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ANALYSIS OF THE DECREASE OF THE APPARENT YOUNG'S MODULUS OF ADVANCED HIGH STRENGTH STEELS AND ITS EFFECT IN BENDING SIMULATIONS

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ABSTRACT

In this paper the evolution of the Young's Modulus (E) during unloading with plastic deformation has been studied for different Dual-Phase AHSS from DP780 to DP1400. During unloading, all the DP steels studied showed the presence of microplasticity so an Apparent Young's Modulus (E_A) has been defined. Although that in all cases E_A decreased with a non-linear behavior as the plastic strain was increased, it has been observed that the final percentage of decrease seems to be related to the microstructure of DP steels. As the ferrite content increased as in the lower strength DP steels, the reduction of E_A is larger, reaching a 21%.

The introduction of the variation of the elastic response during unloading in the simulation of a bending operation has allowed obtaining an improvement of the accuracy in springback prediction in all the DP steels studied. For the low strength DP steels the final shape obtained by simulation is in fact the same than the real one. As the strength of steel is increased, the accuracy is less, especially in the DP 1400 steel, in which differences in bending angle higher than a 15% are still found.

Keywords: Young's Modulus, springback, DP steels,

1. INTRODUCTION

One of the main problems associated with sheet steel forming is springback. Traditionally, the way to get the desired shape after the press process has been the trial and error method. Nowadays the previous design by Finite Element Analysis (FEA) of the sheet steel forming process is used in order to predict the final shape of the formed part. The studies developed in this field have confirmed the importance of many factors not only in FEA numerical parameters but also physical parameters, including in this topic the mechanical properties of the steel grades. The Young´s Modulus (*E*), and specially its evolution with plastic deformation has appeared as one important parameter that can help to explain the springback phenomenon. The introduction of the variation of the elastic response after deformation into the FEM codes has allowed to improve the prediction of the final shape of formed parts in various forming operations [1,2].

Recently, the Advanced High Strength Steels (AHSS) have been introduced in automotive companies in order to obtain lower thickness of the press parts and consequently lightweight equipment. Dual-Phase steels (DP) are one of the most relevant AHSS, with maximum strengths ranging from 600 to 1500 MPa. The implementation of DP steels, especially in the harder grades, has generated some difficulties since the springback is larger than in current steels sheets used before.

The decrease of the Young's Modulus has been related to the presence of an extra microplastic strain produced by the movement of dislocations during the loading and unloading processes. The existence of mobile dislocations already present in the material and mainly created during the plastic deformation are the responsible for the certain amount of *recoverable plastic strain* reported in some studies [3,4]. The introduction in the FEA simulations of this increase of the microplastic recovery during unloading has rendered better accuracies in springback predictions.

Since DP steels have a wide spread of strengths and microstructures, and being the microplasticity a phenomenom that depends on dislocations and therefore on microstructure too, the variation of the elastic response must vary within the different steel grades. In order to obtain better springback predictions by this approach the individual variation of the elastic response for each DP steels is then needed.

In the present study four DP steel grades has been chosen in order to cover the full range of strengths. In each case, the variation of the elastic response with plastic deformation has been checked along its uniform strain path. Each one of the curves obtained has been introduced in the FEA simulation of a bending test and the predicted angles have been compared to the experimental ones. By this procedure it is expected to know the elastic response in each type of DP steels and the influence in each case on the accuracy in the springback prediction.

2. MATERIALS

The chemical composition of the DP steel grades used in this study is displayed in Table 1, whereas the mechanical properties and the percentage of martensite can be observed in Table 2. In Table 2 are included too the commercial name for each DP steel and the specific designation that will be used in this paper. This is done in order to avoid confusion between the number that appears in commercial specifications of DP steels and its real mechanical properties. In this special designation, the yield stress and ultimate tensile strength of the DP steel are included. Finally, the microstructures of the four DP steels are exposed in Figure 1.

