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APPARENT YOUNG MODULUS OF SHEET METAL AFTER PLASTIC STRAIN

POZORNY MODUŁ YOUNGA BLACH STALOWYCH PO ODKSZTAŁCENIU PLASTYCZNYM

The effect of plastic strains on the change of sheet metal behavior during unloading and reloading has been studied. On the basis of uniaxial tensile tests a little influence of plastic strains on the change of elastic properties of Al 6061 alloy has been shown, a 16% decrease of apparent Young modulus of DC04 steel and as much as 22% DP600 steel. Apparent Young modulus decrease during plastic strains has a great influence on the accuracy of modeling the final shape of a drawpiece. The corrected Young modulus allowed to significantly improve the accuracy of modeling a three-point sheet metal bending.

Keywords: Young's modulus, plastic strain, sheet metal, steel, Al alloy

Zbadano wpływ plastycznych odkształceń na zmianę zachowania się blach podczas odciążania i ponownego obciążania. Na podstawie przerywanych prób jednoosiowego rozciągania wykazano niewielki wpływ plastycznych odkształceń na zmianę właściwości sprężystych blach ze stopu Al 6061. Dla stali do głębokiego tłoczenia DC04 wraz ze zwiększaniem wstępnego odkształcenia plastycznego nastąpił spadek pozornego modułu Younga o 16% a dla ferrytyczno-martenzytycznej stali DP600 spadek zwiększył się do22%. Zmiana pozornego modułu Younga podczas plastycznego odkształcania ma duży wpływ na dokładność końcowego kształtu uzyskanego podczas matematycznego modelowania. Zastosowanie skorygowanego modułu do modelowania trzypunktowego zginania pozwoliło na poprawę dokładności obliczonego kąta sprężynowania w porównaniu do obliczeń z początkowym modułem sprężystości.

1. Introduction

The accuracy of a drawpiece, especially in a car industry, is becoming more and more important. The requirements are the result of assembly automation demand, the product quality, enormous global competition as well as the consumer's requests. Typical deviation from the nominal size in whichever point for autobody drawpieces is 0.5 mm whereas for products of increased precision amounts 0.25 mm; therefore, designing a technological process and tools is becoming a huge challenge, which demands from the designer to have a great deal of experience; this, however, does not secure from time-consuming and expensive correction of manufactured tools.

The main cause of difficulties with ensuring the accuracy of drawpieces is springback arising after unloading a drawpiece. Predominant processes of bending with heterogeneous distribution of strains on the metal sheet thickness, big curvature radiuses, big sheet metal areas unsupported by tools cause considerably big springbacks. It is more troublesome in open drawpiece forming processes or, in the case of parting drawpieces with closed flange. Currently, the problem is becoming more and more serious, since the increasing share of shaped materials consists of metal sheets of high strength- AHSS steels (dual phase steels, TRIP, TWIP) with yield point of 500-1200 MPa, which multiplies springback.

The possibility to predict spring-backs, which is essential for the capability of correcting them, apart from simple bending process, were extremely limited up till now. Using the finite-element method for designing metal sheet forming processes allows for modeling loading as well as unloading process. While loading process usually enables for receiving good accuracy, in the unloading process accuracy of mapping and convergence problems still contribute to troublesome difficulties [1-4]. The lack of convergence is most often caused by incorrect model parameters. Springback during metal sheet forming is so big that unloading in one step can cause errors of contact and convergence. Big stress gradients and their

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fast changes usually require other parameters of unloading process modeling in comparison to loading phase. Rapid development of commercial FEM packages, corrected contact algorithms enable more efficient and effective modeling of unloading and springbacks in the metal sheet forming processes.

The main factor deciding about the unloading stage mapping fitting is still the accuracy of material parameters. The work [5] depicted the important role of the accuracy in Young modulus determination as well as flow stresses within the yield point proximity (Fig.1). During loading modeling, which from forming forces and strain limit point of view is the main task, both elastic properties and flow stresses within initial strain range, are not so important since big strain values of the most stressed areas are crucial. This is why the Young modulus catalogue value and the mathematical approximation of a stress-strain curve are usually considered sufficient as a material model. During the unloading process all loaded areas of metal sheets including those very stressed, those of small plastic strains as well as those in the elastic state decide about the springback value. In such a situation comparatively weak adjustment of mathematical approximation of stress-strain curve for initial strains, typical for with the least-squares regression becomes important. The easiest solution is the use of a numerical experimental form of strain-stress curve, with the exact curve image within the whole range of strains [1,5].

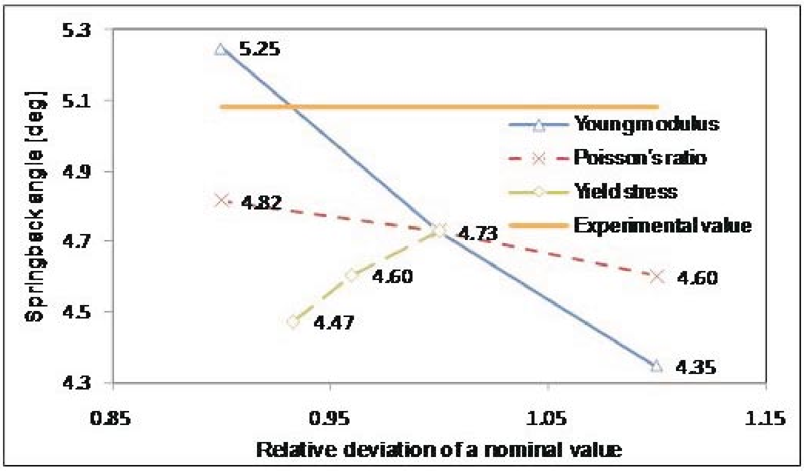

Fig. 1. The effect of the relative change of modeling parameter on the calculated springback angle during three-point bending

