Case Studies on Chain-die Forming for AHSS

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Abstract: In this study, three case studies were conducted to develop a reliable finite element-based numerical model of Chain-die Forming (CDF) with AHSS. These simulations demonstrated the effectiveness of this forming process while capturing the mechanical behaviours of AHSS. The numerical modelling and simulations serve as Computer Aided Engineering (CAE) tools which determined tool geometries and control unwanted spring back. An automotive martensitic steel DOCOL 1400M from SAAB was adopted for this research as a typical AHSS material, which has a yielding strength of 1,150 MPa and a tensile strength of 1400-1600 MPa. There were three case studies involved (a) Case Study – 1: Forming AHSS 60° section; (b) Case Study – 2: Forming AHSS 90° section; and (c) Case Study – 3: Forming top-hat section. All three cases were conducted to achieve desired profiles in minimum number of passes without defects. Validation and verification of the CDF process were further demonstrated based on these case studies. According to the numerical and experimental results obtained, Chain-die Forming (CDF) can be considered as an affordable, sustainable and environmental friendly manufacturing process.

Keywords: Chain-die Forming, Advanced High Strength Steel, Channel Section Forming, and Optimal Design.

1. Introduction

There is a high demand for the automotive industry to manufacture light, fuel efficient, and safe vehicles by using new grade steels that are strong, affordable and recyclable. As a result, steel manufacturers continuously develop high strength materials, such as Advanced High Strength Steels (AHSS) and Ultra High Strength Steels (AHSS), with high tensile strengths greater than 700 MPa. However, these high strength materials are difficult to form using cold forming technologies such as roll forming and deep drawing because of their low ductility.
As an alternative, the incremental cold forming process – Chain-die Forming (CDF) was recently developed to form AHSS/UHSS materials. Chain-die Forming (CDF) is a linear incremental sheet metal forming process which is a combination of roll forming and bending. The primary advantage of this process is the elongated deformation length increases the effective radius for the die set or punch segments [1]. The outer and inner shapes of the desired profile geometry were machined into the split die and punch segments, which are similar to the U bending tooling [2]. The dies and punch segments were assembled to chain links and were simulated on a guided track board with a large radius in real-time CDF with ellipse interpolation as shown in Figs. 1(a) and 1(b) [3]. Having a large radius reduces the redundant strain on the material, minimising the defects and improving the quality of final products [4,5]. The roll radius of the CDF assembly has a wide range, for example, a 100:1 ratio in radius compared to cold roll forming [5,6]. The very large effective forming radius of the CDF process enables less residual stress, negligible redundant strain and avoids end flaring. As a result, it avoids defects such as end flaring, wrinkles and cracks at the corners [7,8].

![Chain-drive diagram]

**Figure 1.** (a) Chain-die former and (b) CAD Model of Chain-Die Forming

### 2. Finite Element-based Optimal Design of CDF Die-punch Segments for AHSS

A four-step finite element-based optimal design process was established to perform the design of CDF Die-punch segments with only one pass for AHSS. In Step 1, an analytical design analysis of the existing 2nd generation Chain-die Former was conducted to determine the geometric and dynamic features of die-punch via developing a CAD model and its motion analysis with the commonly-used CAD software package – SolidWorks. Standard tensile testing was conducted in Step 2 to determine material properties and mechanical behaviours of AHSS/UHSS samples of research interests as input data to define the material model for AHSS/UHSS in the devised finite element model of the Chain-die Forming process next step. Step 3 was then carried out to develop a series of three-dimensional (3D) finite element models for the dynamic analysis and simulation of CDF processes of three typical AHSS channel sections for an enhanced understanding of each case. These three channel section picked up in this research are (a) 60° AHSS section; (b) 90° AHSS section; and (c) Top-hat AHSS section. In the last step – Step 4, an iterative design process was executed to focus on optimising the die-punch set for forming three section profiles with only one pass via parametric studies. As a result of numerous case studies, the correct profile geometries of die and punch were achieved and validated via comparing to the desirable channel section profiles. Meanwhile the experimental studies of 60° AHSS section, 90° AHSS section and Top-hat section are under development to obtain the data for validation and verification by using the die and punch segments optimally designed. In the following three sections, three case studies for are conducted to show how the CDF is utilised to form the AHSS sections with only one pass.
3. Case Study 1: Forming 60° AHSS Section

A 3D finite element model was devised to form the 60° section by single pass using the exact process in Chain-die Forming. The primary purpose of this modelling is to study the CDF process to capture data such as stress, strain, spring back and dimensional accuracy of the profile when forming AHSS. The assembly of the split die and punch segments were simulated similar to a CDF with a forming lead radius of 150 mm and effective forming radius of 20 meters. The interaction property; surface to surface contact with penalty contact method for all twenty-four segments and contact property tangential behavior; with friction penalty coefficient of 0.3. The mesh C3D8R elements were again used to conduct the meshing of the blank material. The channel and die-set geometry shown in below Figs. 2(a) and 2(b) were for reference only. Initially, the dies and punch segments were simulated appropriately as the blank progressively formed the shape as shown below in Fig. 2(c). A material model to define the AHSS’s elastoplastic behaviours was created using the experimental data obtained from a standard tensile testing of AHSS DOCOL 1400M, and the main parameters listed in Table 1 was also implemented into all case studies.

