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OPTICAL MEASUREMENT OF THE STRAIN-STRESS RESPONSE DURING UNLOADING OF METAL SHEETS UNDERGOING LARGE PLASTIC DEFORMATIONS

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Abstract: *The optical measurement techniques have shown more precise results about the mechanical behaviour of materials. They enjoy the advantages of being non-contact, full-field, with a high spatial resolution and offer the possibility to observe the local mechanical behaviour. The paper presents the analysis by Electronic Speckle Pattern Interferometry (ESPI) of the unloading behaviour of metal sheets that undergone large plastic deformations. The springback of the sheet metals after large deformations during deep drawing is not a strongly linear process with a constant Young's modulus but, the stress-strain behaviour during the unloading phases, shows considerably non-linear and inelastic effects. Unloading of two types of steel sheets for cold forming, a cold-rolled high strength micro-alloyed steel and a low carbon steel sheet, and an aluminium alloy sheet have been analysed using the ESPI method. The experimental measurements showed that the stress-strain curve during unloading is non-linear and the secant moduli of unloading curves decrease with increasing of prestrain.*

Key words: *unloading, ESPI method, springback, metal sheets*

1. Introduction

The springback prediction in deep drawing is an important issue for the production of car bodies in the automotive industry. Springback, the elastically-driven change of the shape of a part during unloading after forming, has become a growing concern in the assembling process as currently the manufacturers increasingly use steels with higher strength.

A fundamental assumption of most plasticity models is that the unloading process, after elastic-plastic deformation, is elastic and linear with the same Young's modulus as in loading (Figure 1a). Sometimes, it is pointed out that the unloading process and a following reloading could show non-linear and inelastic effects (Figure 1b). On the one hand, the theoretical tool of Bauschinger effect and kinematic hardening can describe reasonably well the deformation behavior of reverse loading but, on the other hand, it doesn't describe the material behavior shown Figure 1b.

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Yamaguchi at al. (1998) [1] reported some experimental observations and that Young's modulus of sheets metals after biaxial stretching drastically decreases with prestraining. Yoshida et al. (2001) [2] investigating elastic-plastic behavior of steel sheets for deep drawing, observed during loading reversal a decrease in Young's modulus with increasing prestrain. Cleveland (2002) [3] have found that the average tangent modulus during unloading and reloading differs from their elastic values in the undeformed state and that this modulus referred as the "springback modulus" decreases linearly with plastic prestrain.

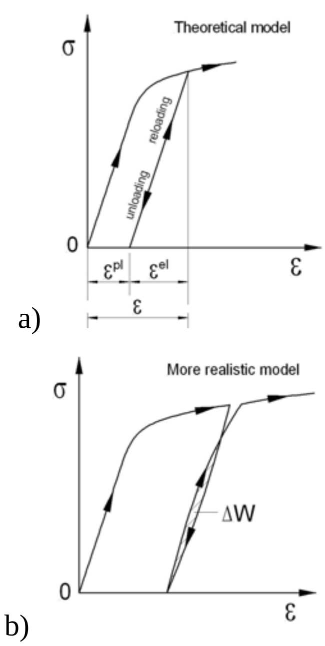

Fig. 1. *Elastic-plastic material behaviour a) theoretical model, b) realistic model*

The paper presents a study of strain-stress response during the unloading of metal sheets undergoing large plastic deformations. The applied experimental method is the Electronic Speckle Pattern Interferometry (ESPI). High precision of strain measurement, no-contact, non-destructive and full-field information are major advantages of the method in comparison with other techniques.

2. Materials and Methods

The ESPI is an optical measuring technique that allows rapid and highly accurate measurement of displacements and deformations. It enjoys the advantages of being non-contact, full-field, it has a high spatial resolution and sensitivity. The ESPI principle is well described in the literature [4,5]. Instrumentation for the in-plane, one-dimensional ESPI set-up includes as typical components an Nd:YAG laser (100 mW, λ=532 nm) and optical elements presented in Figure 2.