The Young modulus contributes more nagging problem. Its influence on the accuracy springback calculation is, as a matter of fact, the most considerable, obvious and well-documented. As a material constant the modulus is tightly connected with a material crystal structure and is used for calculation as such. It causes the unloading process after the strain to proceed according to the line marked by the Young modulus. Actually, a growing number of studies show that the Young modulus is not constant, but decreases in correspondence with a plastic strain value, and the size of change can reach as much as 30 per cent of the initial value [6-15]. Such a big change must influence the modeling of unloading processes accuracy. Although for bulk forming the entire change of shape and dimensions after the unloading is comparatively small and the problem with the accuracy of the springbacks evaluation is almost inexistent, for drawpieces the entire change of shape and dimensions after the unloading is significant for the quality of the product itself as well as the assembly process efficiency. Thus, it is important for metal sheets modeling processes to calculate such elastic constant for material used that it would improve the accuracy of mathematic modeling.

The loading and unloading process is most convenient to observe on the example of uniaxial tensile test (Fig.2). On the extended area of unloading and reloading a non-linear unloading course with an average obliquity clearly different from the initial strain obliquity is visible. The reloading also depicts non-linearity, tough not so noticeable. The reason for such a behavior of a material could be:

- an internal stress
- a change of texture
- an increase of mobile dislocations density

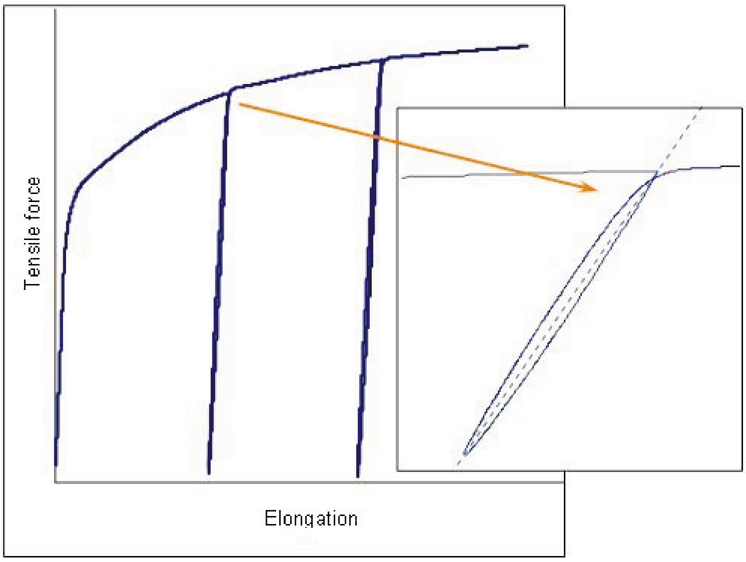

Fig. 2. The scheme of unloading and reloading in uniaxial tensile test

As an intermolecular interaction derivate, an elastic constant is a material constant connected with the crystal net and because of this dependent on the orientation. Isotropy of elastic properties of polycrystalline materials, assumed often from practical reasons, does not have to be true in the case of the clear texture presence. The actual material structure grain boundary, linear and point defects presence can also change material elastic properties, however, the material should stay linear elastic without hysteresis.

During uniaxial tensile test with small strains the values and heterogeneity of the internal residual stress are small and if only they could influence the yield point with the strain direction change (Bauschinger's effect), it is hard to expect that it could have any influence on the non-linearity during reloading and consequentially during unloading. Similarly, the texture change present at small strains is too little to have an influence on elastic material behavior changes. Non-linearity in the range of elasticity as well as the changes of material elastic properties during not big strains could be caused by the considerable number of mobile dislocations which are piled before obstacles during straining and reoccurring during unloading under the influence of local inner stresses near the obstacles.

Studies which are conducted in this field [7-9] confirm a dominant influence of mobile dislocations even for small plastic strains which is also an indicative of the possible contribution of bulging of parts of dislocations between points of their blocking. The movement of dislocations during unloading and reloading in a normal elastic state makes the straining not purely elastic and because of that fact in the works cited more adequate term of 'inelastic strains' appears. However, in the further part, remembering of a complex character of occurrences during unloading, a traditional term of elastic strains being closer to the technological term of springback would be used. The real value of Young modulus after loading stays unknown, since it is not an obliquity of a curve belonging to a nominal elastic range. Such elastic modulus can be determined with the help of elastic wave propagation velocity measurement. Values calculated from the tensile curve obliquity in this situation are not elastic constant, thus for such value 'apparent Young modulus' term more and more often begins to be incorporated [10,11].

Taking into consideration forming process modeling needs, the process of unloading and reloading can be treated as a non-linear elastic process, which requires calculating a material model that is to say the apparent Young modulus not only within the function change of inelastic strain during unloading and reloading but also within the function of global strain. Because there is no such model, as an initial specification for technological purposes, an average apparent modulus value dependent only on a total plastic strain could be accepted.

