Springback characteristics of a martensitic steel for warm U-shape bending: Experiments and FE simulation

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Abstract. Martensitic (MS) steel, a modern type of Ultra-high Strength Steel (UHSS), offers a significantly improved strength-to-weight ratio compared to conventional cold rolled steel grades. This is especially important for weight saving applications on crash-relevant automotive structures. However, it is challenging to conventionally cold form MS steel sheet into complex components due to the lower formability and excessive springback. In this present work, both experimental and finite element simulation methods have been used to investigate the springback characteristics of MS steel in U-shape bending at cold and warm stamping conditions. It was found that the amount of springback is greatly reduced by approximately 62.3% at elevated temperature compared to cold forming. Fast forming speeds were also found to be beneficial for reducing the springback. FE models were successfully developed for the U-shape forming process and close agreement between experimental data and FE simulation results has been achieved.

1. Introduction
With increasing demands to reduce the fuel consumption with a contemporaneous improvement of the crashworthiness performance, there is a great need to reduce the weight of vehicles [1]. One of the most effective ways to achieve weight reduction is to use materials with a high strength/weight ratio. Ultra-high Strength Steel (UHSS), a new generation of alloys such as martensitic (MS), dual-phase (DP), complex-phase (CP) and transformation induced plasticity (TRIP) steels, have been increasingly used in the automotive industry which can provide superior strength and ductility properties compared to conventional steels. In recent years, cold forming was able to form UHSS sheets with an ultimate tensile strength (UTS) up to 1180MPa level. However, cold forming UHSS sheets in complex geometric shapes are difficult due to the excessive springback and reduced formability at room temperature compared to conventional steels, which limited their further application. To improve strength-ductility combinations of such materials, an efficient and economical sheet metal forming technique is required. Forming techniques such as hot or warm stamping are preferable solutions for forming high-strength parts from steel sheets [2].

Previous research has claimed that hot and warm stamping processes for UHSS are preferable methods to form UHSS with minimized springback [3-5]. In recent years, special attention has been paid on the accurate springback prediction in such forming technologies which is essential for tool
design and reducing the tool refining cost [6]. Finite element analysis (FEA) is an economical and effective method for springback prediction, with commercial FE simulation software such as PAMSTAMP and Autoform used to model forming processes and identify physical parameters that are sensitive to springback [7, 8]. Extensive studies have been also carried out on the basic springback characteristics of high strength steels in warm and hot stamping processes numerically and experimentally. V and U-shaped bending of 980MPa strengthened steel sheets have been used to investigate the springback at various conditions followed by a numerical analysis using the analytical material model to determine the effects of stress relaxation and unloading creep [6]. The springback evaluation of DP980 steel was conducted on S-rail part geometry at different forming parameters, such as forming temperatures and bending speeds, and FE simulations have shown accurate estimations of springback [9].

There has been a particular interest in the study of MS steel, as it is especially appropriate for weight saving applications for crash-relevant automotive components such as bumper beams and door intrusion beams. MS steel normally consists of fully martensitic microstructures and sometimes with low traces of ferrite, which offers a significantly improved strength-to-weight ratio compared to conventional cold rolled steels grades. Currently, roll forming, bending or crash forming are typical manufacturing operations to produce MS components with an ultimate tensile strength up to 1700MPa. However, considerable springback after cold forming limits its wider applications. There are few detailed studies available reporting on the warm stamping of MS steels, which has the potential to improve the formability and minimize the springback sufficiently.

In this present research, both experimental methods and FE simulations were investigated in terms of springback characteristics of MS steels in U-shape bending under warm stamping conditions. The effects of the forming temperatures and forming speeds have been experimentally studied by forming U-shaped demonstrator components. The setup of FE models is developed using PAM-STAMP and the results were experimentally verified according to the proposed warm stamping process.

2. Materials and experiment details

2.1. Materials

The as-received material used in this research is the hot rolled multiphase martensitic grade (MS-W900Y1180T) developed by ThyssenKrupp Steel, with a UTS of 1180 MPa. Its chemical composition (wt. %) is given in Table 1.

MS steel is characterized by a martensitic matrix sometimes containing a small fraction of ferrite or bainite. The high volume fraction of martensite offers superior strength and hardness. The material used for the study was as-received MS steel with a thickness of 1.6mm exhibits 930MPa yield strength, 1220MPa tensile strength and elongation of approximately 5%. Microhardness of samples were tested using a Vickers indenter with a load of 1 kg and the mean hardness value of the as-received material was approximately 400Hv.

| Type of steel | C  | Mn  | Si  | P  | S  | B  | Al  | Cr  |
|---------------|----|-----|-----|----|----|----|-----|-----|
| MS-W900Y1180T | 0.25 | 2.50 | 0.80 | 0.06 | 0.015 | 0.005 | 0.015 | 1.20 |

2.2. Experimental set-up and procedure

In order to study the effect of process parameters such as temperatures and forming speeds, the U-shaped warm stamping tool set was initially designed and fabricated, and assembled on a dedicated lab-scale pilot production line named Uni-form [11]. The Uni-form system comprises of a contact heating facility, an automated conveyer system, and high rate stamping tool set on a 100 tonnes hydraulic press. The schematic diagram of stamping tool set with important dimensions for U-shape bending tests is shown
Two critical angles are defined to characterise the springback of formed components, as shown in Figure 1 (b). The angle \( \theta_1 \) is measured between the vertical line and the tangential line of the sidewall that represented the side wall deflection. The angle \( \theta_2 \) is measured between the horizontal line and flange extensional line representing the flange springback.

