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SPRINGBACK ANALYSIS OF DP600 STEEL AFTER WARM STAMPING: EXPERIMENTAL AND FE MODELLING

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ABSTRACT

In this paper, the springack of DP600 steel was characterized under various experimental warm stamping conditions based on Numisheet 1993 benchmark problem. Simulations using the Hensel-Spittelequation for FE modelling at ABAQUS software were performed in order to compare the springback prediction to experimental results. It was found that springback effect decreases as the temperature rises.The FE modelling based on Hensel-Spittel equation was in good agreement to the experimental results with no more than 6% error for θ1 and θ2 springback parameters. Although DP600 steel was originally designed for cold work, the study of this material at different temperatures should improve control of springback of AHSS in deep drawing operations.The springback analysis can lead to a further understanding about the influence of temperature and strain rate over springback effects, avoiding extra costs of tool reworking and enhancing the process control.

Keywords: Springback, DP600, temperature

1. INTRODUCTION

Nowadays there is a major effort to produce lighter and crashworthiness automobiles and autonomous vehicles. The use of advanced high strength steels (AHSS) instead of conventional steels is a commitment to the automotive industry to manufacture vehicle parts.

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In this context AHSS have emerged as a very interesting alternative to reach these new requirements [1].

Dual-phase (DP) steels are able to lower the vehicles body weight and reduce fuel consumption and emissions. Specifically, the DP600 steel was designed to allow the weight reduction of structural components and improve safety performance [2].

The AHSS mechanical behavior can be related to the temperature and strain rate of the operation processes. Warm and hot stamping AHSS parts production requires a deep knowledge over the material behavior and parameters control of operation processes. Despite of this, sheet manufacturers normally offers mechanical properties about their materials only under quasi-static loading at room temperature [3,4, 5].

Generally, the structural components of vehicles are produced by deep drawing operations. In the U-draw operations the part material experiences stretching, bending and unbending deformations. However, there is a critical issue of DP600 steel in deep drawing operations related to the increase of springback magnitude compared to conventional steels. Springback is the elastic driven change of the shape for formed parts that results in dimensional variations and assembly difficulties, as can be seen in Figure 1. In this way, the correct prediction of springback and its control is essential for the design of forming processes and tools with no extra costs of tool reworking [6].

Figure 1. Effects of springback in U-drawbending parts. Adapted from IISI, 2006.

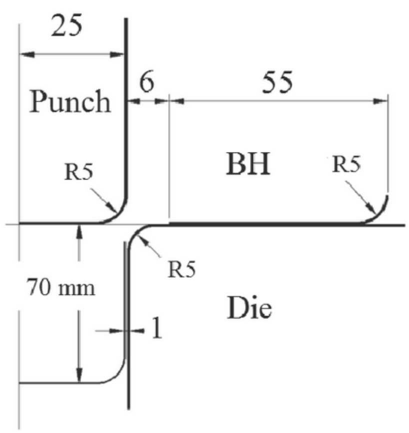


Figure 2. U-draw bending test. Numisheet 1993 benchmark.

Springback issues practically could be overcome by warm and hot stamping processes compared with that at room temperature. However, the proper design of warm and hot stamping process chain requires the deep knowledge of both interface phenomena and material behavior at different temperatures. The lack of knowledge about mechanical behavior of materials at warm and elevated temperature is the main reason of restricted application of hot stamping in industry [6, 7].

The Numisheet 1993 U-draw bending test is often used as a benchmark problem to assess springback effects under practical forming conditions. Tool dimensions are presented in Figure 2.

The stroke velocity can be used to describe strain rate. The equivalent deformation rate can be stated as a function of the machine velocity and the specimen length, as can be seen in Eq.1

$$\dot{\varepsilon} = \frac{d\varepsilon}{dt} = \frac{d}{dt}\left(\frac{l-l_0}{l_0}\right) = \frac{1}{l_0}\frac{dl}{dt} = \frac{v}{l0} \tag{1}$$

where $\dot{\varepsilon}$ is the equivalent deformation rate, ε is the equivalent true strain, v is the velocity of the machine, $l$and l_0 are the final and initial specimen length [8, 9].

