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ONLINE FIRST

The International Journal of Advanced Manufacturing Technology

ISSN 0268-3768

Int J Adv Manuf Technol
DOI 10.1007/s00170-020-04975-x

The International Journal of Advanced Manufacturing Technology
https://doi.org/10.1007/s00170-020-04975-x

ORIGINAL ARTICLE

Numerical study on variation of chord modulus on the springback of high-strength steels

Sérgio Fernando Lajarin[1] · Ravilson Antonio Chemin Filho[1] · Claudimir José Rebeyka[1] · Chetan P. Nikhare[2] · Paulo Victor Prestes Marcondes[1]

Received: 18 October 2019 / Accepted: 21 January 2020

Abstract

The advanced high-strength steels (AHSS) have become an interesting alternative to the automotive industry to reduce vehicle weight and therefore reduce fuel consumption. However, the wide variety of applications in the automotive industry is still limited due to challenges in its formability and unloaded behavior of these steels popularly called as springback. Computational tools for numerical simulation have been employed in the industrial environment to help predict the occurrence of springback and defining the appropriate parameters to eliminate or reduce their magnitude. However, the accuracy of the numerical results for AHSS still failed to reach a satisfactory level. The limitation in predicting the springback of AHSS by means of finite element method (FEM) is assigned to computationally difficult to characterize the mechanical behavior of these steels during the plastic strain. The variation of elastic modulus during plastic strain is considered as a major cause of non-linearity of the behavior of these steels. This work aims to study the declining behavior of the modulus of elasticity with an increasing plastic strain objecting to an improvement in the computational prediction of the springback phenomenon of AHSS. Specimens of various AHSS steels were loaded and unloaded in uniaxial tension in 0°, 45°, and 90° to the rolling direction. For all AHSS, it was found that the elastic modulus decreases during loading and unloading after each acquired plastic strain approximately up to 10% of plastic strain and then saturates at higher strain values. Further, the L-bending test was simulated where the change of elastic modulus with respect to plastic strain as observed in the uniaxial tension test is informed through the user subroutine VUSDFLD material model. The springback results were then compared with the experiments. It was found that predictions are in close agreement with experiments after informing the model with the decline of elastic modulus with respect to plastic strain through user subroutine material model as compared to the baseline model.

Keywords Chord modulus · Springback · Advanced high-strength steel · Sheet forming · Numerical simulation · L-bend test

1 Introduction

The automotive industry has made several efforts to reduce emissions of greenhouse gases in the atmosphere. One of the alternatives explored to reduce fuel consumption is by reducing the overall weight of the vehicles. This was achieved by implementing the lower gage thickness of high-strength alloys like advanced high-strength steels (AHSS). AHSS exhibits not only high strength but also good formability. Thus, due to their high-strength levels, the thickness of these sheet steels can be compromised to reduce the vehicle weight without compromising the crashworthiness. The two most popular sheets of steel within the AHSS group are dual-phase (DP) and transformation-induced plasticity (TRIP) steels. Lajarin et al. [1] studied various materials and claim that these steels ensure higher strength than conventional steels combined with high ductility. However, their wide application in the automotive industry is still limited due to the challenges in formability, sheet metal coupling, tool life, and springback behavior. Placidi et al. [2] concluded that the springback is the main obstacle that compromises the mass production of automotive structural components with AHSS. Springback is known as a manufacturing defect in which the deformed metal to the

✉ Paulo Victor Prestes Marcondes
marcondes@ufpr.br

1 DEMEC, Federal University of Parana, Av. Cel. Francisco H. dos Santos, 210, Caixa Postal 19011, Curitiba, Paraná CEP 81531-990, Brazil

2 Mechanical Engineering, The Pennsylvania State University, The Behrend College, Erie, PA 16563, USA

Table 1 Material grades, commercial thicknesses, and chemical composition [1]

Material	Thickness (mm)	Supplier	Chemical composition (% weight)		
			C	Si	Mn
HSLA490	1.57	A	0.080	0.030	0.60
DP600-A	1.50	A	0.140	0.400	2.10
DP600-B	2.06	B	0.086	0.053	1.739
DP750	1.96	B	0.142	0.046	1.760
DP980	1.52	B	0.154	0.047	2.224
TRIP780	2.00	A	0.250	–	2.0

Mean values obtained from three samples of each condition

desired shape when unloaded deviates from the desired profile. The deviation occurring in the metal is due to the elastic behavior of a material caused by the gradient of residual elastic stress.