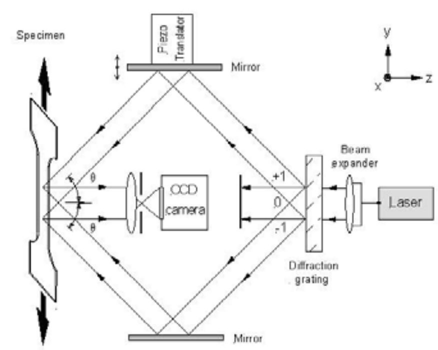

Fig. 2. *Optical arrangement of in-plane ESPI set-up*

The beam splitter used was a diffraction grating (1200 lines/mm). The "+1" and "-1" diffraction orders form two plane coherent waves at an angle of $\theta = 25.40^o$ for the illumination of the measuring field with a size of approximately 20 x 20 mm. To increase the performance of the ESPI, a temporal phase shifting technique is used. The image processing system consists of a CCD camera (AVT Dolphin F145B, 1392x1040 pixels resolution, 15 fps frame rates) and self developed software for image acquisition and evaluation of interference images. The speckle interferometer components were mounted on the 100 kN capacity Zwick/Roell testing machine. The load–crosshead displacement data were collected from the testing machine and the full-field specimen displacements and strains during unloading were measured by ESPI.

With the above described method three types of metal sheets were investigated in the as-received state: two types of steel sheets, cold-rolled high strength micro-alloyed steel sheet (H320LA / EN10268), a low carbon steel sheet (DC04 / EN10130) and an aluminium alloy sheet (AlSi1.2Mg0.4 / EN AW6016). All sheets had a thickness of 1 mm. The main focus of the investigations was oriented to the steel type H320LA. The traditional deep drawing steel sheet DC04 and aluminium alloy AlSi1.2Mg0.4 were investigated for comparison.

2. Results and Discussion

The stress-strain curves of specimens are shown in Figure 3. For all sheets the difference between rolling (RD) and traverse (TD) directions was very small.