The influence of a plastic strain on the change of the apparent Young modulus is currently often examined because of the data needed for modeling and designing forming processes [9, 10, 15]. A modulus change together with the strain is schematically depicted in Fig. 3. A quick modulus change with initial strains and vanishing of the change with a strain increase to the saturation value or even to receiving minimum with bigger strains are the characteristic features. Recommended formula which would describe those changes is a dependence suggested by Yoshida and Uemori [11]:

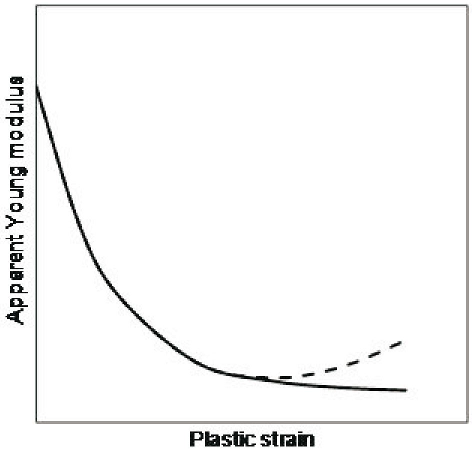

Fig. 3. Exemplary changes of the apparent Young modulus with the plastic strain

$$E_A = E - (E - E_S)[1 - e^{(-Bz_p)}]$$

where – E_A is the current, apparent Young modulus

E – the initial Young modulus

ε_p – the plastic strain

E_S – the saturation modulus

B – the constant

Dependences of such type can concern only averaged value of the apparent Young modulus not taking into consideration its non-linearity. Scarce data forces an experimental designation of the apparent Young modulus for material used change.

The aim of the work was determination of the plastic strains effect on the Young modulus for chosen materials of metal sheets used in a automotive industry.

2. Experiment

Three metal sheets have been chosen for the purpose of the study – low carbon steel DC04, dual phase steel DP600 and aluminum alloy 6061 T4. The choice of materials was driven by those particular metal sheets used in the Institute for products forming modeling and analyzing as well as for conducting crash tests. The first material is the typical low-carbon, soft steel for deep drawing, with a big elongation, high strain hardening and high normal anisotropy. DP600 steel, dual phase steel belongs to a modern group of AHSS steels of high strength with good plastic properties. High flow stresses cause considerable springback, and that is the reason for the difficulty with ensuring the proper accuracy of drawpieces. Metal sheets from Al 6061 alloys are often used for manufacturing light constructions. The low Young modulus and resulting from it big springback also cause problems with drawpieces accuracy. Determined chemical constitution of studied metal sheets was situated in the middle of proper subjective standards whereas basic mechanical properties were shown in Tab. 1.

TABLE 1

Tested metal sheets properties

Material	Yield Point R_e[MPa]	Ultimate Strength R_m[MPa]	Elongation A [%]	Thickness [mm]
DP 600	377	650	29	1,25
DC04	210	310	38	0,8
6061	192	302	18	1,05

Straining was conducted in uniaxial tensile test on the Instron 3360 testing machine equipped in 50mm base extensometer, using the samples according to PN/EN 10002 standard, 12mm width and 80 mm parallel part length. The main strain scheme were the series of the strain increments in correspondence to assumed value after which unloading and reloading were applied up till the maximal force exceeding were conducted. On the basis of recorded results true stress vs. the true strain were calculated, on the basis of which the apparent Young modulus has been determined.

3. The results

In the Fig. 4 the interrupted tensile curves of the DP600 steel sample together with the continuous curve have been depicted. Curves after reloading go the uninterrupted curve alike and even with this particular scale the hysteresis during the unloading and reloading are visible. For the DC04 steel (Fig.5) tensile curves, both continuous and interrupted, go similarly, however, after reloading curves show insignificant overgrowth similar to the upper yield point, even though the pause between unloading and loading never went beyond 3 seconds. Aluminum alloy samples (Fig.6) after direct reloading showed the upper yield point as well as comparatively long transient area. In Fig.7 initial reloading curve fragments in true stress vs. true strain of DP600 steel are moved in the way that beginnings cover themselves. The difference between curves slopeand curvature in the nominally elastic area which pictures the influence of the plastic strain on the elastic behavior change of steel during the reloading are clearly visible. The detailed picture of changes during unloading and renewed loadingof DP600 steel has been depicted in Fig. 8. The line that connects the points of origin and end of unloading depicts a considerable non-linearity during the unloading and a bit smaller during reloading. The choice of parameters is considered important for the description of such a process. For the sake of the observation of the change connected with plastic straining, there has been chosen a line which were a linear approximation of the initial fragment of loading E_L, choosing arbitrary at the same time a fragment for regression. The slope of the line connecting the beginning and the ending of the unloading curve E_u was the second parameter. Slopes of the unloading curve at the beginning E_{ub} and the ending of the curve E_{uf} have been also determined. Those slopes were calculated as chords of the first and fourth point of the curve. Slopes calculated as an approximating curve derivative determined at its ends have been also checked. For studied materials the second degree approximating curves were exactly fitted whereas derivatives at the endings different only slightly from the value calculated by the chords; this is why in the further part of the work only the latter values were analyzed.