The occurrence and magnitude of the springback prediction during the tool design is a major challenge. Computational simulation applications using finite element methods (FEM) are generally employed, but the results are not satisfactory because of the difficulty in accurately describing the non-linearity behavior of the material during the unloading stage after the materials have gone through plastic deformation. Morestin and Boivin [3] investigated the decrease in elastic modulus for diverse kinds of steel after the number of plastic strain and found that Young's modulus can decrease 17.5% of its value at only 5% of plastic strain for high-strength steels. Cleveland and Ghosh [4] noticed that the inelastic strain released from the deformed state could be a major source of additional strain recovery. They established that for 7% of plastic prestrain, the elastic modulus can lose 19% of its value for high-strength steel. Perez et al. [5] conducted the study of the elastic response before and after the tensile plastic strain was undertaken for two commercial low-alloyed TRIP steels. The behavior of the instantaneous tangent modulus versus stress during loading and unloading was measured for each degree of prestrain. They observed that the elastic modulus decreases in high-strength steel with respect to the microplastic strain caused by the displacement of mobile dislocations. After a continuous study on the effect of plastic strain on Young's modulus, there is still a gap in the literature to accurately implement the knowledge of elastic modulus variation during unloading in numerical models. Therefore, the objective of this study is to improve de computational prediction of springback during L-bend test. For this, the computer model in commercial finite element software ABAQUS was informed with the declination of the modulus of elasticity during unloading for different automotive materials by the user subroutine material model. L-bend tests were carried out on six steels including HSLA, TRIP, and four DPs grades for different bend radii and then compared with finite element simulation predictions.

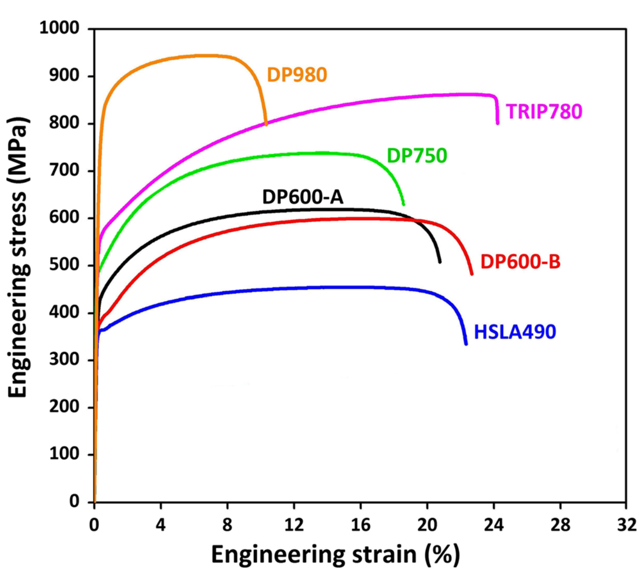

Fig. 1 Stress–strain curves for six tested steels

2 Procedures

The monotonic uniaxial tensile tests for six alloy steels were carried out in order to characterize the elastic behavior during unloading and to register the chord modulus. Detailed procedures describing the uniaxial tensile test and its interpretation have been presented in Lajarin et al. [1]. Based on the previously published result in [1], the data was fed in the numerical model in the form of a user subroutine material model. To predict the springback, the L-bend test setup was model in ABAQUS software. Finite element simulations were conducted using a subroutine implemented in ABAQUS to describe the degradation of the modulus of elasticity (chord modulus) during unloading and in order to analyze its influence on the springback computational prediction in the L-bending trials. A similar procedure was used by Lajarin and Marcondes [6] to simulate the Numisheet'93 U-channel benchmark proposed by Makinouchi et al. [7]. In addition, L-bend tests, with different bend radii, i.e., 5 mm, 10 mm, and 15 mm, were simulated to predict the effect of bend radii on springback.