In the other hand, some studies have been made in order to assess springback effects based on Finite Element (FE) modelling. Computer simulations can be used to establish relationships between the formed part and the operation parameters in order to predict the behavior of materials under several forming conditions [8, 9].

The Hensel-Spittel is one of the most complete constitutive models for flow stress curves representation. The Hensell-Spittel equation can be used to represent experimental data at strain rate and different temperatures, as can be seen in Eq. 2.

$$\sigma = Ae^{m_1 T}\varepsilon^{m_2}\dot{\varepsilon}^{m_3}e^{\frac{m_4}{\varepsilon}}(1+\ \varepsilon)^{m_5 T}e^{m_7 \varepsilon}\dot{\varepsilon}^{m_8 T}T^{m_9} \tag{2}$$

where σ is the scalar value of flow stress, ε is the equivalent true strain, $\dot{\varepsilon}$ is the equivalent deformation rate and T is the temperature [6, 10, 11].

Based on the practical approach it is possible to reduce the effects of springback with the temperature control. In this way, it seems very reasonable to undertake a set of practical experiments with different temperatures based on the Numisheet 1993 benchmark problem in order to reduce the springback. Based on the computational approach the Hensel-Spittel model can be represents the flow stress for different temperatures and strain rates. In this way, it seems very reasonable to undertake a set of simulation based on Hensel-Spittel model in order to predict the springback effects on the U-draw bending parts. Comparison of experimental resultsand simulation predictions can lead to complementary understanding of springback effectsfor DP600 steel subjected to different temperature and strain rate conditions.

There is a lack of information about the springback effects of AHSS steels at warm and hot working temperatures and different strain rates. Although DP600 steel was originally designed for cold work, the study of this material at different temperatures should improve the control of springback in deep drawing operations. Therefore, the main objective of this work was to evaluate the springback of DP600 after U-draw bending operations to different temperatures and strain rates.

2. MATERIAL AND EXPERIMENTAL PROCEDURE

Dual phase steels are one of the most commonly advanced high strength steels used for sheet forming. The present study was conducted using DP600 based samples, produced by ARCELOR MITTAL. Chemical composition of the material is shown in Table 1.

Table 1. Chemical composition (weight %)

	C	Mn	P	S	Si	Al	Ti	B
DP600	0.09	1.75	0.018	0.005	0.2	0.02	0.003	0.0005

Uniaxial tensile tests were performed using MTS 810-Flex Test 40 machine. The specimens were prepared according to ASTM E8M-03 and ASTM E21-05 standards. Yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE) and total elongation (EL) were determined. Table 2 shows the mechanical properties of DP600 at room temperature.

Table 2. Mechanical properties under quasi-static loading at room temperature

	t (mm)	YS (MPa)	UTS (MPa)	UE (%)	EL (%)
DP600	1.65	395	620	15	20

In order to assess the springbackof DP600 steel after warm stamping, there were performed a set of U-draw bending tests according to the Numisheet 1993 benchmark problem.The dimensions were the same as in Figure 2 and the punch stroke was set to 70mm. Blank holder force was set to 2.5kN and blanks were 1.65mm thick, 300 x 30mm (length x width) cut in the rolling direction. Punch and the die were at room temperature before each test. Blanks were heated to initial 30, 400 and 600°C temperatures at a furnace followed by U-draw bending tests performed at 2.5mm/s and 15mm/s stroke velocities. There was no lubricant at the blank/tool interface. After the U-draw bending test the punch and die were cooled back to the room temperature.

Table 3 describes all the units from the full factorial design for 3 temperatures and 2 stroke velocities. There were three U-draw bending parts for each unit, performing 18 specimens.