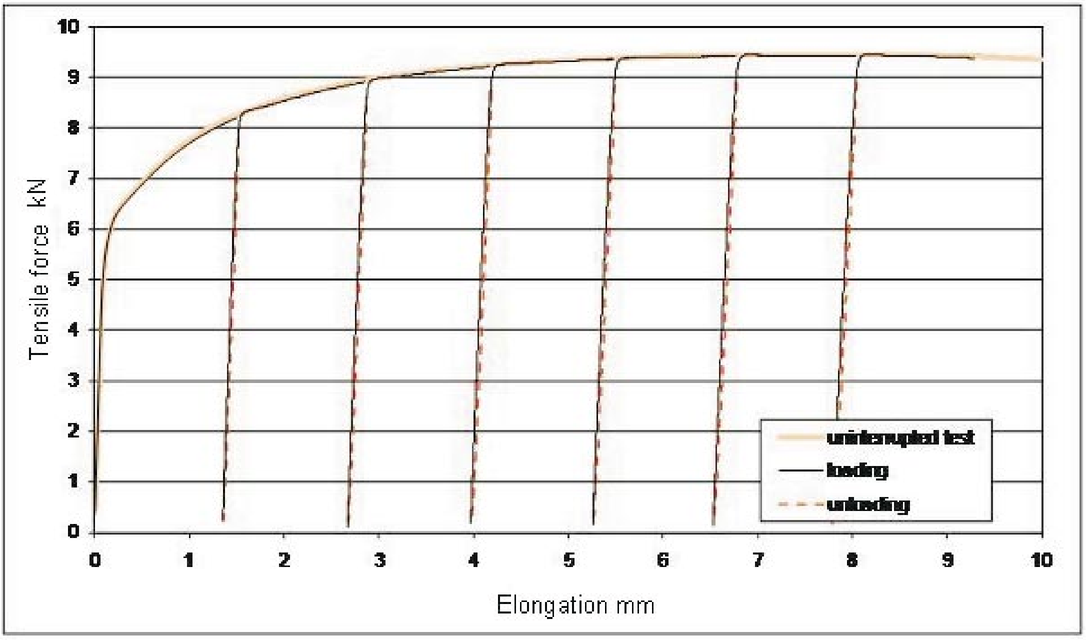

Fig. 4. Interrupted tensile curves of DP600 steel

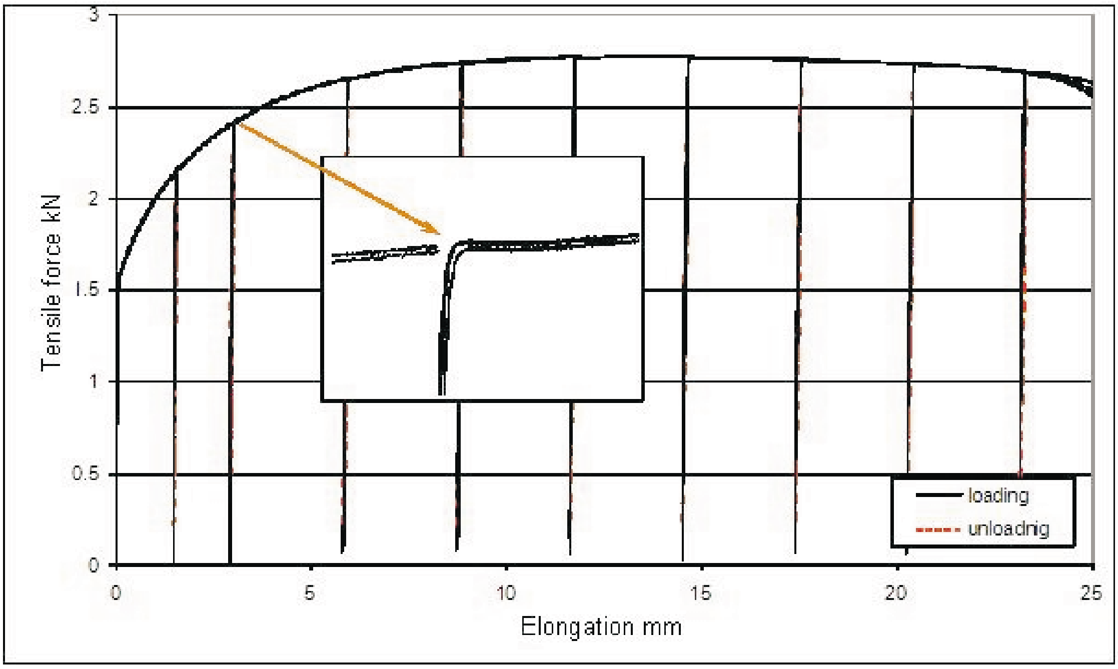

Fig. 5. Interrupted tensile curves of DC04 steel

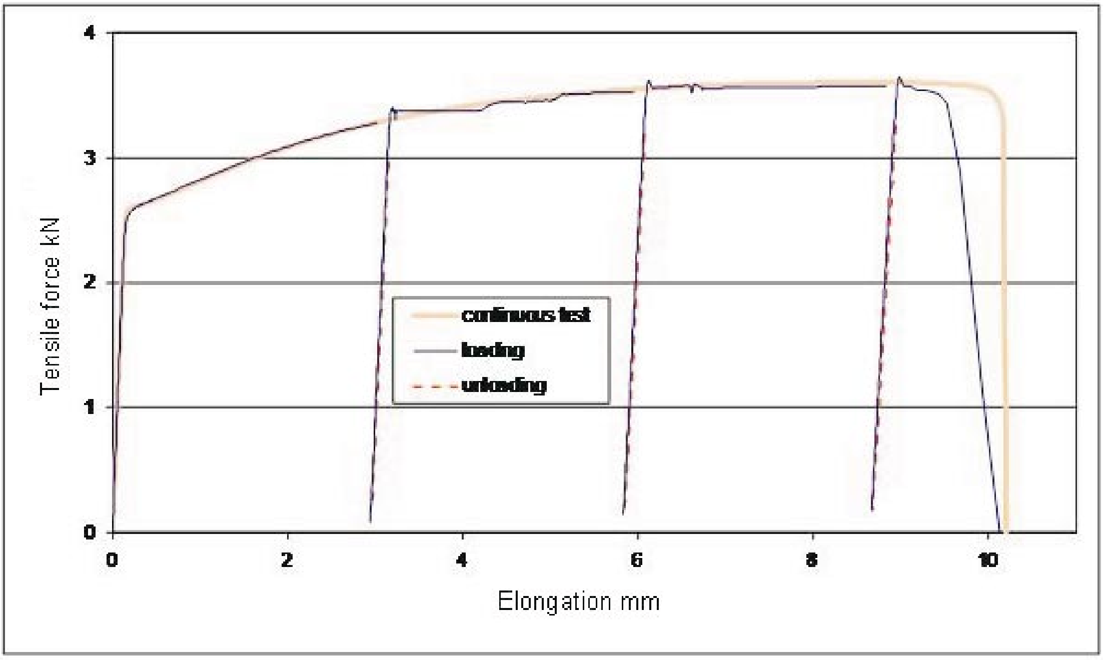

Fig. 6. Interrupted tensile curves of Al 6061T4 steel

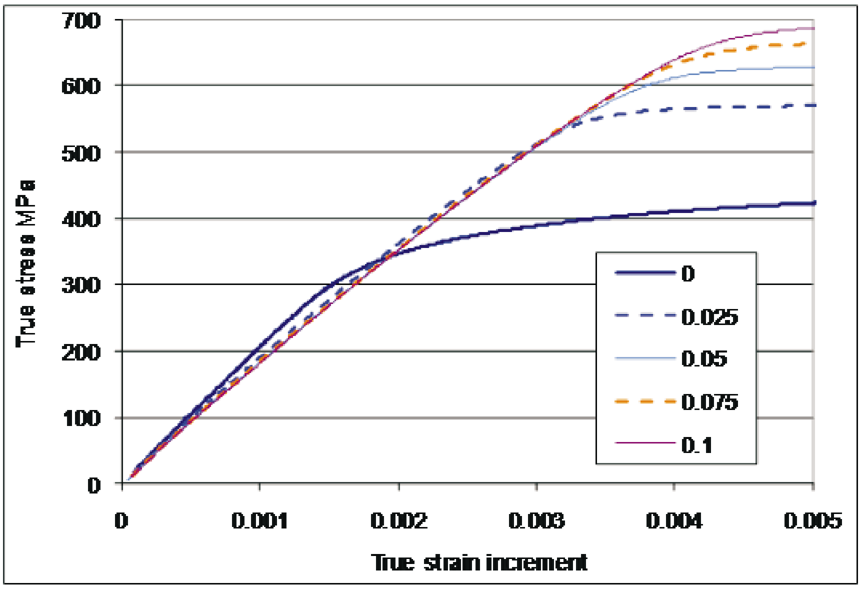

Fig. 7. The comparison of the successive reloading curves moved to the mutual beginning

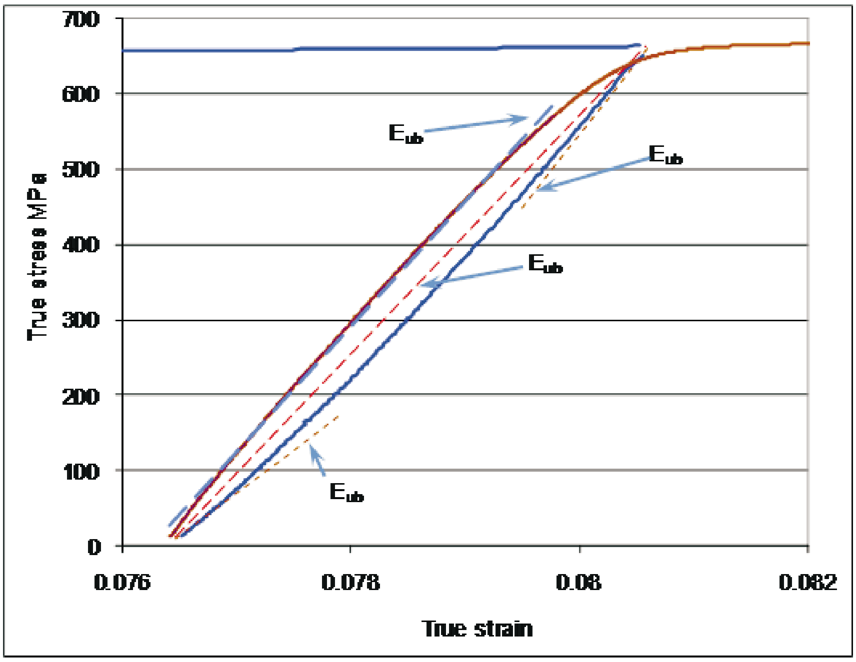

Fig. 8. Detailed picture of DP600 steel unloading and loading and parameters used for the process description

The influence of plastic strain on the studied parameters for Dp600 steel has been showed in Fig. 9. According to the data provided by the literature apparent elastic coefficients decrease with plastic strain, faster when it comes to smaller strains. For this steel practically all changes undergo within the range of strains up till 3%, and with bigger strains changes are extremely insignificant. Two basic curves are the average apparent Young modulus during E_L loading which decrease by 16 per cent and an average modulus during E_u loading differing with 21 per cent from the initial elastic modulus. Due to the significant curve slope of the unloading curve the slope at the beginning (E_{ub}) decrease by only 4 per cent whereas at the end of the unloading (E_{uf}) it decreases by as much as 38 per cent.

