A (A_1 , A_2 , A'_1 , and A'_2 are shown in Fig. 26) for the moment during the forming process and after springback respectively. Fig. 28(a) shows that during the U profile forming process, a tensile longitudinal strain is introduced on the edges, and a significant difference can be observed between point A'_2 and point A_2 . For the hat profile, both the edge and web experience tensile deformations, and the difference between edge and web is much smaller. More importantly, longitudinal plastic strain distribution along section A'-A tends to be different for hat and U profiles, as shown in Fig. 28(b). The decreased and increased longitudinal strain variation from the web to edge indicate a relatively elongated and compressed edge for U and hat profiles, respectively, which would lead to upward and downward longitudinal bow respectively.

As aforementioned, the longitudinal strain induced on the edges is limited in the hat profile chain-die forming process, corresponding to the limited redundant deformation benefited from the constraints of top die blocks. The longitudinal strain developed on the edges of the hat profile is much smaller than those for the U profile. Meanwhile, the downhill in the hat profile chain-die forming process introduces a relatively larger longitudinal strain on the web (as shown in Fig. 24). Furthermore, based on the comparison of the non-uniform longitudinal strain distribution along the path A'-A shown in Fig. 28, it is reasonable to expect a downwards longitudinal bow in chain-die formed hat profiles after springback.

(a)

(b)

Fig. 28. Non-uniform longitudinal strain distribution across the width (from point A' to point A) for (a) a random forming moment, and (b) after springback ($L = 420$ mm,

$$R = 5.0 \text{ mm}).$$

The longitudinal plastic strain differences between points A and A' ($\delta\epsilon = \epsilon_{\text{nodeA}} - \epsilon_{\text{nodeA}'}$) for the hat and U profiles with different length and corner radius are presented in Fig. 29. It shows that $\delta\epsilon$ remains positive for U and negative for hat profiles after springback, signifying elongation on edges and web, respectively. Therefore, the disparate non-uniformity of longitudinal strain for hat and U profiles should lead to a downward and upward longitudinal bow, respectively.

In general, two co-existing longitudinal strains determines the behavior of longitudinal bowing in chain-die forming processes, the longitudinal strain developed on the edges of the plate (ϵ_{edge}), caused by redundant deformation, and the longitudinal strain introduced on the web (ϵ_{web}) due to the downhill deformation, respectively. If the value of ϵ_{edge} is greater than ϵ_{web} , an upward longitudinal bow is expected; otherwise, there will be a downward longitudinal bow. The measured longitudinal bow behaviors (upward or downward, shown in Fig. 14) for both the U and hat profiles are consistent with the calculated longitudinal strain difference between edge and web. The experimental results confirm that the non-uniform distribution of the longitudinal strain caused by redundant deformation and downhill deformation is responsible for the disparate longitudinal bow behaviors in the chain-die forming. Since the downhill naturally exists in chain-die forming processes, and the longitudinal bows are ascribed to the non-uniformity of longitudinal strain, the longitudinal strain developed on the web and edges should be simultaneously taken into consideration in future process design of chain-die forming.

Fig. 29. Comparison of longitudinal plastic strain difference between the edge (point A) and the web (point A') of the strip.

6. Conclusions

In this study, shape errors in chain-die forming of AHSS channels are numerically and experimentally studied. Hat and U profiles with different lengths are formed to illustrate the characteristic mechanism of chain-die forming and its effect on springback and longitudinal bow. Three characteristic deformations are discussed by FE simulation. Specifically, downhill in chain-die forming are qualitatively and quantitatively investigated, and the longitudinal strain developed on the edges and web are simultaneously studied. The following conclusions can be drawn.

1). Chain-die formed AHSS hat and U products exhibit different inhomogeneous springback along the longitudinal direction and disparate longitudinal bowing behavior. By the established model, both the springback and longitudinal bow behavior for chain-die formed AHSS products can be determined. Future process design should take the non-uniformity in springback and longitudinal bow into account simultaneously.

2). Two major causes lead to the non-uniform springback in chain-die forming, the bending and reverse-bending deformation and the redundant deformation. Both effects have resulted from the gradual forming process. For the hat profile, the influences of the redundant deformation are limited and the bending and reverse-bending deformation at the web is dominant. For U profile, non-uniform springback is mainly attributed to the redundant deformation.

3). Redundant deformation will lead to longitudinal strain on the edges. The downhill deformation in chain-die forming causes the longitudinal strain on the web and alleviates the maximum longitudinal strain induced on the edge. The non-uniform longitudinal strain along the transversal direction signifies different longitudinal bow behaviors for the hat and U profiles. Chain-die forming experiments confirm that the disparate longitudinal bowing for the hat and U profiles have resulted from the transversal non-uniformity of longitudinal strain.