Table 3. U-draw bending experimental parameters

Unit	Temperature (^{0}C)	Strokevelocity (mm/s)
1	30	2.5
2	400	2.5
3	600	2.5
4	30	15
5	400	15
6	600	15

A thermocouple was used to monitor the temperature of the blanks inside the furnace. For each experimental unit, a set of three blanks were heated inside a high temperature furnace, preserved for 10 minutes for temperature homogenization, wrapped in a carbon blanket to prevent oxidation. One at a time, the heated specimens were transferred to the tool in the press and the forming process was carried out. Finally, a cooling system was activated to remove the heat from the tool and the specimens by circulating ice water through the punch and the die. The temperatures were monitored with a thermocouple leaning directly on the specimens.

The springbackof specimens was characterized after the experimental procedure for U-draw bending test by three parameters (θ1, θ2 and ρ) as can be seen in Figure 3. The specimens were scanned into a computer and images were analyzed via CAD software.

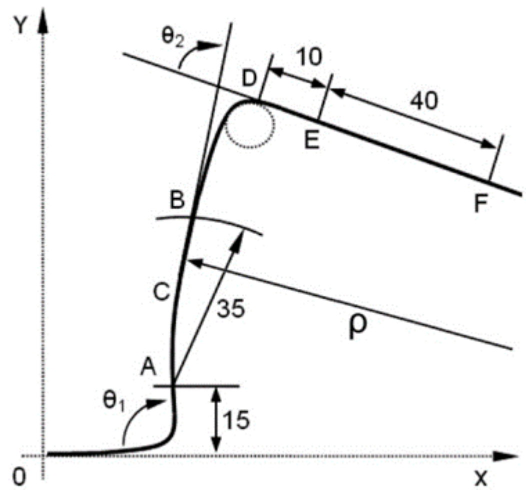


Figure 3. Springback characterization.

3. Simulation Procedure

The finite element analysis (FE) of the U-draw bending testwas performed with ABAQUS version 6.14, considering the Numisheet 1993 benchmark problem tool dimensions. Simulations were performed to 30, 400 and 600°C temperatures and 2.5mm/s and 15mm/s stroke speeds. Punch and die were modelled as analytical rigid surfaceswith invariant dimensions for simulation procedure. The blank was meshed with reduced integration shell (S4R) elements. Penalty was assumed as the contact method.

Blank dimensions were set to #1.65 mm x 150 mm x 17.5 mm. A plane strain condition was assumed and the blank holder force was set to 2.5kN. Just one quarter of the part was considered for the simulations due the symmetry of the U-draw parts. Figure 4 shows the deep drawing tool design at the computational environment.

The process was designed to four steps. First step the die shoulder push the blank toward the blank holder. Second step the blank holder applies 2.5kN force. Third step the punch push the blank 70 mm into de the die to bend the U-draw part. Fourth step all the conditions are removed, and the part is released to springback.

In this simulation, DP600 was considered as an isotropic elastic-plastic material at initial constant temperature. Poison´s ratio was set to 0.3 and the hardening law was introduced by fitting the Hensel-Spittel equation.

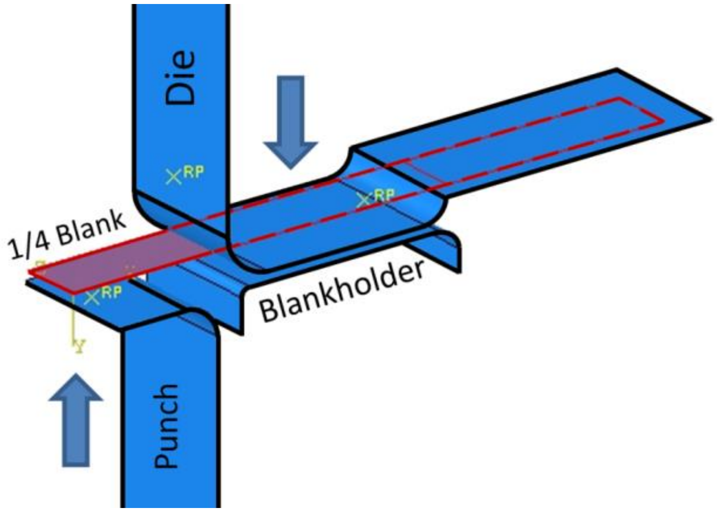


Figure 4. Tool design for U-draw bending simulation.