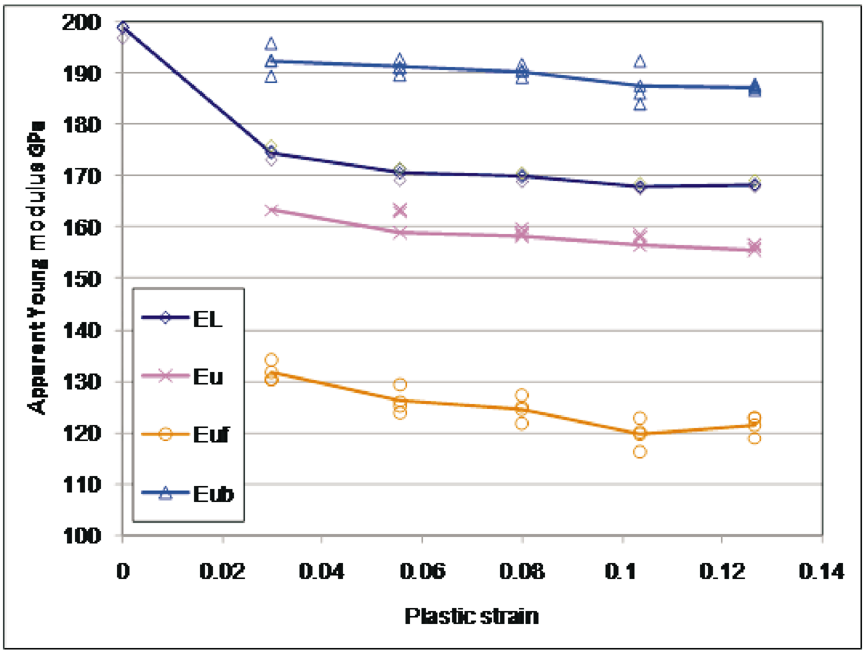

Fig. 9. The effect of plastic strain on the changes of the parameters depicting DP600 steel unloading and reloading

The results for DC04 steel has been showed in Fig. 10 whereas the comparison with DP600 steel in Fig. 11. Soft steel depicts lesser changes of elastic properties with the plastic strain both during unloading and reloading. Non-linearity of changes is also lesser especially during unloading, however, initial slopes during unloading (E_{ub}) for both steels are very similar. A considerable difference at the end of the unloading is noteworthy.

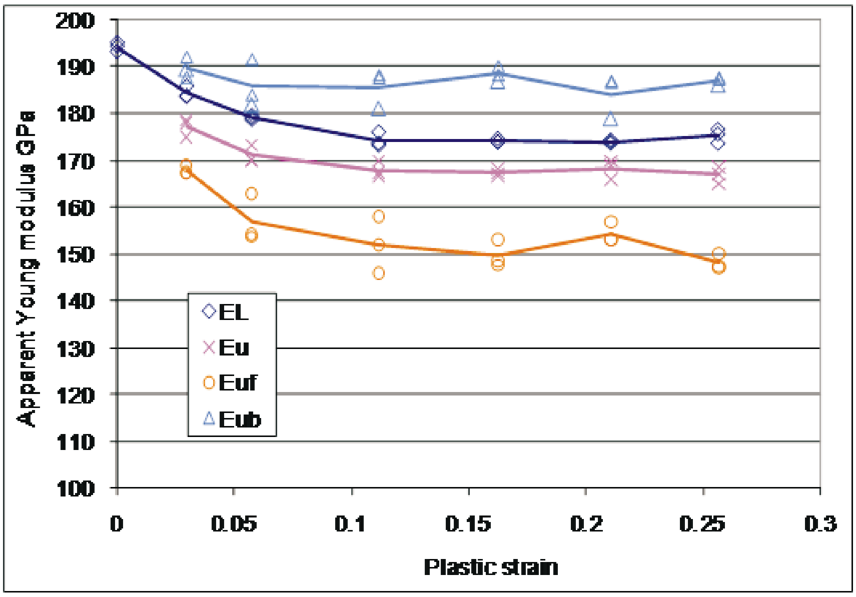

Fig. 10. The effect of plastic strain on the changes of parameters depicting DC04 steel unloading and reloading