In the production line, U-shape bending experiments were conducted at room temperature and elevated temperatures ranging from 350 to 500°C. Three inserted thermocouples were used to provide temperature feedback of the blank at different positions. The cold blank was initially placed between stamping die and punch. The automatic conveyor system transported the cold blank to the furnace and heated it up to the target temperature. Then the warm blank was transferred to stamping tools via conveyor system within a pre-determined period of time. Afterwards, the blank was formed and simultaneously quenched within the cold die followed by 5s in-die quenching at a constant die closing force of 170 kN.

![Plan of symmetry](image1) ![Axis of symmetry](image2)

**Figure 1.** (a) Schematic diagram of U-shaped components stamping tool set (b) demonstration of two critical angles to quantify springback.

### 3. FE simulation setup
To effectively predict springback, FE models were developed in FE software PAM-STAMP for the U-shape bending process. The material properties of 1.6mm MS steel blank such as the flow behaviour of the MS steels at different temperatures (25, 300, 350, 400 and 450°C) and at various strain rates (0.01, 0.1 and 1s\(^{-1}\)) were utilised as input data, which were characterised from uni-axial tensile tests via a thermo-mechanical simulator Gleeble 3800. Figure 2 shows the flow-stress curve of MS steel at different temperatures and strain rates. The other input parameters utilized based on the experiments are provided in Table 2. The material’s properties of MS steel blank used in this FE analysis were given in Table 3.

The simulation process was divided into four stages; holding, stamping, quenching and springback measurement, as shown in Figure 3. The stamping tools were defined to be rigid parts as tool distortion during the whole process was negligible. The tool geometries are all symmetrical thus only half of the component was simulated via a symmetry plane condition. In the holding stages, the blankholder is placed on the top of the blank and provides a constant blank holding force of 5kN. Afterwards, the punch moved towards with the blank at the selected forming speed, continuously drawing the blank into the die. The formed components were subsequently quenched within the cold tools for 5s at a constant die closing force. In the springback measurement stage, the geometry of formed components was scanned for further precise evaluation of springback angles.
Table 2. FE model parameters for U-shaped forming tests.

| Forming parameters                      | Value          |
|------------------------------------------|----------------|
| Initial tool temperature (°C)            | 20             |
| Forming temperature (°C)                 | 20, 300, 350, 400, 450 |
| Forming speed (mm/s)                     | 50, 150, 250, 380 |
| Blank-holding force (kN)                 |                |
| Die closing force (kN)                   | 170            |
| Quenching time (s)                       | 5              |
| Friction coefficient                     | 0.2            |
| Lubricant                                | Omega-35       |

Table 3. Material properties of MS steel blank [12].

| Property                              | Temperature (°C) |
|---------------------------------------|------------------|
|                                       | 25               | 300               | 350               | 400               | 450               |
| Young’s modulus (GPa)                 | 210.0            | 185.6             | 169.8             | 160.3             | 148.7             |
| Thermal conductivity (W/(m·K))        | 24.5             | 27.9              | 28.0              | 28.1              | 28.2              |
| Poisson’s ratio                       | 0.3              |
| Dissipation factor                    | 0.9              |

Figure 2. Flow stress-strain curves for MS steel specimens tested at various temperatures and at 450°C for various strain rates.

Figure 3. Schematic diagram of the FE model setup and springback measurement.

4. Results and discussion

4.1. Effects of stamping temperature on springback of U-shaped components under warm stamping conditions
Figure 4 illustrates the effect of stamping temperature on springback angle of formed MS steel components by warm stamping and cold stamping. It can be seen that the extent of springback decreased significantly as temperature was increased from room temperature to 300°C and was subsequently followed by a linearly drop as the stamping temperature was increased above 300 °C. The magnitude of springback angle $\theta_1$ dramatically decreased by 60.7 % from 8.36° to 3.28° as the stamping temperature was increased from 25 to 400 °C. The springback angle $\theta_2$ showed similar tendency by decreasing approximately 62.3% over the same temperature range compared to the springback angle $\theta_1$. The primary reason for springback reduction is the lower residual stress at elevated temperatures. When the blank was formed at room temperature, the high strength and material draw-in from the blank holding area leads to a significant springback. At elevated temperatures, the reduction of flow stress is considerable, subsequently reducing material draw-in and increasing the tensile deformation. The FE simulation results showed a good agreement in comparison with experimental results at reasonable errors of 5.1%. It can be concluded that the warm stamping for MS steel is an effective method in reducing springback.