In order to calibrate the Hensel-Spittel equation, uniaxial tensile tests were conducted for 30, 400, 600 and 800°C at 2.5mm/s crosshead speed. Specifically for 800°C there were three different crosshead speeds of 2.5, 25 and 100mm/s. Each tensile test condition leads to a specific strain rate, obtained from the ratio between final and initial length of the specimen. The results can be seen in Table 4.

Table 4. Strain rates on different temperatures and crosshead speed

DP600	30 °C 2.5 mm/s	400°C 2.5 mm/s	600°C 2.5 mm/s	800°C 2.5 mm/s	800°C 25 mm/s	800°C 100 mm/s
$\dot{\varepsilon}$	0.0346	0.0351	0.0346	0.0351	0.3147	1.2496

Table 5. Hensel-Spittel adjusted coefficients

Coefficient	DP600
A	0.00532
m_1	0.00638
m_2	0.13996
m_3	-2.81979
m_4	1,018E-4
m_5	8.358E-5
m_7	-0.17128
m_8	0.00360
m_9	0.79506

Table 6. U-draw bending simulation parameters

Parameter	Description	Level 1	Level 2
A	Time period	0.1	1
B	Friction coefficient	0.025	0.144
C	Number of integration points	5	25
D	Number of radius contact elements	5	18

The Hensel-Spittel coefficients were calibrated to experimental uniaxial tensile tests data via non-linear regression in the OriginPro® V2016 – b9.3.2.303 software, at confidence level of 95%. Table 5 shows these adjusted coefficients.

In order to calibrate the computational model, a full factorial design was set for 4 simulation parameters at 2 levels. Table 6 shows the parameters and its correspondent levels.

Table 7 shows the units for simulations corresponding to fullfactorial design.

Table 7. U-draw bending simulation units

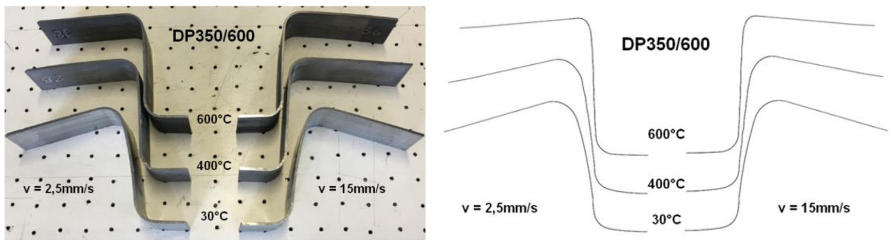
Unit	Time Period	Friction Coefficient	Number of Integration Points	Number of Radius Contact Elements
1	0.1	0.025	5	5
2	1	0.025	5	5
3	0.1	0.144	5	5
4	1	0.144	5	5
5	0.1	0.025	25	5
6	1	0.025	25	5
7	0.1	0.144	25	5
8	1	0.144	25	5
9	0.1	0.025	5	18
10	1	0.025	5	18
11	0.1	0.144	5	18
12	1	0.144	5	18
13	0.1	0.025	25	18
14	1	0.025	25	18
15	0.1	0.144	25	18
16	1	0.144	25	18

The main objective of simulation procedure was to evaluate the influence of simulation parameters on springback prediction. Springback prediction results from U-draw bending were characterized in the same way as the experimental results. The assessment of springback was taken by three parameters ($\theta 1$, $\theta 2$ and ρ) as described in Figure 3. The images were print and the parameters were measured via CAD software.

The prediction results to 30°C and 2.5mm/s were superposed to experimental results in order to perform some graphical analysis and calibrate the computational model. Finally, the results from the experimental procedure were compared to a new set of results from calibrated simulation procedure to 30, 400 and 600°C with 2.5mm and 15mm/s stroke velocities.