Table 2 Mechanical properties of the materials [1]

Material	0.2% YS (MPa)	UTS (MPa)	UE (%)	TE (%)	E (GPa)	*n* value	*K* value
HSLA490	415	542	14.1	20.2	208	0.116	781
DP600-A	395	620	14.9	20.0	207	0.149	967
DP600-B	387	605	15.8	23.0	207	0.188	1010
DP750	488	741	12.7	17.0	205	0.164	1193
DP980	828	934	7.0	10.4	208	0.078*	1232*
TRIP780	548	860	22.6	24.4	206	0.252	1568

YS yield strength, *UTS* ultimate tensile strength, *UE* uniform elongation, *TE* total elongation, *n* strain hardening coefficient, *K* strength coefficient

Both n and K obtained from $0.04 < \varepsilon < 0.12$

*Obtained from $0.03 < \varepsilon < 0.06$

Average values obtained by three samples in the 0°, 45°, and 90° from rolling directions

2.1 Materials

The material grades, thicknesses, and chemistry of the six tested steels appear in Table 1 and the stress–strain curves are shown in Fig. 1. The sheet materials studied were various grades of steel commonly used in the automotive industry. The HSLA has been used for many years in the production of automotive body structures and is still widely used today. HSLA is higher strength steel which is primarily obtained by microadditions of microalloying elements used to control the grain size. The AHSS utilized consisted of four dual-phase steels (DP) with a range of ultimate tensile strengths of 600, and 980 MPa and a transformation-induced plasticity steel (TRIP) with an ultimate tensile strength of 780. The AHSS steels studied are the most used in the automotive industry and were obtained from two suppliers (A and B) with thicknesses between 1.5 and 2.06 mm. The material surface condition was galvanized. Table 2 shows some mechanical properties, and Table 3 shows the coefficients of anisotropy of the materials.

2.2 L-bending test

L-bending test was conducted for six steel with consideration of three different die radii (Rd). This bending test was adapted from Gau and Kinzel [8] who proposed to analyze the influence of the Bauschinger effect on the prediction of elastic return and was very simple and efficient. A schematic representation of the test setup is shown in Fig. 2. Samples with a length of 100 mm, 12-mm wide, and thicknesses ranging from 1.5 to 2.06 mm (see Table 1) were clamped between the die and the blank holder. The punch with the end radius of 2 mm (refer to Fig. 2a) was moved down with a stroke of 50 mm to bend the sheet over the radius of the die (Rd), approximately 90°. Subsequently, the punch was displaced upward to release the load. During this process, the sample recovered elastically making it deviate from its formed shape, generating springback. The clearance "c" between the punch and the die was kept constant at 1.5 times the thickness of the sheet. The radius of the die (Rd) varied from 5, 10, and 15 mm by means of interchangeable inserts. The die and the punch were set into a universal testing machine. Three samples of each of the six materials for the three different die radii were analyzed, totalizing 54 samples.

2.3 Finite element simulation

A finite element model of the L-bend test was constructed using a commercial finite element software ABAQUS/Explicit. Punch, die, and blank holder were considered as rigid

Table 3 Coefficients of plastic anisotropy of materials [1]

Material	r_0	r_{45}	r_{90}	Δr	r_m	Anisotropy parameters of HILL'48			
						R_{11}	R_{22}	R_{12}	R_{33}, R_{23}, R_{13}
HSLA490	0.988	1.015	0.568	−0.237	0.897	0.854	0.852	0.848	1
DP600-A	0.835	0.676	1.088	0.285	0.819	1.070	1.019	1.151	1
DP600-B	0.638	1.097	0.802	−0.377	0.909	1.069	0.955	0.926	1
DP750	0.682	1.113	0.814	−0.365	0.931	1.052	0.957	0.922	1
DP980 *	0.875	1.038	0.932	−0.134	0.971	1.016	0.983	0.971	1
TRIP780	0.847	0.902	1.092	0.068	0.936	1.067	1.020	1.055	1

*Obtained by $\varepsilon = 0.06$; the other materials were obtained by $\varepsilon = 0.12$

Average values obtained by three samples in the 0°, 45°, and 90° from rolling directions.