4.2. Effects of forming speed on springback of U-shaped components under warm stamping conditions

Figure 5 shows the experimental and simulated results on the effect of forming speeds (75, 150, 250, 380 mm/s) on springback at a stamping temperature of 400°C. The results achieved of both springback angles showed a similar trend where increasing the forming speed initially leads to a steady reduction of springback angle, after which the amount of springback remains nearly constant and is hence unaffected by forming speed. The improvement to reducing springback angles $\theta_1$ and $\theta_2$ when increasing forming speed from 75 to 380 mm/s is 20.9% and 38.6% respectively. Figure 5 also shows a close correlation between experimental springback and springback determined from FE simulations with an errors of approximately 6.1%. This springback reduction with speed phenomenon can be explained by the difference of the tangential stress in the top and bottom surfaces of the blank after forming [13]. A smaller through-thickness stress gradient normally accompanied with lower level of springback [14]. Higher forming speeds induced higher tensile stress in both top and bottom surfaces resulted in lower through-thickness stress gradient of the formed parts and thus springback was decreased. Additionally, the fast quenching rate and slightly higher stamping temperature at faster forming speed were beneficial for reducing springback.
5. Conclusions
In the present study, springback characteristics of MS steels were successfully investigated via U-shaped bending tests at warm stamping conditions. The result shows that the parameters such as forming temperatures and forming speed have a significant effect on the springback. The springback angles $\theta_1$ and $\theta_2$ were reduced markedly by approximately 60.7% and 62.3% respectively utilising warm stamping process compared to conventional cold forming. It is also observed that the higher forming speed was found to be beneficial for reducing the springback. FE model was developed using PAM-STAMP to predict the springback of the formed U-shaped components at selected parameters with a good agreement achieved between the experimental and FE simulation results.

References
[1] Merklein M and Lechler J 2006 Investigation of the thermo-mechanical properties of hot stamping steels J. Mater. Process. Tech. 177 452-5
[2] Mu Y, Zhou J, Wang B, Wang Q, Ghiotti A and Bruschi S 2018 Numerical simulation of hot stamping by partition heating based on advanced constitutive modelling of 22MnB5 behaviour Finite. Elem. Anal. Des. 147 34-44
[3] Mori K, Maki S and Tanaka Y 2005 Warm and hot stamping of ultra high tensile strength steel sheets using resistance heating CIRP Annals-Manufacturing Technology 54 209-12
[4] Yanagimoto J, Oyamada K and Nakagawa T 2005 Springback of High-Strength Steel after Hot and Warm Sheet Formings CIRP Annals 54 213-6
[5] Karbasian H and Tekkaya A E 2010 A review on hot stamping J. Mater. Process. Tech. 210 2103-18
[6] Saito N, Fukahori M, Minote T, Funakawa Y, Hisano D, Hamasaki H and Yoshida F 2018 Elastoviscoplastic behavior of 980 MPa nano-precipitation strengthened steel sheet at elevated temperatures and springback in warm bending Int. J. Mech. SCI. 146-147 571-82
[7] Papeleux L and Ponthot J-P 2002 Finite element simulation of springback in sheet metal forming J. Mater. Process. Tech. 125-126 785-91
[8] Biradar A and Deshpande M D 2014 Finite Element Analysis of Springback of a Sheet Metal in Wipe Bending Process Int. J. Sci. Res Volume 3 852-8
[9] Wang Z, Hu Q, Yan J and Chen J 2017 Springback prediction and compensation for the third generation of UHSS stamping based on a new kinematic hardening model and inertia relief approach Int. J. Adv. Manuf. Technol. 90 875-85
[10] Thyssenkrupp 2018 Steel MS-W Product information for martensitic-phase steels 1-8
[11] Luan X, Zhang O, El Fakir O, Wang L and Gharbi M M 2017 A Pilot Production Line for Hot/Warm Sheet Metal Forming Integrated in a Cloud Based SMARTFORMING Platform Advanced High Strength Steel and Press Hardening 492-7
[12] Huang Q, Li C, Li Y, Chen M, Zhang M, Peng L, Zhu Z, Song Y and Gao S 2007 Progress in development of China Low Activation Martensitic steel for fusion application Journal of Nuclear Materials 367-370 142-6
[13] Wang A, Zhong K, El Fakir O, Liu J, Sun C, Wang L, Lin J and Dean T A 2017 Springback analysis of AA5754 after hot stamping: experiments and FE modelling Int. J. Adv. Manuf. Technol. 89 1339-52
[14] Oliveira M C, Alves J L, Chaparro B M and Menezes L F 2007 Study on the influence of work-hardening modeling in springback prediction International Journal of Plasticity 23 516-43