Table 1. *Chemical composition of the DP steels used in this study (FE% balance).*

Commercial name	%C	%Si	%Mn	%P	%S	%Cr	%Mo	%Nb	%Al	%Ni	%Ti
DP 1400	0.156	0.504	1.629	0.011	<0.001	0.034	0.014	0.026	0.055	0.054	0.003
DP 1200	0.109	0.205	1.619	0.011	0.003	0.044	0.017	0.024	0.046	0.040	0.002
DP 980	0.134	0.214	1.904	0.020	0.002	0.173	0.007	0.011	0.029	0.032	0.022
DP 780	0.150	0.215	1.938	0.022	<0.001	0.171	0.007	0.011	0.031	0.038	0.020

Table 2. *Designation of the DP steels used in this study together with some mechanical properties (Y.S= Yield Strength; U.T.S= Ultimate tensile strength).*

DP STEEL	THICKNESS (mm)	Y.S (MPa)	U.T.S (MPa)	UNIFORM ELONGATION (%)	MARTENSITE (%)	INITIAL YOUNG'S MODULUS *E* (GPa)
DP 780 DP 550/800	1.5	550	800	13.5	25	206
DP 980 DP 950/1200	1.6	950	1200	5.9	90	208
DP 1200 DP 1070/1220	1.6	1070	1220	3.9	95	207
DP 1400 DP 1430/1520	1.5	1430	1520	2.5	98	206

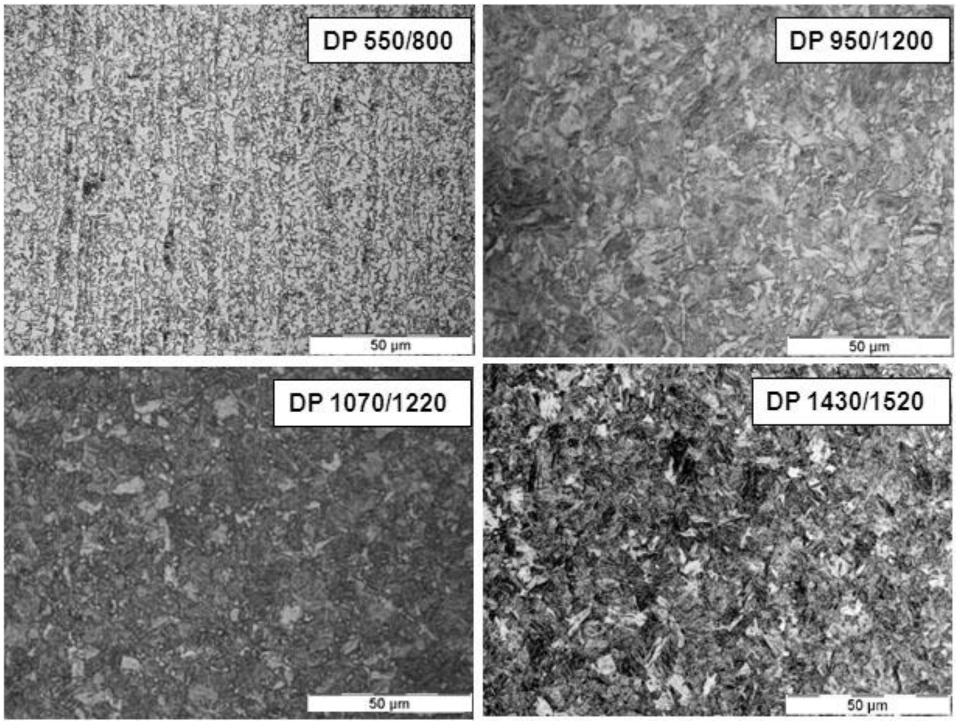

Figure 1.*Microstructures for the DP steels studied in the longitudinal section.*

All the steels studied had a similar thickness in order to minimize the variations that can be produced during the Young's modulus determination and press forming. The microstructural study revealed that all DP steels are formed by a mixture of ferrite and martensite. In the DP 550/800 a banded martensite is found in a ferrite matrix, but in the stronger steels the matrix is martensitic being the ferrite intergranular. In Table 2 it can be seen that the strength of steel increased as the ferrite content decreased. In the case of DP 1430/1520 the percentage of ferrite found was only a 2%. The ductility, measured as uniform elongation during the tensile test was also strongly influenced by the ferrite content. The DP 550/800 with the lower martensite content reached a 13.5% uniform elongation and a 21% of total elongation in the tensile test, whereas DP 1430/1520 only arrived to a 2.5% uniform elongation and a 5.5% total elongation. However, the effect of increasing the martensite content seems to not have any influence in the first elastic response of the steel in the tensile test since the values of the initial Young's modulus are very similar in all the steels studied.