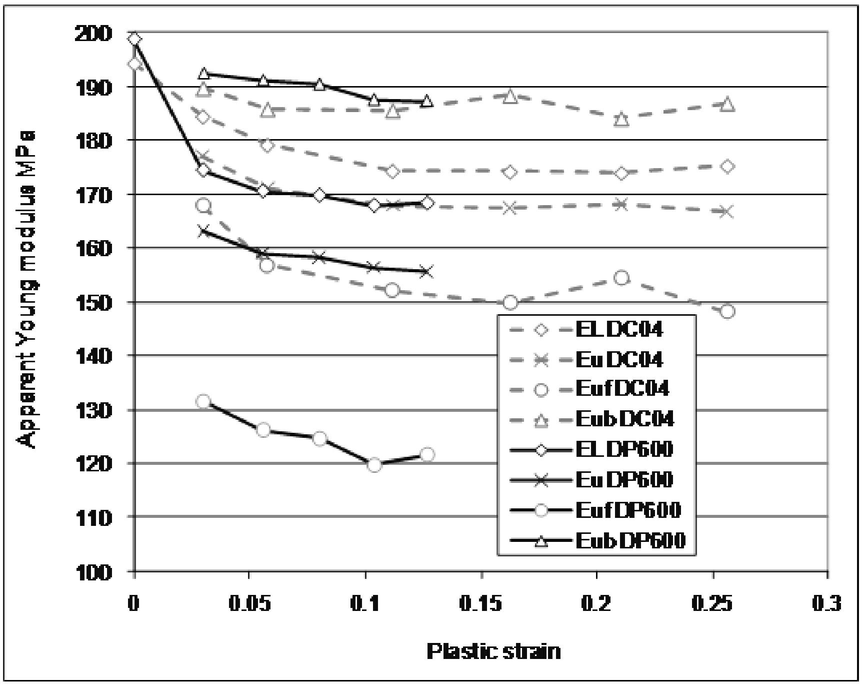

Fig. 11. The comparison of the change of elastic properties of the tested steels after straining

Average elastic modulus changes of the studied Al alloy during straining (Fig. 12) are considerably smaller than for steels and the character of changes is different – average modulus slowly decrease whereas with strains bigger than 0.09 they slowly increase. The comparison of the average, relative Young modulus referred to the basic initial values is shown in Fig. 13, from which it can be concluded that if for Al alloy changes are not significant and stays within the range of 4%, changes were very big for steels especially for high strength steels e DP600.

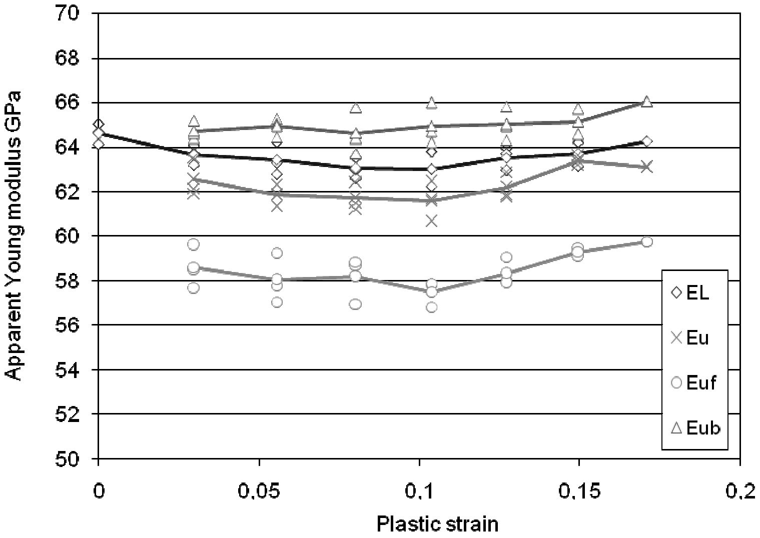

Fig. 12. The effect of plastic strain on the changes of parameters depicting 6061 T4 Al alloy unloading and reloading

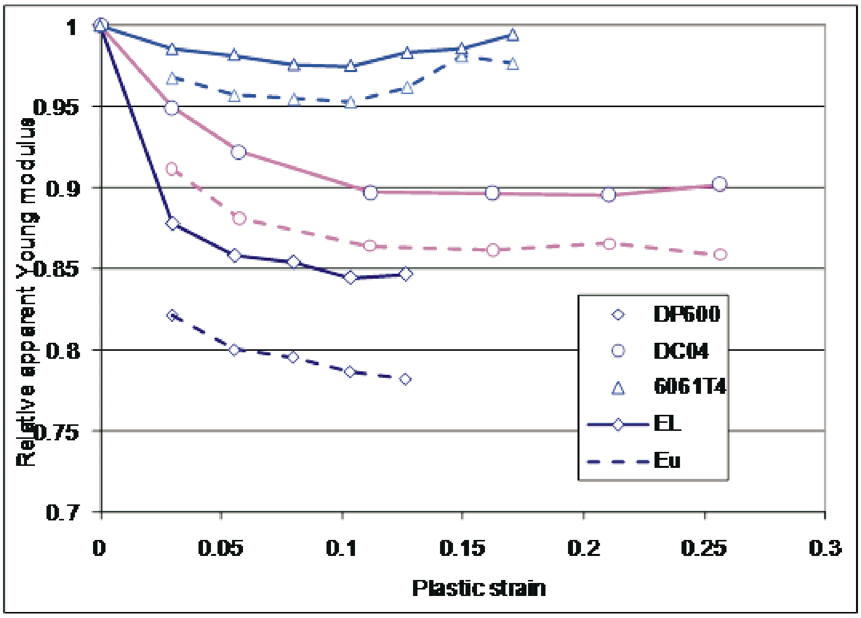

Fig. 13. The effect of plastic strain on the changes of relative parameters depicting unloading and reloading tested materials

Presented data should be helpful with improving the accuracy of the modeling of sheet metal forming processes. Efficient use of this data depends on the capability of using them in FEM programs and on proper choice of parameters describing elastic properties. In loading process, with the significant plastic strains participation. the role of elastic strains is comparatively small and because of that the influence of the elastic modulus accuracy in the case of metal sheets could occur only in elastic areas which are not supported by tools. From the ready drawpiece point of view much more important is the accuracy of Young modulus during unloading. Most often average unloading modulus is chosen, which in the case of materials with comparatively small non-linearity seems to be reasonable. For materials that show big non-linearity during loading such simplification can be insufficient. During uniaxial tensile test the strains distribution and at the same time residual stress arrangement over the cross section is almost homogeneous. In real drawpieces there exists a big strains heterogeneity in the thickness of the metal sheet, and at the same time elastic strains during unloading are not completely removed, the final shape of a drawpiece is an outcome of heterogeneous stress distribution balance. Their values are relatively small thus the final unloading slope seems to be more important in such a moment. Problem would consider mainly sheets metal of the type of AHSS (DP, DC, TRIP, TWIP) with a very high yield point and, as the data shows for DP600 steel, with possible big non-linearity during loading [16-18].