4. RESULTS

With the calibrated computational model there were performed a new simulation procedure for springback predictions according to all the experimental procedure conditions of U-draw bending tests. Both procedures were performed to 30, 400 and 600°C temperatures and 2.5mm/s and 15mm/s stroke velocities. Figure 5 shows the springbackeffects on the experimental procedure and simulation procedure.



a) b)

Figure 5. U-draw bending results a) experimental procedure b) simulation procedure.

4.1. Experimental Procedure Results

The experimental springback effect was characterized by three parameters (θ1, θ2 and ρ) according to the temperature and stroke press velocity. The results of the experimental procedure are presented in Figure 6.

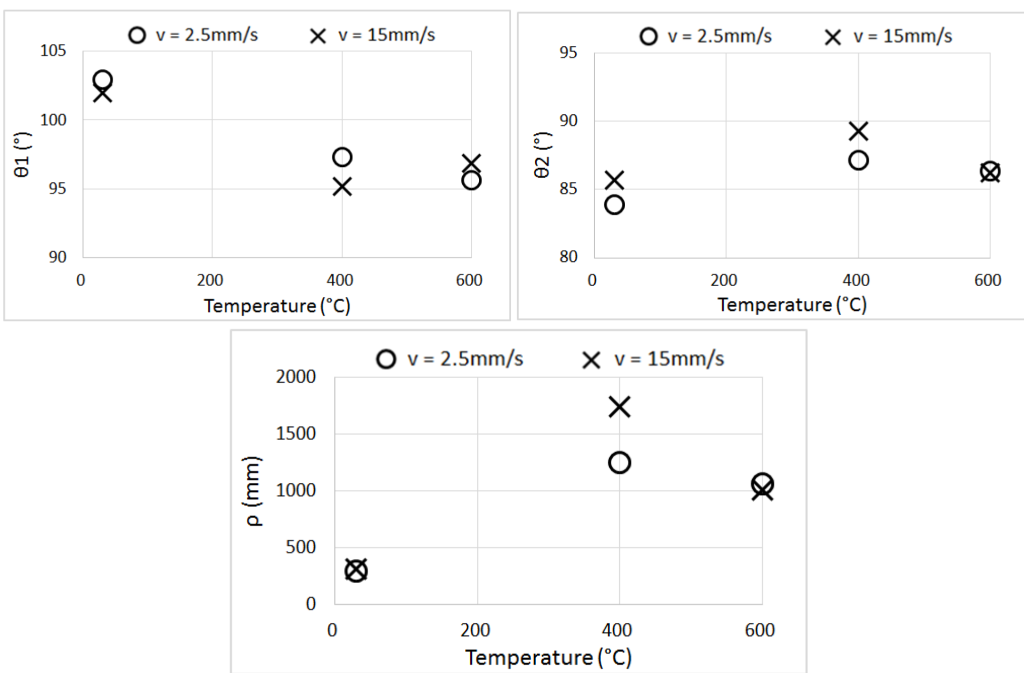


Figure 6. Experimental springback characterization on DP600 U-draw bending parts.

Experimental springbackeffect was improved as the temperature rises. There was a noticeable improved result for the curvature radius, ρ (mm), at 400°C.Considering v = 2.5mm/s and v = 15mm/s, there was no trends for these two different stroke velocities.

4.2. Simulation Calibration

There were performed 16 simulations according to Table 7 in order to calibrate the based on Hensel-Spittel computational model. The computational model was calibrated to fit the experimental results for 30°C and 2.5mm/s stroke velocity.Figure 7 shows the effects of computational parameters related to the experimental result.