![Figure 2](image)

**Table 1: Main parameters of FE Models of CDF**

| Parameter                  | Value                                      |
|----------------------------|--------------------------------------------|
| Material Model             | Isotropic, elastic-plastic, and strain hardening |
| Young’s modulus (E)        | 230 GPa                                    |
| Poisson’s ratio (ν)        | 0.30                                       |
| Step type                  | Dynamic, Explicit                          |
| Blank thickness (t)        | 1 mm                                       |
| Blank width (w)            | 90 mm                                      |
| Blank length (L)           | 1,200 mm                                   |
| Rolls property             | Rigid bodies                               |
| Mesh Global Size           | 3                                          |

The simulations were carried out using Abaqus/Explicit, and the geometric design of the split dies and punch segments were conducted according to on the obtained numerical result. By using the optimal die and punch segments, the final formed shape was extracted from the 3D FE formed channel as shown in Fig. 3 (a). The U-channel had no defects as it was flat, no end flaring, and the measured spring back was 0.5°. Path analysis was also conducted at three cross sections as shown in Fig. 3(b): the front, middle and end of the formed channel and the maximum strain measured along cross sections was found around 0.025 as illustrated in Fig. 3 (c). The study clearly showed that it was possible to form the 60° Channel of High Strength Steels with a tensile strength of 1500 MPa for AHSS by one pass using the Chain-die Forming process [2].
Figure 3 (a) Deformed 60° AHSS Channel; (b) Cross section profile; and (c) Strain results at Front, Mid, and End cross sections.

4. Case Study 2: Forming 90° AHSS Section

This study focused on simulating the CDF of AHSS to devise an optimal solution for forming a 90° U-channel in one single pass by developing an exact finite element model and constructing a reliable process for it. An FE model was also developed to form the 90° section based on the existing 2nd generation Chain-die Former with die and punch segments. Numerical simulations were then performed with the newly developed CDF model with a lead radius of 125 mm and a forming radius of 20 meters as shown in Fig. 4(a). The die and punch segments were interpolated similar to an ellipse shape as shown in Fig. 4(b).

Figure 4: (a) FE model of 90° U-channel; and (b) Models of punch and die segments

The final formed shape was extracted from the 3D FE channel as shown in Fig. 5(a). The U-channel has no defects as it is flat, no wrinkle on web, and the measured spring back was 1.35° on the cross section Fig. 5(b). Path analysis was also conducted on two cross sections: the front and end of the deformed channel and the strain measured along cross sections was found around 0.02 as illustrated in Fig. 5(c) [3].

Figure 5: (a) Formed U-channel; (b) Cross section; and (c) Strain distributions
5. Case Study 3: Forming Top-hat AHSS Section

This numerical study focused on simulating the CDF of AHSS to devise an optimal solution for forming a top-hat section with only one pass by developing an exact finite element model to construct a reliable manufacturing process. The die and punch set was designed to form the target top-hat section at an angle of 120°, a top width of 30 mm and a web of 15 mm per side as shown in Fig. 6(a). The numerical model was designed to have in total eight sets of die and punch segments as shown Figs. 6(b) and 6(c).

![Figure 6: (a) The top-hat section; (b) Die and punch set; and (c) 3D FE model of die and punch segments](image)

As a result of an iterative optimisation process, the correct profile geometry was finally achieved with the optimised die and punch segments as shown in Fig. 7. The final formed shape was extracted from the 3D FEA of the top-hat section as shown in Fig. 8. It shows that the profile has no defect as it is flat and minimum spring back was observed. When comparing to the desired profile, the formed cross-section was very close to final shape as illustrated in Fig. 9 [9].

![Figure 7: Formed top-hat section Logarithmic Strain](image)

![Figure 8: Cross section profile Logarithmic Strain](image)

![Figure 9: Comparison of profile shapes](image)
6. Concluding Remarks

The following conclusions could be drawn for the Chain-die Forming of AHSS according to the numerical results obtained from the numerical simulations of three case studies of 60° AHSS section, 90° AHSS section and Top-hat section using CDF:

- For all the three cases, the Chain-die Forming process with optimally-designed die-punch set is able to form profiles of AHSS sections in only one pass.
- The numerical results also show that it is true that large roll radius has a less residual stress on a profile and a very low stress or strain on formed AHSS channel sections.
- The die and punch set with a compensation design could be effectively control the unwanted springback due to the high strength of AHSS to achieve the expected channel section profiles.

Currently the optimally designed die and punch segments are being manufactured based on the research findings extracted from these numerical studies. The experimental work will be performed in the very near future for forming 60° channel, 90° channel and Top-hat section of the AHSS DOCOL 1400M from SAAB by a single pass using CDF process.

Acknowledgments

The authors would like to show their gratitude to the financial support on this research via Western Sydney University Partnership Program from Western Sydney University and the SNS UniCorp, Australia. They also would like to thank SSAB, Sweden for providing the blank material of Ultra High Strength Steel DOCOL 1400M.

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