MSC MARC package, used by the author, is not currently capable of directly incorporating the Young modulus changeable with the plastic strain. Analysis of capabilities of creating appropriate user procedures or choosing other software for modeling are currently being conducted. In spite of it the program was used for preliminary testing of corrected Young modulus using for analyzing three-point bending of DC04 steel which was studied experimentally and modeled for the elastic modulus constant (Fig.1) [5]. The experimental set has been depicted in Fig.14. Bending modeling was conducted with an average apparent Young modulus during unloading after 12% plastic prestrain (Fig.10) and with the initial Young modulus The differences of the shapes after full load and after unloading for initial and corrected modulus are shown in Fig.15.The comparison shows that shape differences during loading are relatively small while during unloading they are significantly bigger. The results of experimental and modeled of the spring back angle has been displayed in Tab.2 together with the angle of the sample's arm for full loading . The use of two different Young modulus caused the angle difference in loading by only 0,5° with the big elastic only strained areas. Changes after unloading are bigger especially for bigger punch strokes and for steel with the high yield point. The comparison of the experiment's outcome showed that the modeling accuracy of sprin gback angles has been significantly improved.

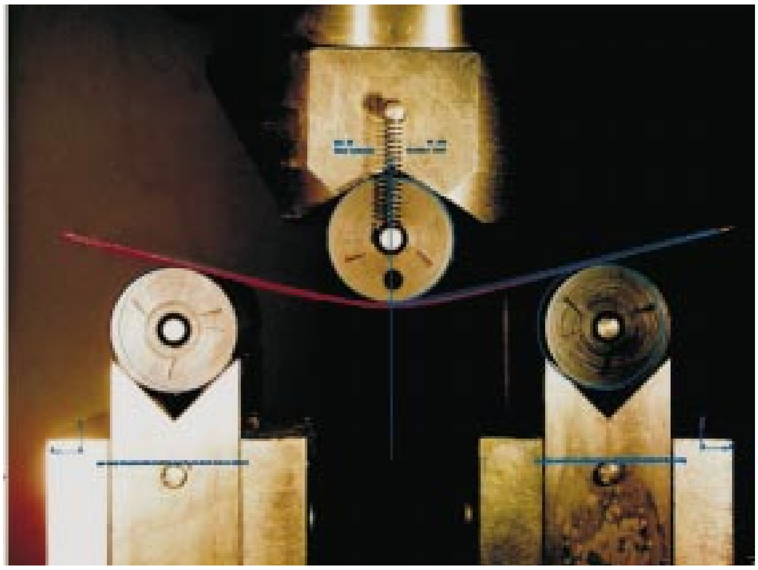

Fig. 14. Experimental set for three-point bending

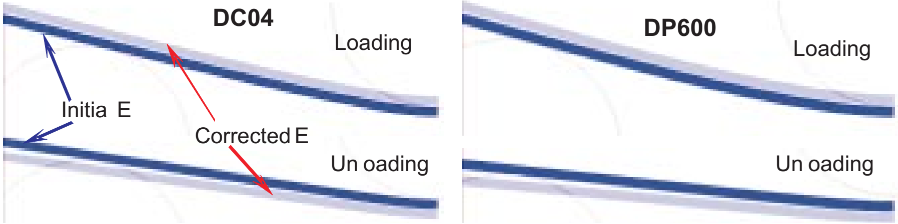

Fig. 15. The modeled shapes of bended parts for full load and after unloading

TABLE 2

Comparison experimental and calculated springback for initial and corrected Young modulus

Material	DC04		DP600	
Punch stroke mm	10	30	10	30
α_L° – E $_{\text{initial}}$	14,0	38,8	14,8	40,5
α_L° – E $_{\text{corrected}}$	13,8	39,1	15,7	41,0
springback – E_{initial}	4,7	6,2	8,6	11,5
springback – $E_{\text{corrected}}$	5,4	7,3	10,5	13,6
springback – experimental	5,1	7,0	9,9	13,0

The distinctive improvement of modeling quality even for simplified Young modulus correction points only at the intentionality of preparation of FEM programs for using Young modulus changeable with plastic strain.

4. Conclusions

Plastic strains of metal sheets change to a great extend material's elastic properties, which overlooked, causes significant decreasing of the accuracy in modeling the final shape of a drawpiece.

The apparent Young modulus changes, studied during interrupted tensile tests, were insignificant (5%) for AL 6061T4 alloy, significant (12%) for DC04 steel and very big (16%) when it comes to DP600 dual phase steel.

The usage of the corrected Young modulus for modeling the three-point bending process significantly improved the accuracy of modeling springback and at the same time the accuracy of the predicted final shape of a drawpiece.

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