3. EXPERIMENTAL PROCEDURE

3.1 Young's modulus measurements

The procedure used to determine the variation of the elastic response along plastic deformation has been exposed before [3,5]. Tensile test samples were prepared according to EN-10002-1 standard with the axial direction aligned with the rolling direction of the sheet. Tensile test were conducted in an INSTRON 5585. High precision electrical resistance strain gauges (FLA-2-11-1L from TML) were glued to the flat surface of each sample. The samples were deformed step by step according to the following procedure: starting in the initial state (e = 0%), the elastic response was measured during loading and then the plastic strain was introduced. Finally, the elastic response was again measured during unloading. This cycle was repeated for greater strains until the appearance of the neck. In order to ensure the precision of the strain gauges, the maximum strain allowed to each strain gauge was limited to less than 3%.

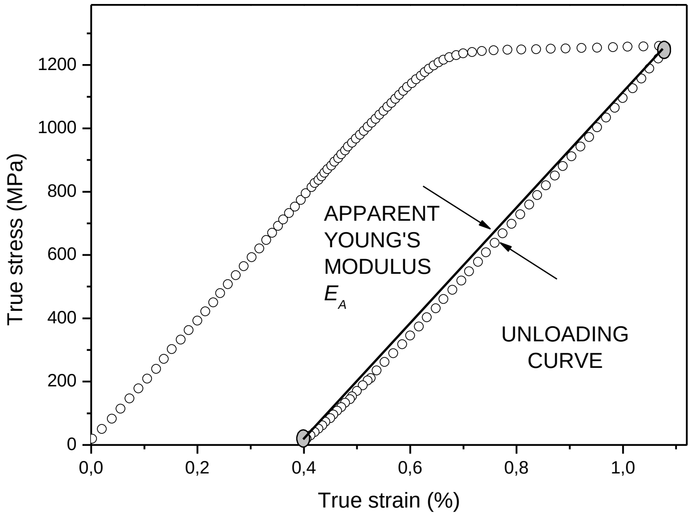

Figure 2. *Determination of the Apparent Young´s Modulus (E_A) from the unloading tensile curve. The slope is calculated supposing a straight curve form the initial point in the unloading to the final point at zero stress.*

Figure 2 shows a true stress-true strain curve in which the loading and unloading periods of the test can be seen. The young's modulus (E) was calculated in the initial loading period and for all the cases the coefficient of linear regression was above 0.999. On the unloading, due to the non-linearity of the curve, an apparent Young's Modulus (E_A) had to be calculated. This parameter represents the slope between the points at maximum and minimum load of the unloading curve, and it is displayed in fig.2. Although E_A is not a physical magnitude, for practical purpose it may represent the real deformation of the sheet during the unloading process. This value will be used in the FEM calculations instead E in order to a better prediction of the springback in the formed sheets.

3.2 Bending tests

For the bending tests rectangular sheets of 126 mm length and 100 mm width were used. The sheet was positioned over the punch and bending was carried out by the drop of the die. In all the cases the radius of the die was 3.5 mm and three different punches were used varying the bend radius, 6, 10 and 17.5 mm, with no flat surface at the top of the punch. Tolerance between the punch and the die, as it is defined in Figure 3,is a particular point that has a strong influence in the final springback analysis. Therefore, it has been carefully measured and controlled to be equal or less than 0.1 mm.

