Experimental, Statistical, and Analytical Evaluation of The Springback Behavior of Martensitic 1400 Sheet in V-Bending

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Abstract

Ultra-high-strength Martensitic 1400 steel is preferred in the automotive industry because of its high strength as well as its light weight. In this study, Martensitic 1400 steel was subjected to the V-bending process. As a result of 48 different tests, the amount of springback resulting from the V-bending process was determined. A finite element (FE) model was then created based on these experimental data. After it was determined that the experimental results concurred with the FE model, without performing new experiments, further analyses were carried out at different temperatures. Using the results of a total of 96 FE analyses, variance analysis was performed and the effects of the operation parameters on springback were determined. As a result of the study, it was concluded that the most effective parameter on springback in the V-bending process was the die angle and that holding time had no significant effect. It was observed that the springback increased in parallel with the punch radius and die angle and that increases in temperature reduced the springback.

1. Introduction

In the automotive industry sheet metal is generally used after plastic deformation and forming. The chassis and most of the parts used in the vehicles are made of metal. This indicates that metal parts make up the majority of the weight of the vehicles. The current fuel-saving strategy emphasizes the use of light but durable materials. Consequently, the use of martensitic sheets in the automotive industry is becoming widespread. The most important features of these sheets are high strength and light weight. These materials increase the safety of the vehicles and can save lives in the event of an accident. They also lower fuel consumption and carbon emission [1].

Studies have been carried out on the forming of martensitic sheets, but when the literature is examined, these studies are seen to be limited. Among the researchers working on this subject, Xie et al. applied the V-bending process to AZ31B magnesium alloy sheet and investigated the influence of direct-current pulses on springback. They determined that when grain size and the number of twinning crystals decreased, springback decreased as well [2]. Park et al. combined martensitic steel sheet with polymer material as a laminate and produced a new material with high strength (500 MPa). They subjected it to the V-bending test and examined the delamination mechanism formed during the bending process [3].

Springback is caused by the elastic behavior of the material. In the metal forming process, springback error is defined as the deformation that occurs in the geometry when the force on the part is removed [1, 4]. Reducing this defect is of great industrial importance. For this reason, many studies have been aimed at understanding and reducing springback. Springback can occur in all bending methods: tube bending [5, 6], L-bending [7–9], U-bending [10, 11], press bending [12, 13], V-bending [14, 15], air bending [16, 17].

In this study, experimental, statistical, and analytical investigations were performed on the springback behavior in the V-bending process. A total of 48 different experiments were conducted and the amount of springback of the samples was determined via a 3D coordinate-measuring machine (CMM). A finite element (FE) model of the bending process was then created using Simufact Forming V16 software. Using the experimental sets and the same parameters, 48 different analyses were performed. The analysis results were found to concur with the experimental results. Without the need for new experiments, 48 more FE analyses
were then conducted using different temperature values. Consequently, a variance analysis (ANOVA) was performed using the 96 analysis results obtained, and the effects of the experimental parameters on springback were determined.

2. Material And Methods

2.1. Material

In the experiments of this study, Martensitic 1400 sheet with a thickness of 1.5 mm was formed by bending in a V shape. Samples were prepared in 40 × 40 mm dimensions using guillotine shears. The chemical composition and stress-strain curves of the material are given in Fig. 1. Its strength perpendicular to the rolling mill was 1441.8 MPa. Information on its strength in the other directions can be seen in the figure. Tensile tests were carried out using a 100 kN UTEST flexure testing machine. Spectral analysis was performed using the GNR Metal Lab Plus spectrometer.

2.2. Method

Experimental studies were carried out at two different temperatures: room temperature (22 °C) and 300 °C. Samples were heated by adjusting the proportional-integral-derivative (PID) temperature control panel (± 1 °C temperature sensitivity) on the experimental setup. Temperature control was provided using the thermocouple on the resistor rod. The sheets were heated on the die by this heating system (Fig. 2). Only local heating was applied [18]. The warm forming process is often used to reduce springback in metal forming [19, 20]. The sheet was formed immediately after it was heated without removing the die.

In the literature, holding time has also been examined as a parameter in V-bending [21–23]. Holding time is when the punch waits for a certain period of time on the die before withdrawing after pressing the sheet metal. At the end of the forming process, two different periods were determined for holding time: 0 s and 10 s.