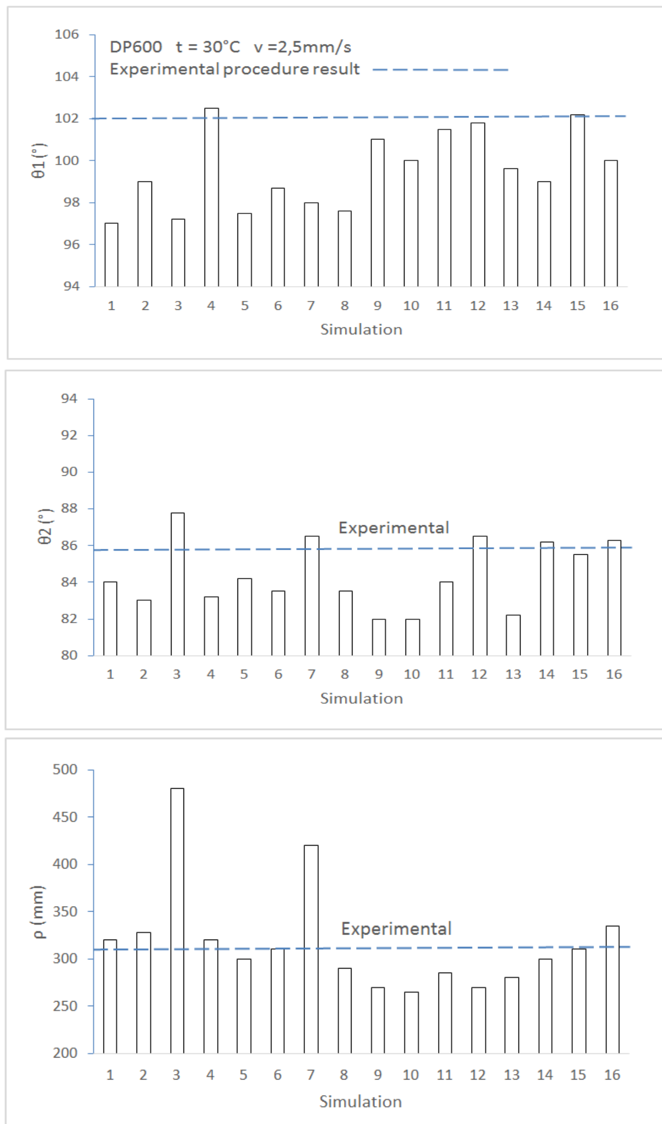


Figure 7. Effect of simulation parameters on springback prediction.

Most of the simulation results were below the experimental value. For θ1, the most accurate simulations can be noticed at numbers 12 and 15. For θ2, the better results were simulations numbers 14, 15 and 16. For ρ, the better results were number 6 and 15. The best result for springback prediction was achieved at simulation number 15. Therefore, the Hensel-Spittel computational calibrated model was parametrized with 0.1 time period, 0.144 friction coefficient, 25 integration points and 18 contact elements on radius.

4.3. Results Comparing

Experimental procedure results can be compared to the simulation predictions. Table 8 and Figure 8 shows thespringbackparameters.

Table 8. Experimental results vs simulation prediction

		Experimental Results			Simulation Prediction		
Temperature (°C)	Strokevelocity (mm/s)	θ1 (°)	θ2 (°)	ρ (mm)	θ1 (°)	θ2 (°)	ρ (mm)
30	2.5	102.0	85.7	309	102.0	86.0	380
400	2.5	95.2	89.3	1742	100.2	87.8	720
600	2.5	96.9	86.3	654	95.0	88.4	1480
30	15	102.9	83.9	291	101.5	83.5	390
400	15	97.4	87.2	1249	99.7	86.0	750
600	15	95.6	86.4	1257	93.0	87.2	1695