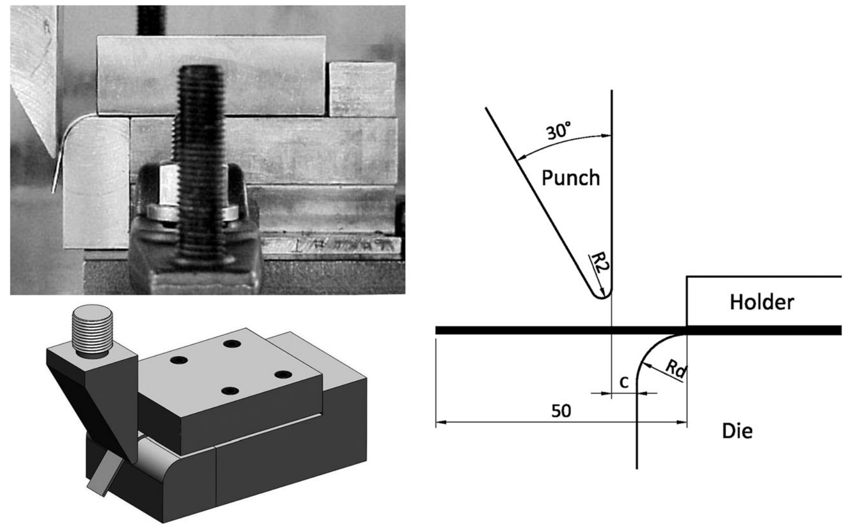

Fig. 2 L-bending test: **a** test tool, and **b** schematic of the L-bending test

bodies and the sheet was meshed with deformed elements of type CPE4R. According to Chatti and Hermi [9], eight elements through the thickness of the sheet were sufficient to obtain accurate results in springback simulations, thus those number of elements were applied through thickness. After preliminary tests, the sheet was divided into three regions. In the central region, where the bending process occurs and where it is in contact with the radius of the die, the sheet was marked with elements of 0.2 mm in width, and in the other regions 1 mm. The contacts between the rigid bodies like a punch, die, and blank holder with sheet surfaces were defined by a penalty contact method using a coulomb friction coefficient of 0.1.

The true tensile stress–strain curves measured for the six materials were the best fit using a Hollomon hardening law, and the values are listed in Table 2. For an anisotropic effect, Hill's quadratic yield function was adopted and the coefficients are given in Table 3.

2.3.1 Young's modulus vs chord modulus

To assess the magnitude of this effect, cyclic loading-unloading tensile tests for six materials were performed and reported in [1]. Figure 3 shows the difference in the initial modulus of elasticity and the chord modulus after $\varepsilon_p = 0.085$ for the DP600-A steel. In order to evaluate the influence of chord modulus on springback results, simulations of the L-bending test were performed with two definitions of the elastic regime of the material. In the first case, the elastic regime of the materials was defined