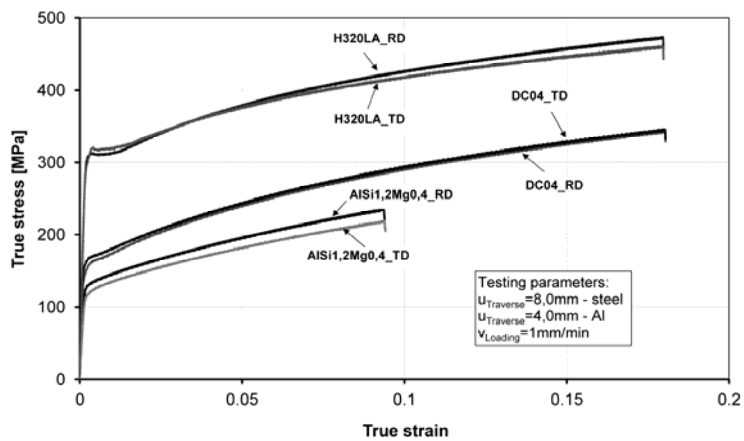

Fig. 3. *Stress-strain curves for tested metal sheet specimens*

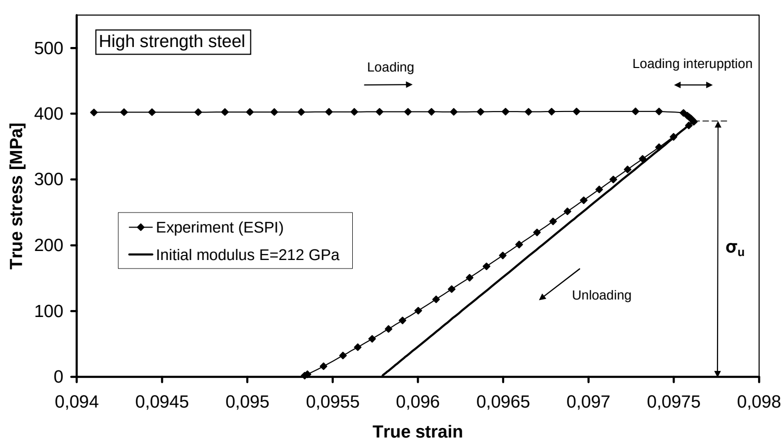

Fig. 4. *Unloading strain-stress response for the high strength steel sheet*

Figure 4 shows the typical stress-strain curve of the high strength steel sheet H320LA corresponding to a prestrain value of approximately $\varphi = 0.095$. The dots represent discrete full-field ESPI measurement steps and only a small part is visible near the end of the loading curve. After loading the specimen up to a desired prestrain level the crosshead was stopped for a short period of time and then unloading began. If the loading of the specimen is interrupted, a drop in stress was observed experimentally.

If the unloading response is observed carefully, the stress-strain curve shows two remarkable effects. First, in contrast to the basic assumptions in plasticity theory, the mechanical behaviour during unloading is clearly non-linear. Secondly, it can also be noticed that the springback is considerably larger than expected according to the primary Young's modulus.

The high strength steel as well as the low carbon steel showed the described non-linear effects. In case of aluminium alloy the effect is small. For the steel samples prestrained in tension to φ=0.18**,** the measured strain recovery exceeds the expected linear recovery by about 25% for the high strength steel and 21% for the low carbon steel. For aluminium alloy prestrained in tension to φ=0.094 the measured strain recovery was with 6% greater than the linear expected value.

All measurement results are comparatively presented in Figure 5.

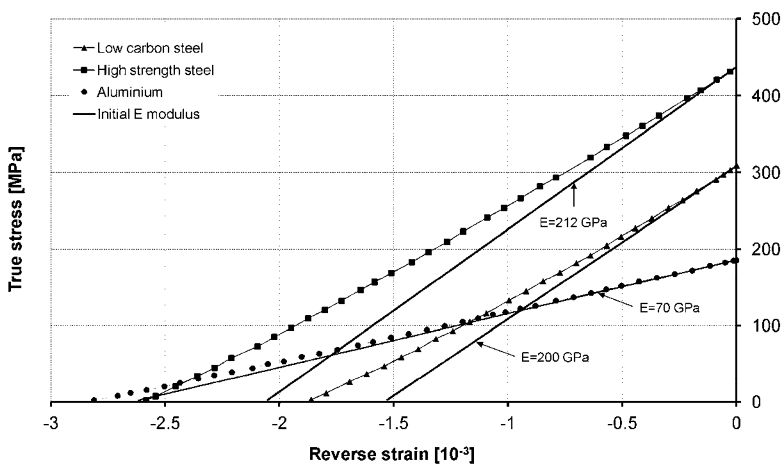

Fig. 5. *Inelastic recovery for the steel and aluminium sheets in comparison with the initial E-modulus*

To study the influence of the strain rate upon the strain-stress response during unloading the high strength steel specimens were loaded to a prestrain of $\varphi = 0.18$ with four crosshead speeds of 0.02, 1, 10 and 100 mm/min. This is equivalent with an initial strain rate of $0.07x10^{-5}$, $3.5x10^{-5}$, $35x10^{-5}$ and $350x10^{-5}$ s^{-1}. The obtained results point out that there is no marked influence of the loading strain rate upon unloading strain-stress response of the steel sheets.

It was found that inelastic strain recovery increased when the value of prestrain became larger.

Unloading secant modulus is obtained by calculating the slope of the line joining the coordinates of the start and end of unloading. From the unloading stress-strain curve at each value of stress decrement, the instantaneous secant modulus defined as the stress to strain ratio

$$E_S = (\sigma_u - \sigma)/(\varepsilon_u - \varepsilon)\,, \qquad (1)$$

can be calculated.

Values of instantaneous secant modulus as function of prestrain and normalized stress σ/σ_u are plotted in Fig. 6. The instantaneous secant modulus also decreases with increases of prestrain. The curves corresponding to a higher prestrain value are situated under those corresponding to a lower prestrain value.