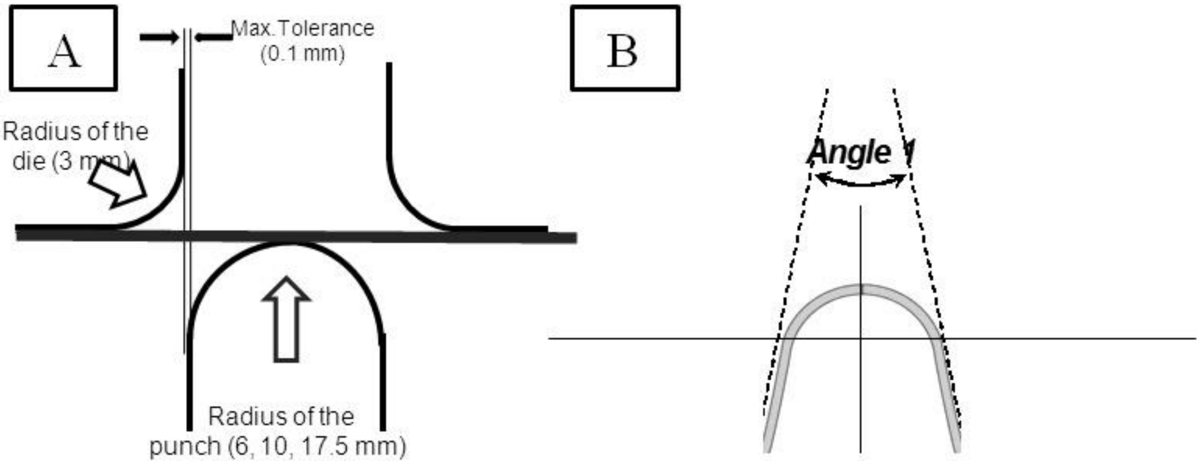

Figure 3. *A) Experimental set-up and definition of tolerance between die and punch. B) Definition of angle 1 in the bended sheet used to compare experimental results with the simulated ones.*

For every type of punch and DP steel three sheets were tested. In all cases no blankholder was applied and the speed of the die was 22 mm/s in all cases. After bending, the sheet was measured with a Mitutoyo Euro-C-A9106. The definition of the bending angle is showed in Figure 3.

3.3 FEA analysis

In order to understand the influence of the variation of E_A as a function of plastic strain in the prediction of springback, two types of models have been carried out. In the first one, a constant elastic modulus has been used. In the other one, a variation of E_A as a function of plastic strain has been used through a USDFLD subroutine. In both cases, the problem has been solved with a two-dimensional model and the symmetry of the parts has been used to reduce the size of the model. An isotropic hardening model has been chosen for the steel sheets. The tools were modeled by rigid surfaces. The forming process is considered almost static and 3 steps have been used: bending, withdrawal and springback.

There are two interactions (sheet-die and sheet-punch) defined by a surface-to-surface contact, and using a node-to-surface discretization. The simulations were done using an implicit formulation with elements in plane strain

As for the mesh, CPE4 fully integrated elements have been used. Once all the simulations with a constant elastic modulus were done, the same forming process was simulated, but changing some properties of the steels used in order to make them compatible with the variation of E_A as a function of plastic strain. At this moment, a USDFLD subroutine comes into play. In all cases, the tolerance introduced in simulations between the die and the punch was 0.1 mm.

To finish with this section, the effect of friction coefficient in springback will be discussed. It has been seen through simulation that a variation of this coefficient between 0.10-0.15 does not affect the value of angle 1 in this bending operation.

4. RESULTS & DISCUSSION

4.1 Young´s modulus measurements.

The variation of E_A with true strain in tensile test is exposed in Figure 4. The curves are divided in two sections. The first one corresponds to the experimental values obtained during the uniform elongation period. Once the neck in the sample is produced, there is no chance to continue with the determination of E_A. From this point and up to the maximum strain registered in the sheets during the bending operations, the behavior of E_A had to be estimated. In the case of DP 550/800 after a strong decrease just at the beginning of plastic deformation, there was a quick stabilization of the values of E_A, remaining almost constant as plastic deformation increased. The initial drop of E_A has been reported in the literature [3,5,6,7] and it is related to the increase of the dislocation density in the initial stages of cold working. When the sample is unloading, most of the dislocations that have been pushed and stored in pile-ups go back producing an extra microplastic strain.

The existence of a long period in which E_A has no further decrease as the plastic deformation goes on has been also reported in literature [3,5,6,7]. When the amount of strain is increased, the dislocations are getting entangled or trapped into high density dislocation walls (HDDW) which produces that the number of mobile dislocations arrives to a steady state [5]. Therefore, the total microplastic strain during unloading would remain constant with no further increase. For the DP 550/800 this stabilization of the E_A values was produced at low strains, since from $\varepsilon = 0.04$ a saturation value of 163 GPa was observed.