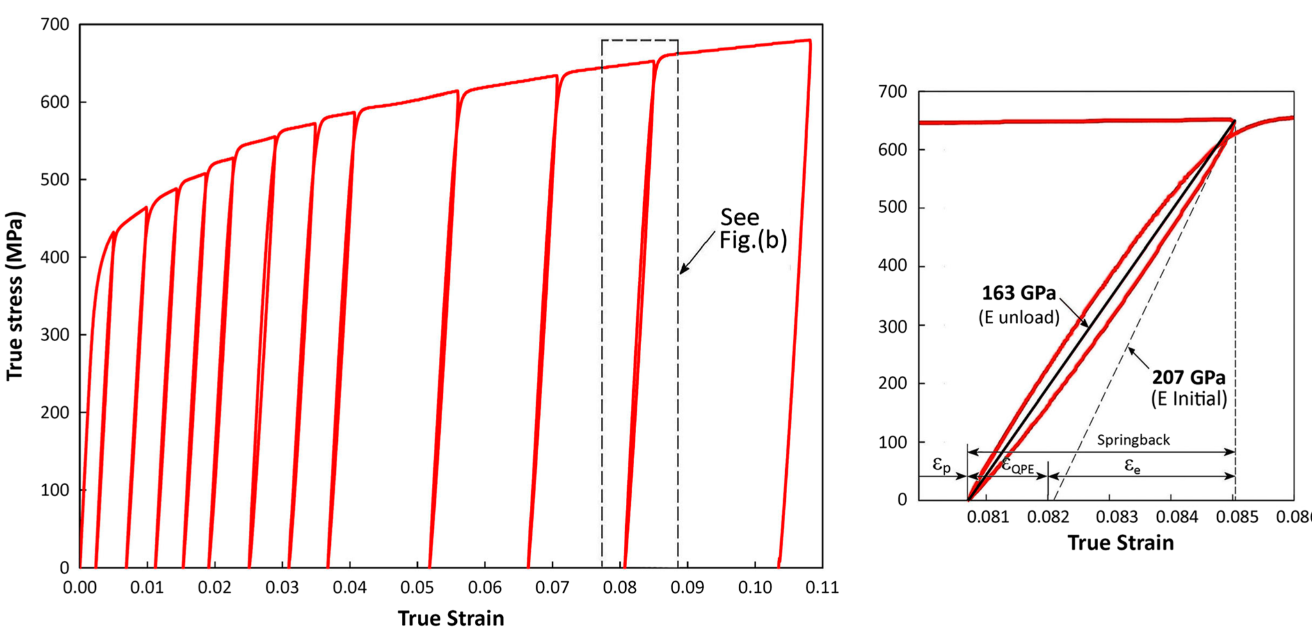

Fig. 3 Unloading-loading cycles obtained from the uniaxial tensile tests: **a** DP600-A, **b** detail showing the behavior of the unloading elastic modulus [1]

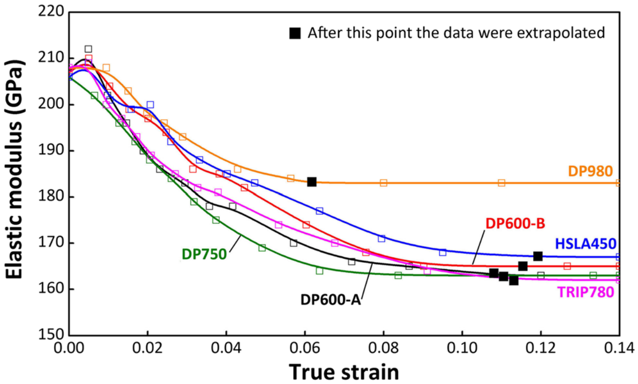

Fig. 4 Elastic modulus during unloading (chord modulus) vs. plastic strain in rolling direction [1]

with a constant initial Young's modulus (constant E modulus) (see Table 2) and the coefficient of Poisson (υ = 0.3). In the other case, the chord modulus variation curve (varied E modulus) as shown in Fig. 4 was fed in the numerical simulation by means of a user subroutine VUSDFLD which redefines the field variables at a material point.

3 Results and discussion

The numerical and experiment results of the L-bend tests are shown in Fig. 5a, b. The springback angle (θ°) in the experimentally deformed samples were measured on a profile projector with a resolution of 0.01° and the numerical results were measured with the help of computer-aided design (CAD) application. Figure 6 shows the results of springback after bending operation with three different values of the radius. The results from the experiments are compared with results obtained by numerical simulation with a constant initial Young's modulus (constant E modulus) and with varying the chord modulus (varied E modulus). It can be observed that the DP600-B steel showed the lowest elastic recovery with the three bend radii utilized. The values were lower than those obtained with the HSLA 400/500 steel which has a lower limit of resistance. In addition, the springback of the DP600-B was quite different from that observed for another supplier for the same DP600-B grade.

Simulations with varying chord modulus presented a higher springback angle. With the exception of DP600-B, the results were closer as compared to the experimental