Four die angles (30 °, 60 °, 90 °, and 120 °) were used to determine the effects of different die angles. For each angle, 2, 4, and 6-mm tip radii were used. The experimental setup and dies used in the study are shown in Fig. 3, with R referring to the punch tip radius. The bending angle is given in Eq. (1), where α is the die angle.

\[
Bending \ angle = \frac{180 - \alpha}{2}
\]  

(1)

A total of 48 bending tests were conducted within the scope of the study. The experimental parameters used in these experiments are given in Table 1. The first 24 experiments were conducted at room temperature. The next 24 experiments were carried out at 300 °C, with the first 24 test sequences and the following 24 test sequences being identical except for the temperature parameter, i.e., Experiment No. 2 and Experiment No. 26 were the same except for the temperature. This was also the case for the other experiments.

At the end of the experiments, the springback values of each sample were measured using a Hexagon CMM (Fig. 4). Figure 4a and 4b show images of the measurement process. The samples were attached to the CMM base with a special paste. Then, as shown in Fig. 4c, via contact points on the two different planes created by
the surfaces of the samples, the angle read by the CMM device and recorded. The difference between the measured angle of the sample and the intended angle indicated the amount of springback.

### 2.3. Finite element analysis

Finite element (FE) analyses were made using the experimental sets given in Table 1. Finite element analysis was performed via the Simufact Forming V16 program. In the analysis, the die and punch were defined as rigid and the sheet as elastoplastic. The values obtained from the previous tensile test were established as the material model. A 0.621-mm hexahedral mesh was generated for the sheet using a total of 12,288 elements. The thickness of the sheet was divided into three parts to increase the accuracy of the calculation. Views of the FE analysis during bending simulation and the measuring of springback are given in Fig. 5.

As described in the next section, 48 FE analyses were performed with 48 experimental sets using the same parameters (room temperature and 300 °C). Later, it was seen that the experimental results and the analysis results concurred. Finite element analyses for higher temperatures were then carried out without further experiments. In the experimental set given in Table 1, a total of 48 more analyses were performed using 400 °C instead of 22 °C and 500 °C instead of 300 °C, using the other parameters as given in the aforementioned table. Thus, a total of 96 different analyses were carried out.

