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EXPERIMENTAL AND BY SIMULATION ANALYSIS OF RESIDUAL STRESS AND SPRINBACK IN THE CASE OF METAL SHEETS FORMING BY USING THE “THREE BARS” METHOD

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ABSTRACT

The experimental investigation of the residual stresses in the case of drawn parts is a difficult problem because of the complexity of forming operations and formed parts geometry. A solution of the problem can be than the simulation of the forming process and residual stresses distribution, but for a much more certitude of the results the simulation method must be experimental verified. An efficacious method proposed and used by Chandra (1993) and LMecA-ESIA Annecy consists in the experimental control of residual stresses for a simple case by applying the “*three bars*” *method. Based on the experimental investigation, the results obtained from simulation can be compared and in the case of their coincidence a mathematical model can be than elaborated, adopted and extended for complex forming operations and formed parts.*

The paper presents the results obtained from such simulation and experimental investigation of residual stresses and springback generated in the case of metal sheets tensile.

KEYWORDS: stresses, springback, three bars method, simulation.

1. INTRODUCTION

Springback is a phenomenon caused by the residual stresses that occurs in machined parts after the tools removing [2, 4]. Hence, to investigate this phenomenon we must know the state of residual stresses developed in part by its machining [1, 3]. But, the determination of residual stresses will return us to the classical problem of stress determination in machined materials. Much more, in the case of drawn parts made from metal sheets, the experimental determination and theoretical estimation of the residual stresses will be very difficult to be achieved because of complexity of the forming operations and formed parts geometry. An efficacious method proposed by LMecA-ESIA Annecy [5] consists in the experimental determination of springback and residual stresses for the simple case of metal sheets tensile. Based on this control a procedure can be elaborated, adopted and extended for determination of springback and residual stresses distribution in the case of complex forming operations and formed parts.

The present paper analyses the results obtained from experimental investigation, calculation and simulation of the residual stresses distribution and springback in the case of homogeneous sheets by using the tensile test on the basis of the “*three bars*“ method. The procedure proposed to investigate the residual stresses distribution and springback by applying the above presented method can be developed in the following steps: the experimental investigation, the calculation based on an elaborated model and the FEM simulation of the process in order to determine the springback, axial stresses generated by tensile loading and residual stresses by using the above mentioned “*three bars*“ method; the comparison and validation of the results obtained from the above mentioned techniques and the elaboration of conclusions concerning the possibility to determine the springback and residual stresses distribution in the complex cases.

2. PRINCIPLE OF THE METHOD

2.1 Experimental conditions

The method proposed by LMecA-ESIA Annecy [5] investigates the stresses and springback generated by the tensile test using an experimental device that performs the simultaneous investigation of three specimens having different modules of elasticity and lengths (Fig. 1). The device is composed by three samples which are fixed at both extremities by two grips. The lateral samples have the same lengths l_1 and the central sample has the length l_3. The grips are coupled on the tensile testing machine.

The samples, being fixed on the both extremities will suffer the same displacement Δl after the tensile test but different strains due to the difference in length, according to the following relations:

$$\varepsilon_1 = \varepsilon_2 = \ln\left(1+\frac{\Delta l}{l_1}\right), \quad \varepsilon_2 = \ln\left(1+\frac{\Delta l}{l_3}\right). \tag{1}$$

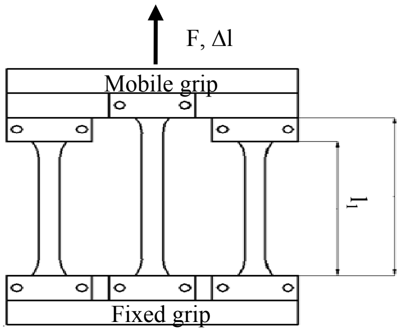


Fig. 1. Experimental device

After tensile the samples are unloaded and due to different strains of the samples, the equilibrium condition imposes the generation of the residual stresses in all three samples. Because the tensile load is the same the level of the stress-strain curves will be the same, but the position of the corresponding points of the both curves and materials will be different located on the curve (Fig. 2). This is because the shorter specimens will present higher strains for the same displacement Δl and hence it will start to be plastically deformed before the central one.

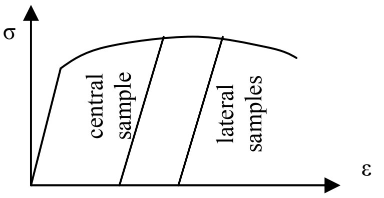


Fig. 2. The stress - strain curve for all three samples

After the loading is stopped, the length of the deformed specimens will be as follows: shorter specimens: $l_1^{'} = l_1 + \Delta l$ and longer specimen: $l_3^{'} = l_3 + \Delta l$. The discharge of the specimens will determine their springback and hence their identical displacement with $\Delta l^{'}$ (Fig. 3). The springback of the shorter specimens will be greater than the springback of the longer ones; the difference between the springback of specimens can be expressed by the inequality:

$$\varepsilon_{r1} \rangle \varepsilon_{r3} . \tag{2}$$

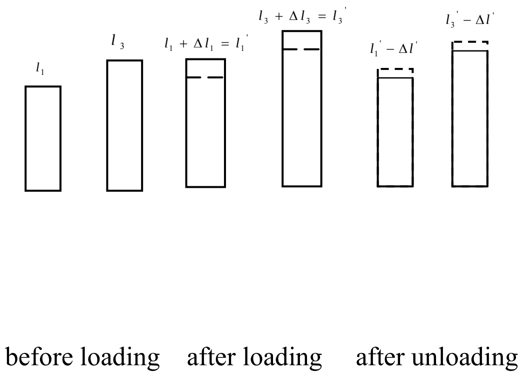


Fig. 3. The sample deformations

The experimental investigation of the residual stresses and springback based on the “three bars“ testing device (Fig. 4) was performed using the following two techniques for the strains determination: the technique based on axial extensometer; the image analysis technique using a CV1280 high resolution video camera. In order to record the grip displacement history, a reference point was chosen on the upper extremity of the central sample (Fig. 4), its displacement being recorded by a video camera; the data processing was made using the Vision Builder software. The samples geometry is presented in Fig. 5.

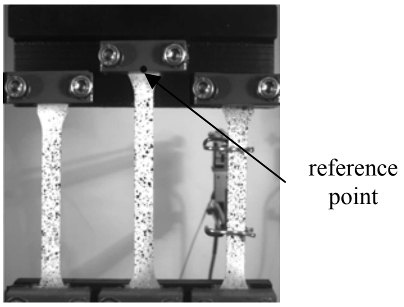


Fig. 4. “Three bars“ testing device

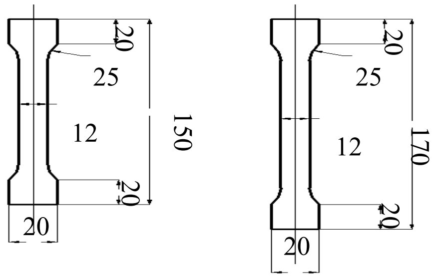


Fig. 5. Geometry of the samples

The mechanical properties of the material were determined using a Lloyd - EZ50 tensile testing machine. The data processing was made using the Nexygen Software.

2.2. Mathematical model

In order to establish a relation between the Δl springback parameter and the stresses, the springback and the stresses were calculated after loading and after unloading. By applying the Hollomon law after samples loading, the axial stresses were given by the following expressions:

$$\sigma_1 = K \cdot \varepsilon_1^n , \quad \sigma_3 = K \cdot \varepsilon_3^n \qquad (3)$$

where: ε_1 and ε_3 are the strains given by the equations (1). After the tensile test the samples are unloaded and due to different strains that were generated in the samples, the equilibrium condition imposes the generation of the residual stresses in all three samples. This state of stresses that were created will generate the springback of all samples. The strains corresponding to the springback are different, the strain for the lateral samples being bigger than the strain for the central sample.

When the grip is unloaded, the force applied by the machine will becomes zero. The equation of equilibrium can be written as follows:

$$\left(\sum F = 0\right): 2 \cdot F_1 + F_3 = 0 , \qquad (4)$$

where: F_1 is the axial force induced in the lateral samples and F_2 is the axial force induced in the central sample. The axial forces in the lateral samples and in the central sample have the following expressions:

$$F_1 = \sigma_1^{'} \cdot S_1^{'} , \quad F_3 = \sigma_3^{'} \cdot S_3^{'} \qquad (5)$$

By substituting the equations (5) in the equation (4) the equation of equilibrium will be obtained in the following form:

$$2 \cdot \sigma_1^{'} \cdot S_1^{'} + \sigma_3^{'} \cdot S_3^{'} = 0 , \qquad (6)$$

where: $\sigma_1^{'}$ is the residual stress induced in the outside samples, $S_1^{'}$ is the cross section area for the outside samples, $\sigma_3^{'}$ is the residual stress induced in the central sample, $S_3^{'}$ is the cross section area for the central sample. By applying the law of the volume constancy $dV = 0$ and substituting it in the equation (6), the following equation was obtained:

$$2\sigma_1^{'} \cdot l_1 (l_3 + \Delta l) + \sigma_3^{'} \cdot l_3 (l_1 + \Delta l) = 0 . \qquad (7)$$

The residual stresses induced in the samples after unloading phase can be written as follows:

$$\sigma_1^{'} = \sigma_1 - E \cdot \frac{\Delta l^{'}}{l_1} , \quad \sigma_3^{'} = \sigma_3 - E \cdot \frac{\Delta l^{'}}{l_3} \qquad (8)$$

where: σ_1 and σ_3 are the stresses after the loading phase in the lateral samples respectively in the central sample given also by the equations (3). By substituting equations (3) into equations (8) the following relations will be obtained:

$$\sigma_1^{'} = K\left[\ln\left(1 + \frac{\Delta l}{l_1}\right)\right]^n - E \cdot \frac{\Delta l^{'}}{l_1}$$

$$\sigma_3^{'} = K\left[\ln\left(1 + \frac{\Delta l}{l_3}\right)\right]^n - E \cdot \frac{\Delta l^{'}}{l_3} \qquad (9)$$

where: σ_0 is the yield stress, K is the strength coefficient, ε is the plastic strain, n is the hardening exponent and $\Delta l^{'}$ is the springback. By using the equation (7) and (9), calculation of the springback $\Delta l^{'}$ can be made on the basis of the relation (10):

$$\Delta l^{'} = \frac{K}{E} \cdot \frac{2 \cdot l_1 \cdot (l_3 + \Delta l) \cdot \left[\ln\left(1 + \frac{\Delta l}{l_1}\right)\right]^n + l_3 \cdot (l_1 + \Delta l) \cdot \left[\ln\left(1 + \frac{\Delta l}{l_3}\right)\right]^n}{(l_1 + 2 \cdot l_3 + 3 \cdot \Delta l)}$$