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Consent to Participate No human or animal is involved in this work.

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Availability of data and materials

The data and materials supporting the results of this article are included within the article.

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Figures

Figure 1

Schematic diagram of the chain-die forming process [9].

Figure 2

Basic configurations of the designed test samples (a) hat profile and (b) U profile (Unit: mm).

Figure 3

Chain-die forming test machine and the measurement of longitudinal strain

Figure 4

The finite element model for chain-die forming (hat profile, L=420mm, R=5.0mm).

Figure 5

Illustration of the analysis strategy for non-uniform springback along the longitudinal direction for the test samples (Unit: mm).

(a)

(b)

Figure 6

Indicators for springback evaluation (a) hat profile, and (b) U profiles.

Figure 7

Measured springback configurations between different cross-sections for the chain-die formed hat profile ($L = 420$ mm, $R = 5.0$ mm).

Figure 8

The variation of springback indicators with longitudinal distance for hat profiles (a) relative springback angle $\Delta\theta_1$ and (b) web-curl curvature p_1 .

Figure 9

Comparison of the measured springback configurations for different cross-sections with varying distance from the lead end of the chain-die formed U profile (L = 420 mm, R = 3.6 mm).

(a)

(b)

Figure 10

The variation of (a) relative springback angle $\Delta\theta_1$ and (b) web-curl curvature ρ_1 with regard to the distance from the lead end for U profiles.

(a)

(b)

Figure 11

Comparison of the experimental and calculated springback configurations between the lead end (Section #1) and tail end (Section #6) for (a) hat profile ($L = 420$ mm, $R = 5.0$ mm), and (b) U profile ($L = 420$ mm, $R = 3.6$ mm).

(a)

(b)

Figure 12

Comparison of the experimental and calculated variation of relative springback angle $\Delta\theta_1$ concerning the normalized distance for hat profiles (a) $L = 420\text{ mm}$, $R = 5.0\text{ mm}$, and (b) $L = 420\text{ mm}$, $R = 3.6\text{ mm}$.

(a)

(b)

Figure 13

Comparison of the experimental and calculated variation of relative springback angle $\Delta\theta_1$ about the normalized distance for U profiles (a) $L = 420\text{ mm}$, $R = 5.0\text{ mm}$, (b) $L = 420\text{ mm}$, $R = 3.6\text{ mm}$.

Figure 14

Illustration of the disparate longitudinal bow for hat and U profiles.

Figure 15

Verification of calculated longitudinal strain evolution (hat profile, L = 420 mm, R = 5.0 mm).

Figure 16

Comparison of measured and calculated maximum longitudinal bow for (a) hat profiles, and (b) U profiles with different longitudinal length and corner radius.

Figure 17

Discrepant deformation process for two representative cross-sections in the hat profile chain-die forming process, representing the lead end and tail end, respectively.

Figure 18

Schematic illustration of (a) bending and (b) reverse-bending deformation engendered at web area in chain-die forming.

Figure 19

Comparison of the transversal strain evolution for the selected points in the hat profile chain-die forming process. (The distance of the points from the lead end is normalized by dividing with the profile's length.)

Figure 20

Redundant deformation in the U profile chain-die forming.

(a)

(b)

Figure 21

Illustration of the flaring out and flaring in resulted from the release of accumulated non-uniform longitudinal stress, (a) release of the lead end and (b) release of the tail end.

Figure 22

Illustration of the flaring out and flaring in resulted from the release of the accumulated non-uniform in-plane shear stress, (a) before releasing, and (b) after releasing.

Figure 23

Downhills in single-pass chain-die forming: (a) an overview of the deformation posture, (b) comparison of deformed configurations for the selected sections, and (c) comparison of deformed configurations without downhill.

Figure 24

Maximum longitudinal strain developed on the web for (a) U and (b) hat profiles chain-die forming process with different virtual roll radii ($L = 800$ mm, $R = 5.0$ mm).

Figure 25

Schematic diagram of the downhill in single-pass chain-die forming.

Figure 26

Comparison of the chain-die forming process between (a) hat profile (where top die blocks prevent the sheet metal from bending upward), and (b) U profile.

(a)

(b)

Figure 27

Illustration of the limited redundant deformation in hat profile chain-die forming, (a) longitudinal stresses evolution and (b) in-plane shear stresses evolution during ($L = 420$ mm, $R = 3.6$ mm; A₁, A₂, B₁, B₂, B'₁, and B'₂ are shown in Fig. 26).

(a)

(b)

Figure 28

Non-uniform longitudinal strain distribution across the width (from point A' to point A) for (a) a random forming moment, and (b) after springback ($L = 420$ mm, $R = 5.0$ mm).

Figure 29

Comparison of longitudinal plastic strain difference between the edge (point A) and the web (point A') of the strip.