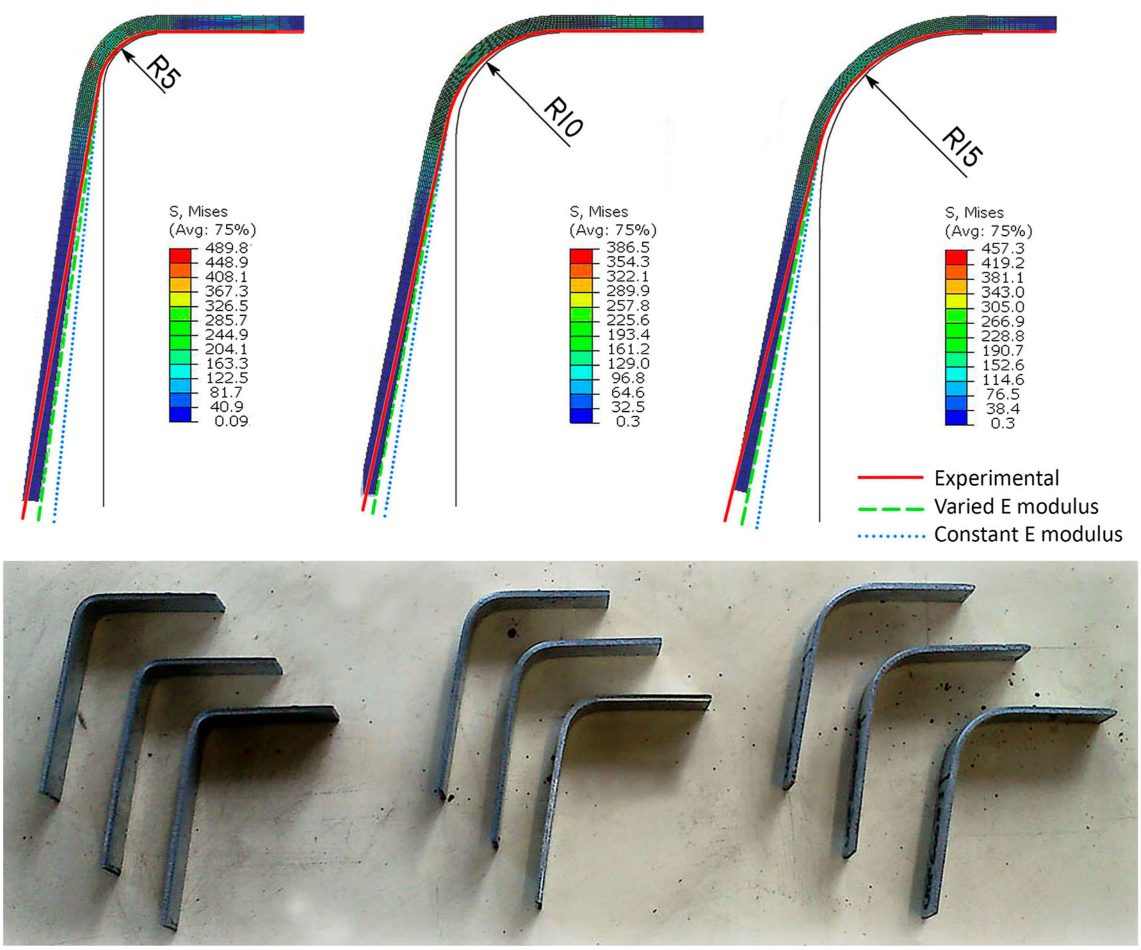

Fig. 5 Samples after L-bending tests using different radii

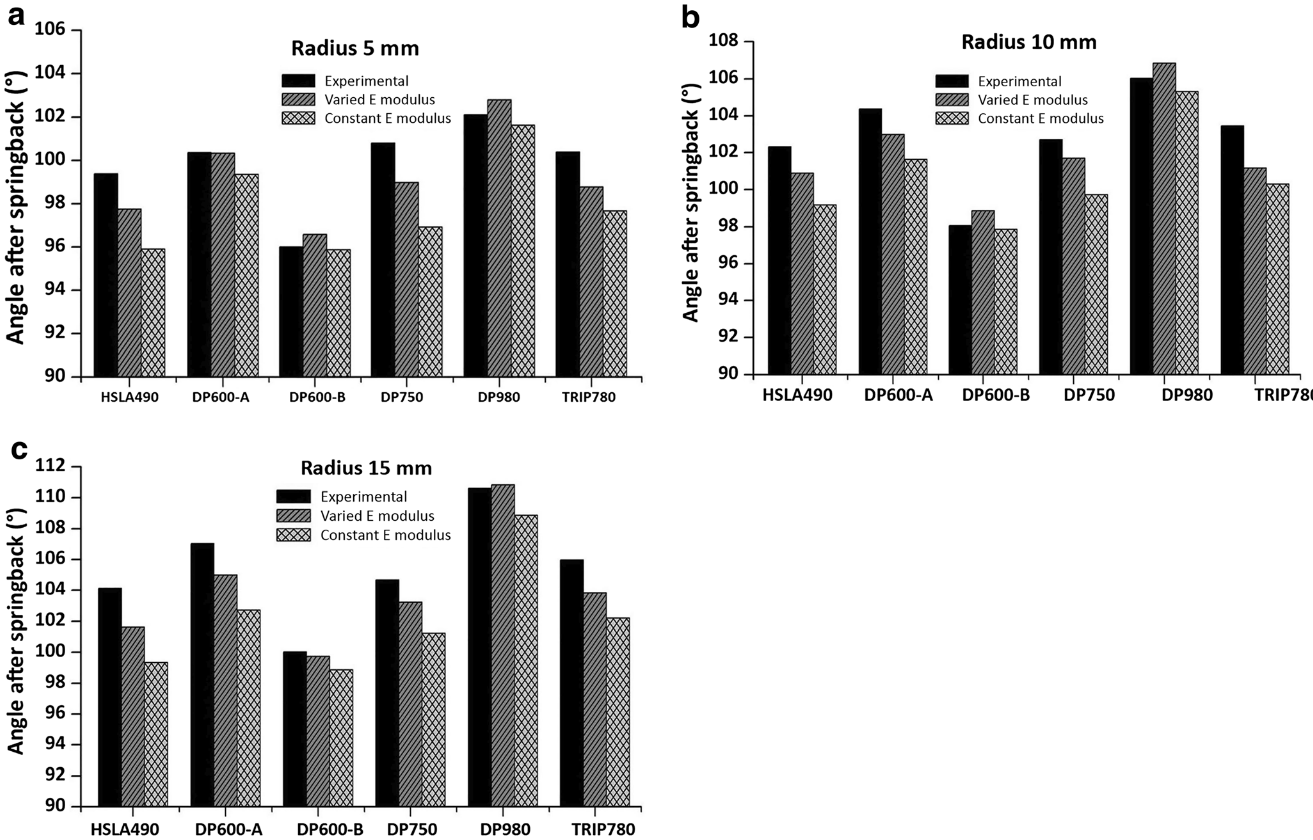

Fig. 6 Bend angles after springback: **a** 5 mm, **b** 10 mm, and **c** 15 mm bending radii

results. Although numerical simulation results are very close to the experimental results, it is clear that with consideration of varying chord modulus during deformation, a more complete description of the behavior of these materials is necessary, such as considering the Bauschinger effect in order to create a more complete phenomenological model.

The DP980 steel presented the highest springback for the three bend radius values, influenced by the high tensile strength. The DP750 presented a springback equivalent to the standard HSLA490 steel for the three bend radius values, and the DP600-A and TRIP780 showed slightly higher springback. Taking into account the much higher resistance of the AHSS compared to HSLA490, the springback presented by them can be considered low because it was not proportionally equivalent.

4 Conclusion

This paper focuses on investigating the springback prediction in the L-bend simulation of advanced high-strength steel materials. Previously, through the uniaxial tension test, it was observed that the elastic modulus of a material decreases if the material is loaded to a plastic strain and then unloaded. It was found that if these AHSS materials were loaded monotonically, the elastic modulus is approximately 210 GPa. But if these materials were strained incrementally through loading and unloading cycles, the elastic modulus decreases at each acquired plastic strain. In the tested materials, the elastic modulus starts with approximately 210 GPa and then decreases at each acquired plastic strain values and then saturates to approximately 170 GPa at a plastic strain of 10%. Further straining of these materials at higher plastic strain does not affect the elastic modulus and it remains constant.

In order to investigate the springback prediction in bending, a simple bending (L-bend) test was proposed to predict the springback angle after the bending of a metal strip over three different bend radii. The purpose of changing the bend radii is to achieve different plastic strain values to analyze the springback. For this, two numerical models were created, one with constant elastic modulus and the other one by informing the varied elastic modulus with respect to plastic strain through the user subroutine material model. It was observed that considering the non-linearity in the elastic behavior during unloading improves the prediction of the elastic recovery phenomenon with respect to the experiment as compared to the constant elastic modulus model prediction. However, a precise prediction depends on other factors being considered, such as the Bauschinger effect and a more realistic phenomenological model. When comparing the results with different bend radii, it can be observed that the smaller bending radius (5 mm) produced the lowest springback in all materials tested. In addition, it is important to note that for all materials, the user subroutine informed material model predicts closer to the experimentally measured value as compared with the baseline model. Thus in general, it is important to characterize these advanced high-strength steel material at each strain value and feed the accurate material behavior model to the simulation package for accurate prediction.

Acknowledgments The authors thank the Usiminas and Arcelor Mittal companies for supplying the steels used in this study and CNPq Agency (Brazil) for a grant.

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