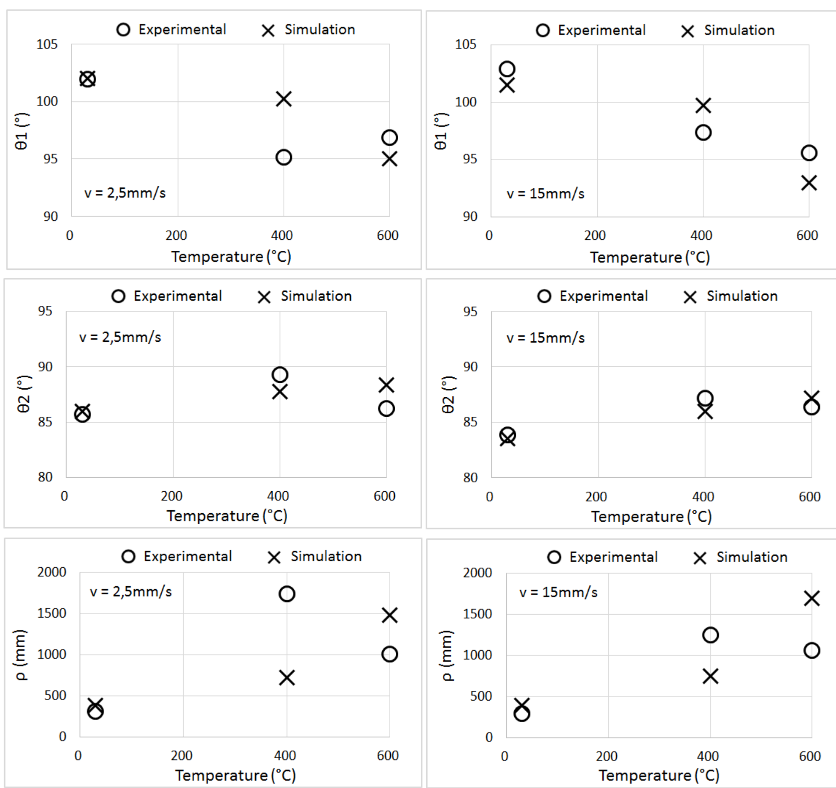


Figure 8. Experimental results vs simulation prediction.

Variation between simulation and experimental springback results was no more than 3% for θ1 and θ2 considering the temperatures of 30°C and 600°C. There was a noticeable variation about 5% for θ1 at 400°C considering v = 2.5mm/s. This simulation result was improved at v = 15mm/s.

For ρ at 400°C there was a difference from -126% (v = 2,5mm/s) and -58.7% (v = 15mm/s) comparing simulation and experimental results. The difference was decreased for v = 15mm/s.

Considering θ1, θ2 and ρ, the better springback result was taken at the temperature of 600°C and v = 2.5mm/s in the experimental procedure. The computational model offers the better accuracy at the temperature of 600°C and v = 15mm/s.

The springback analysis of experimental results and simulation allows the FE modelling validation. Simulation predictions were in good agreement with the experimental results for θ1 and θ2 with error less than 6%. This convergence was expected at 30°C as the computational model was adjusted based on this temperature. It is evident that the increase of temperature for U-draw bending on DP600 steel leads to the reduction of springback effects. On the other hand, there were no noticeable trends for the stroke velocity.

CONCLUSION

Based on the uniaxial tensile tests performed with temperature control it was possible to check some characteristics of the DP600 steels as reported in the literature. Uniaxial tensile tests were carried out at different temperatures, which allowed to observe the influence of temperature on the material at forming processes. The uniaxial tensile tests were also performed at different strain rates. The behavior of the materials as a function of temperature and strain rate was adjusted to the Hensel-Spittel model.

The practical deep drawing experiments allowed the variation of the temperature and the test speed, according to the definitions foreseen in the experimental design. These experiments confirmed the hypothesis of springback reduction with increasing temperature.

The computational model was proposed with the same process parameters, tool parameters and temperature of the practical experiments. This model was adjusted based on the experimental results. The prediction of the springback was made possible by data extrapolated from the Hensel-Spittel model, with an error of less than 6%, which was considered adequate for the present case.

Although DP600 steel is suitable for cold work, this study at different temperatures allows a better understanding of the effects of the springback on manufactured parts with advanced high strength steels. The computational analysis contributes to predict springback as a function of temperature and strain rate.

The springback was reduced with increasing deep drawing temperature. There was no significant reduction of the springback for the different speeds tested. The lowest springback was measured on the test specimens processed at 600°C. It was not possible to perform the deep drawing experiments at 800°C because the heated specimens broke during the practical experiments.

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