### 3. Results And Discussion

#### 3.1. Experimental and FE analyses

From a total of 24 experiments at room temperature, the amount of springback in the samples was measured using a CMM device. The springback values obtained from the results of the experimental measurements and FE analysis are given in Fig. 6. The graph clearly shows that in the experiments at room temperature, springback increased in parallel with the die angle. The results of the springback measurement are given in the last column of Table 1. According to the table, the least springback occurred in Experiment No. 38. In this experiment, 300 °C temperature, 90 ° die angle, 2-mm punch radius, and 10-s holding time were used.
| Experiment No | Temperature (°C) | Die angle (°) | Punch Radius (mm) | Holding Time (s) | Springback (°) |
|---------------|------------------|---------------|-------------------|------------------|----------------|
| 1             | 22               | 30            | 2                 | 0                | 5.234          |
| 2             | 22               | 30            | 2                 | 10               | 4.139          |
| 3             | 22               | 30            | 4                 | 0                | 5.694          |
| 4             | 22               | 30            | 4                 | 10               | 6.052          |
| 5             | 22               | 30            | 6                 | 0                | 6.626          |
| 6             | 22               | 30            | 6                 | 10               | 5.616          |
| 7             | 22               | 60            | 2                 | 0                | 3.859          |
| 8             | 22               | 60            | 2                 | 10               | 3.175          |
| 9             | 22               | 60            | 4                 | 0                | 7.095          |
| 10            | 22               | 60            | 4                 | 10               | 6.708          |
| 11            | 22               | 60            | 6                 | 0                | 8.978          |
| 12            | 22               | 60            | 6                 | 10               | 8.885          |
| 13            | 22               | 90            | 2                 | 0                | 6.915          |
| 14            | 22               | 90            | 2                 | 10               | 6.557          |
| 15            | 22               | 90            | 4                 | 0                | 8.906          |
| 16            | 22               | 90            | 4                 | 10               | 9.259          |
| 17            | 22               | 90            | 6                 | 0                | 11.420         |
| 18            | 22               | 90            | 6                 | 10               | 10.845         |
| 19            | 22               | 120           | 2                 | 0                | 8.959          |
| 20            | 22               | 120           | 2                 | 10               | 7.397          |
| 21            | 22               | 120           | 4                 | 0                | 10.652         |
| 22            | 22               | 120           | 4                 | 10               | 11.034         |
| 23            | 22               | 120           | 6                 | 0                | 14.533         |
| 24            | 22               | 120           | 6                 | 10               | 13.583         |
| 25            | 300              | 30            | 2                 | 0                | 4.898          |
| 26            | 300              | 30            | 2                 | 10               | 5.431          |
| 27            | 300              | 30            | 4                 | 0                | 5.637          |
| Experiment No | Temperature (°C) | Die angle (°) | Punch Radius (mm) | Holding Time (s) | Springback (°) |
|---------------|------------------|--------------|------------------|------------------|----------------|
| 28            | 300              | 30           | 4                | 10               | 6.180          |
| 29            | 300              | 30           | 6                | 0                | 7.038          |
| 30            | 300              | 30           | 6                | 10               | 7.212          |
| 31            | 300              | 60           | 2                | 0                | 3.412          |
| 32            | 300              | 60           | 2                | 10               | 3.747          |
| 33            | 300              | 60           | 4                | 0                | 7.126          |
| 34            | 300              | 60           | 4                | 10               | 7.744          |
| 35            | 300              | 60           | 6                | 0                | 8.551          |
| 36            | 300              | 60           | 6                | 10               | 9.521          |
| 37            | 300              | 90           | 2                | 0                | 2.019          |
| 38            | 300              | 90           | 2                | 10               | 1.678          |
| 39            | 300              | 90           | 4                | 0                | 9.161          |
| 40            | 300              | 90           | 4                | 10               | 9.370          |
| 41            | 300              | 90           | 6                | 0                | 11.159         |
| 42            | 300              | 90           | 6                | 10               | 11.248         |
| 43            | 300              | 120          | 2                | 0                | 2.113          |
| 44            | 300              | 120          | 2                | 10               | 2.373          |
| 45            | 300              | 120          | 4                | 0                | 10.732         |
| 46            | 300              | 120          | 4                | 10               | 11.305         |
| 47            | 300              | 120          | 6                | 0                | 14.390         |
| 48            | 300              | 120          | 6                | 10               | 14.441         |

Experiments were carried out at room temperature (22 °C) and 300 °C. A total of 48 different FE analyses were then conducted according to both room temperature and 300 °C. After the analysis results were found to be compatible with the experimental results, FE analyses were performed using the same FE models and changing only the temperatures to 400 °C and 500 °C. The correspondence of analysis results with experimental studies without the need for retesting is very important in terms of cost reduction and saving time. Therefore, for 400 °C and 500 °C, only FE analysis was performed, without further experiments. Results of the FE analysis are given in Fig. 7.

The figure shows that the amount of springback increased in parallel with the die angle. Here, the importance of the die angle is revealed. During the bending process, compressive stress occurs on the surface of the part.
in contact with the forming tool, while tensile stress occurs on the surface of the part in contact with the die. This unbalanced stress distribution on the part is the main factor that creates springback [24]. Increasing the die angle increases the bending moment. Therefore, it was concluded that the springback increased as a result of the expanding angle of the die.

When the experimental groups were considered separately, less springback was observed at 500 °C. The reason for this might have been that the increase in temperature had homogenized the stress distribution mentioned above [25].

Negative springback occurred in the experiments using 30 ° and 60 ° die angles at 500 °C temperature. This was attributed to the use of a small radius. Especially in Experiments No. 13 and 14, less springback was observed in the same group compared to the experiments having the same parameters except for the die radius. There was a similar situation with Experiments No. 19 and 20. The small radius of the die reduced the bending moment and this had a positive effect on springback.