This model of strong initial drop with plastic strain and subsequent stabilization with further strain was accepted for E_A, and therefore was easy to estimate its behavior beyond the true strain corresponding to the beginning of necking. In the case of DP 550/800 the values of E_A at plastic strains greater than $\varepsilon = 0.12$ were supposed to be 163 GPa, the saturation value observed before.

For the more resistant steels, the same model was adapted. It can be observed from figure 4 that as the strength of the steels increases, necking appeared earlier. At the same time, stabilization seems to take place earlier too so except for the case of DP 1430/1520 it was no difficult to estimate the rest of the curve since the saturation value was quite clear. In the last case of DP 1430/1520 it was not clear that stabilization had taken place and the chosen value may vary in ± 2 GPa.

Looking at Figure 4 is clear that there is a relationship between strength in DP steels and variation of elastic response during unloading. In the softer steel, DP 550/800, the decrease in percentage of the elastic response is ~21%, which agrees well with other results in literature for similar strengths [5]. For the harder steel, DP 1430/1520 the reduction is only of ~8%. The main microstructural difference between the steels studied is the ferrite content. For the DP 550/800 the matrix is ferritic and the total amount of ferrite is ~75%. For the other steels ferrite is intergranular with percentages below 10% in a matrix of martensite. Moreover, in harder steels, the E_A reduction is smaller when the ferrite content is reduced. This fact can be explained assuming that dislocation motion is easier in bcc ferrite that in martensite, so the microplastic strain can be produced in larger amount as the ferrite content is increased.

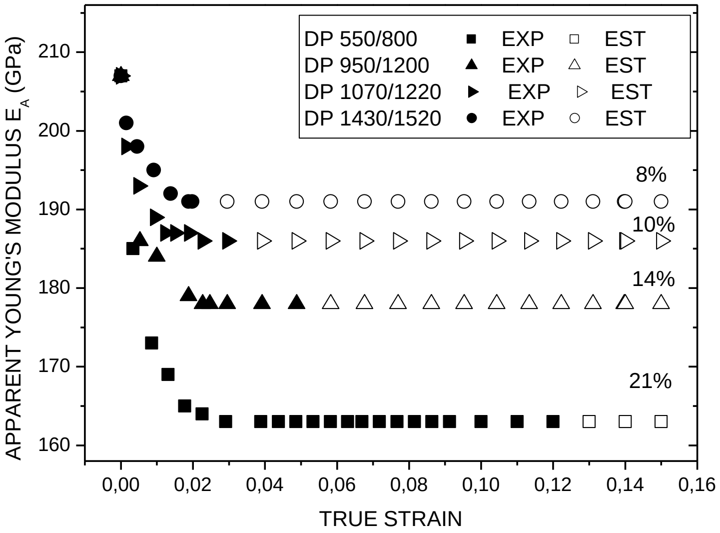

Figure 4. *Variation of the Apparent Young´s Modulus (E_A) with true strain in tensile test for all the DP steels studied. It is included the total variation of E_A with respect the initial Young's modulus E for every steel.*

The main consequence of this is that the influence of E_A in the springback prediction will be different depending on the steel, although the total amount of microplastic strain is related not only with the E_A but also of the final level of stress present in the sheet just before the drawback of the die.

4.1 Bending tests.

The measured angles in the bended sheets together with the simulated ones with E constant and E_A are exposed in Table 3. The experimental angle depends strongly on the radius of the punch and the strength of the DP steel. As the radius increases the angle increases, but this increment is much larger when the strength of steel rises, as in the case of DP 1430/1520, where the measured angle arrives to 60º.