2.3. Simulation conditions

The test has been simulated using the ABAQUS Standard software. The grip was modelled as a rigid body and the samples as deformable shell. The inferior extremities of the samples were fixed in the fixed grip and the upper extremities were fixed in the mobile grip. The model used in simulation is presented in Fig. 6.

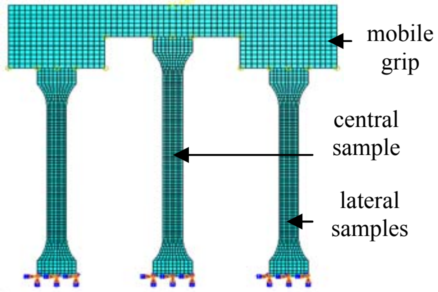


Fig. 6. Geometrical model used in simulation

The elastic properties of the material introduced into ABAQUS were: Young modulus E = 204000 MPa, Yield Stress σ_y = 184MPa, Yield Strength k = 491MPa, Poisson ratio n = 0.20, coefficient of anisotropy r =1.42. The plastic behaviour was described by a set of points from the plastic stress-strain curve. The grip was meshed using 3-D bilinear rigid quadrilateral elements R3D4 and the samples were meshed using S4R elements having 5 integration points on the sheet thickness. The test was performed in the following two steps: the first step (loading) when a displacement of the grip from the reference point was imposed and the second step (unloading) when the displacement was free. During the unloading step the springback occurs due to differences between the samples length.

3. INVESTIGATION RESULTS

The axial stresses developed in samples before springback and the springback values determined on the basis of mathematical model are presented in Table 1. The springback values obtained from experimental investigations are presented in Table 2. The axial stress and springback values obtained from simulation are presented in Tables 3. The residual stress values obtained from calculation and simulation are presented in Table 4.

Table 1. Axial stresses and springback values determined from calculation

Rolling direction	σ_1 lateral samples	σ_3 central sample	$\Delta l'$
[°]	[MPa]		[mm]
0	288.63	279.45	0.162
45	342.31	332.86	0.163
90	281.77	273.20	0.159

Table 2. Springback values determined from experiment

Rolling direction	Springback $\Delta l'$ *image analysis*	Springback $\Delta l'$ *extensometer*
[°]	[mm]	
0	0.210	0.205
45	0.201	0.212
90	0.196	0.193

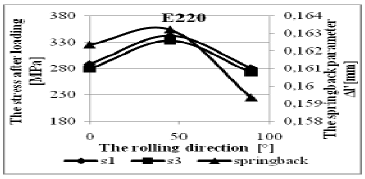
Table 3. Axial stresses and springback values determined from simulation

Rolling direction	σ_1 lateral samples	σ_3 central sample	$\Delta l'$
[°]	[MPa]		[mm]
0	301.10	289.45	0.183
45	354.34	342.41	0.188
90	292.70	281.99	0.185

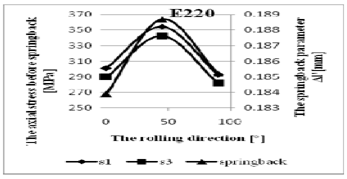
Table 4. Residual stresses obtained from calculation and simulation

Method	calculation		simulation	
Sample	lateral	central	lateral	central
Rolling direction	σ'_1	σ'_3	σ'_1	σ'_3
[°]	[MPa]			
0	-12.46	24.67	-10.94	21.59
45	-15.29	30.27	-13.60	26.79
90	-12.30	24.36	-10.81	21.31

The variations of the axial stresses and springback parameters obtained from calculation and simulation are presented in Fig. 7.



a. calculation



b. simulation

Fig. 8. Variation of axial stresses and springback parameters determined from simulation

4. CONCLUSIONS

The comparison of the springback values determined by calculation, experiment and FEM simulation emphasizes small differences (max. 0,04mm) between the values resulted by using the above mentioned techniques. Also, the springback values determined by using the extensometer are very close by that obtained from the image analysis using.

The comparison between the values of the axial and residual stresses determined by calculation and FEM simulation emphasizes small differences (max. 12 MPa for axial and 3 for residual stresses, respectively) between the values resulted by using the above mentioned techniques.

Based on the results obtained from this investigation and by taking into account the complexity of the deep drawing operation, we can conclude that the FEM simulation can replace the experiment or calculation and can be used with a good precision to determine the springback and residual stress distribution in complex formed parts.

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