Different stages characterize the instantaneous secant modulus curve, noticed also by Cleveland et al. [3]. At the beginning of unloading (0.9< σ/σ_u <1) the instantaneous secant modulus decrease rapidly, then it follows a relatively gradual decrease (0.1< σ/σ_u <0.9). This Young's modulus is reduced in comparison with its initial elastic value and further decreases with the diminishing stress. The first stage is strongly influenced by the load interruption time. Immediately unloading after loading produces a drop of the instantaneous secant modulus, which is attenuated after the stress value reached the threshold value.

Concluding, the unloading secant Young's modulus decrease with the increase of prestrain level and the influence of the prestrain path upon inelastic strain recovery is minor.

When the prestrain values become large enough it approaches its asymptotic value (saturated value).

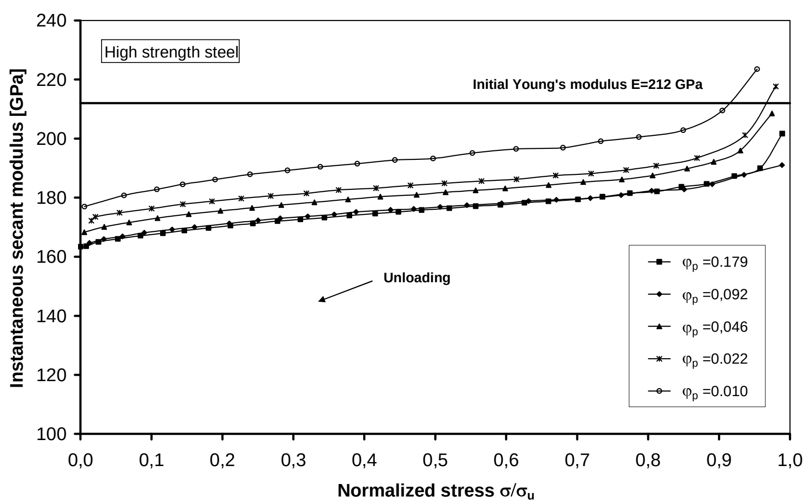

Fig. 6. *Instantaneous secant modulus of unloading for high strength steel sheet*

4. Conclusions

In this paper it has been shown that the full-field and real time technique of the ESPI is eminently suited to analyse the strain recovery by unloading of steel and aluminium sheets for cold forming. High precision of strain measurement, no-contact, non-destructive and full-field information are major advantages of the method in comparison with other measurement techniques. The application of ESPI to precise measurement the Young's modulus of unloading gives the possibility to view in another perspective the unloading response of the metal sheets undergoing large plastic deformation.

For the steel sheets samples stretched to large prestrain value (18%) the measured strain recovery exceeded the expected linear recovery by about 25% for the high strength steel (H320LA) and 21% for the low carbon steel (DC04). For aluminium alloy (AlSi1.2Mg0.4) the recovery effect is reduced (~6%). The unloading Young's modulus decrease with the increase in total amount of prestrain and the influence of the prestrain path upon inelastic strain recovery is minor. It can be assumed that strain recovery is not purely elastic and is microplastic in nature. The inelastic effects are caused by the mobile dislocation response after the load removal and the arrangement of the dislocations structure. In case of long range stresses there is a difference between stored energy of cold work after and before load removal [6]. We assume that supplementary energy release, apart from recoverable elastic energy, is responsible for the inelastic recovery by unloading. The influences of the accumulated prestrain value, unloading stress decrement and initial value upon secant modulus of unloading can be quantified in an empirical relation describing very well its evolution [5].

Prediction of springback considering an inelastic strain recovery by unloading instead of linear elastic theory is significantly improved. Including a "variable" E-modulus in a material model describing the springback effect brings it more closely to reality [7].

The measurement of both components of in-plane strain recovery during unloading and the analysis of the Poissons's ratio evolution can be carried out with a two dimensional speckle interferometry system in a similar way. Full-field strain data will offer interesting information especially in biaxial testing.

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