The simulated values with E constant show an important difference with the real values, no matter the type of DP steels. For DP 550/800 the percentage is around 20%, for the medium DP the percentage drops slightly below 20% and with DP 1420/1530 the difference grows to an average of 25%.whwn the variation of the elastic response is introduced using the E_A values, simulation of the springback is improved in all cases, but certain differences must be noted between the steels studied. In the case of DP 550/800, in which the larger decrease of E_A was observed, the simulated values are very close to the real ones. For the DP 950/1200 and DP 1070/1220, although they are very close in strength, it must pointed out that DP 950/1200 had a larger decrease of E_A, and this is reflected in the calculations because its average percentage of error lies below 5% and for the DP 950/1220 is clearly above this value. Finally, for the DP 1420/1530 the introduction of E_A allows to improve the simulated angles but they are still far from the real ones. In the case of DP steels with very high strengths and in fact fully martensitic the variation of the elastic response during unloading observed in tensile tests is not able to explain the increment of the angle in the bended sheets.

Table 3. *Comparison between the measured angles in bended sheets and the simulated angles using E initial values or* E_A.

	Punch	**Angle *E* constant**	**Angle E_A**	**Experimental angle**	**Variation E constant (%)**	**Variation E_A constant (%)**
DP 550/800	R6	10.65	13.30	13.03 ± 0.15	18.3	2
	R10	15.31	19.20	20.47 ± 0.63	25.2	6
	R17.5	22.50	27.67	27.90 ± 0.14	19.4	0.8
DP 950/1200	R6	12.28	14.43	14.76 ±0.43	16.8	2.2
	R10	21.22	24.02	24.96 ±0.89	15.0	3.8
	R17.5	34.74	39.94	42.24 ± 0.37	17.8	5.4
DP 1070/1220	R6	11.50	13.20	13.75 ± 0.14	16.4	4.0
	R10	20.23	22.94	24.87 ± 0.45	18.7	7.8
	R17.5	35.80	39.52	42.77 ± 0.23	16.3	7.3
DP 1430/1520	R6	16.74	18.33	21.39 ± 1.17	21.7	14.3
	R10	27.55	30.05	38.78 ± 0.69	29.0	22.5
	R17.5	45.80	49.19	60.25 ± 0.43	24.0	18.3

6. CONCLUSIONS

The Apparent Young's Modulus (E_A) decreases with the plastic strain in a tensile test. It has been found that in DP steels with high ferrite content and moderate strength E_A has a decrease of 21% with respect to the initial Young's modulus. As the ferrite content decreases the reduction of E_A is smaller, being only of 8% for DP steels with only 2% ferrite content.

This variation of the elastic response during unloading has been introduced in the simulation of a bending process for the different steels studied. For the DP 550/800, the steel with the lowest strength, the final shape of the sheet obtained by FEA analysis is very close to the real one. For the medium DP steels with maximum strength around 1200 MPa, the accuracy with respect the final shape is clearly improved. The best results are produced with the DP 950/1200 steel that has a larger reduction of E_A. In the case of the higher strength steel in which the drop of E_A is smaller, an improvement is obtained but a moderate error comparing with the final shape is maintained.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

1. R. Cobo, R. Hernández, J.A. Benito, D. Casellas and M. D. Riera: "Study of the influence of the decrease of the apparent young's modulus during unloading in the springback prediction"

, *Proceedings of the iddrg 2008 conference*, (2008) 785-791.

2. T. Suzuki, M. Nakata: "Springback analysis considering Bauschinger effects for high strength steels of various micrstructures", *Proceedings of the iddrg 2008 conference*, (2008) 533-544.

3 R. M. Cleveland and A. K. Ghosh: “Inelastic effects on springback in metals”, *Int. J. of Plast.,* 18 (2002), 769-785.

4 J. A. Benito, J. M. Manero, J. Jorba and A. roca: “Change of Young’s Modulus of cold-deformed pure iron in a tensile tests” *Metall. And Mater, trans. A.* 36 (2005), 3317-3324.

5 R. Perez, J. A. Benito, J. M. Prado: ”Study of the inelastic response of TRIP steels after plastic deformation”, *ISIJ Inter.*45 (2005) 1925-1933.

6 F. Morestin, M. Boivin: “On the necessity of taking into account the variation in the Young’s Modulus with plastic strain in elastic-plastic software”, *Nuclear eng. and design.* Vol. 162 (1996), 107-116.

7 F. Yoshida, T. Uemori, K. Fujiwara: “Elastic-plastic behavior of steel sheets under in-plane cyclic tension-compresion at large strain. *Int. J. of Plast.* 18 (2002), 633-659. 18 (2002), 633-659.