3.2. Variance analysis (ANOVA)

In this study, a total of 96 different FE analyses were made. Using the results of these analyses, an analysis of variance (ANOVA) was performed to determine the effects of the experimental parameters on springback. The ANOVA results are given in Table 2. According to the ANOVA, the die angle (29.73%) was the most effective parameter for springback in V-bending, followed by the temperature (25.23%), and the punch radius (19.14%). When compared with these three parameters, the holding time did not have a significant effect on springback.
Table 2
Variance analysis of finite element analysis results

| Source                        | DF | Seq SS   | Contribution | Adj SS  | Adj MS  | F-Value | P-Value |
|-------------------------------|----|----------|--------------|---------|---------|---------|---------|
| Model                         | 13 | 843.201  | 84.36%       | 843.201 | 64.862  | 34.01   | 0.000000|
| Linear                        | 4  | 747.060  | 74.74%       | 737.577 | 184.394 | 96.69   | 0.000000|
| Temperature                   | 1  | 252.239  | 25.23%       | 250.770 | 250.770 | 131.50  | 0.000000|
| Die Angle                     | 1  | 297.218  | 29.73%       | 292.679 | 292.679 | 153.48  | 0.000000|
| Punch Radius                  | 1  | 191.303  | 19.14%       | 190.752 | 190.752 | 100.03  | 0.000000|
| Holding Time                  | 1  | 6.299    | 0.63%        | 3.377   | 3.377   | 1.77    | 0.186989|
| Square                        | 3  | 23.750   | 2.38%        | 23.750  | 7.917   | 4.15    | 0.008627|
| Temperature*Temperature       | 1  | 1.621    | 0.16%        | 1.621   | 1.621   | 0.85    | 0.359286|
| Die Angle*Die angle           | 1  | 2.577    | 0.26%        | 2.577   | 2.577   | 1.35    | 0.248378|
| Punch Radius*Punch Radius     | 1  | 19.552   | 1.96%        | 19.552  | 19.552  | 10.25   | 0.001943|
| 2-Way Interaction             | 6  | 72.391   | 7.24%        | 72.391  | 12.065  | 6.33    | 0.000017|
| Temperature*Die Angle         | 1  | 2.475    | 0.25%        | 2.475   | 2.475   | 1.30    | 0.257965|
| Temperature*Punch Radius      | 1  | 2.616    | 0.26%        | 2.616   | 2.616   | 1.37    | 0.244870|
| Temperature*Holding Time      | 1  | 6.087    | 0.61%        | 6.087   | 6.087   | 3.19    | 0.077691|
| Die Angle*Punch Radius        | 1  | 59.159   | 5.92%        | 59.159  | 59.159  | 31.02   | 0.000000|
| Die Angle*Holding Time        | 1  | 1.209    | 0.12%        | 1.209   | 1.209   | 0.63    | 0.428195|
| Punch Radius*Holding Time     | 1  | 0.844    | 0.08%        | 0.844   | 0.844   | 0.44    | 0.507721|
| Error                         | 82 | 156.374  | 15.64%       | 156.374 | 1.907   |         |         |
| Total                         | 95 | 999.575  | 100.00%      |         |         |         |         |

Contour plots of springback are given in Fig. 8. According to the die angle * temperature interaction graph, springback decreased with rising temperature, while it increased with the increase of the die angle. According to the punch radius * temperature interaction graph, springback decreased with the rise of temperature, while it increased with the increase of the punch radius. According to the punch radius * die angle interaction graph, the decreasing of both parameter values together reduced springback. When the interaction graphs of holding time were examined with the other parameters, holding time exhibited no significant effect on springback.

Conclusions
In this study, Martensitic 1400 sheet metal was processed via V-bending. Experiments were carried out at room temperature (22 °C) and 300 °C. The effects of these parameters on the amount of springback were investigated using different die angles, tip radii, and holding times. An FE model was then created using Simufact Forming V16 software and 48 different analyses were carried out using these experimental parameters. The accuracy of the model was established by determining that the experimental results and the analysis results agreed. Later, without the need for re-testing, 48 different FE analyses were performed for 400 °C and 500 °C temperatures. An ANOVA was carried out using the results of all FE analyses (96 in total), and the effects of the parameters on the V-bending process were determined. The following results were obtained in the study:

- In the V-bending process, the most effective parameter on springback was the die angle (pure contribution 29.3%).
- The springback increased in parallel with the punch radius.
- The springback increased in parallel with the die angle.
- Holding time had no significant effect on springback (pure contribution 0.63%).
- Increases in temperature decreased springback.

**Declarations**

**Authors’ Contributions**

NS has conducted the experiments and the analysis of the work. He has worked on the preparation of the die and manufacturing of it. ÖS has written the manuscript and conducted the analysis of the work together with NS.

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**Competing Interests**

The authors declare that they have no competing interests.
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