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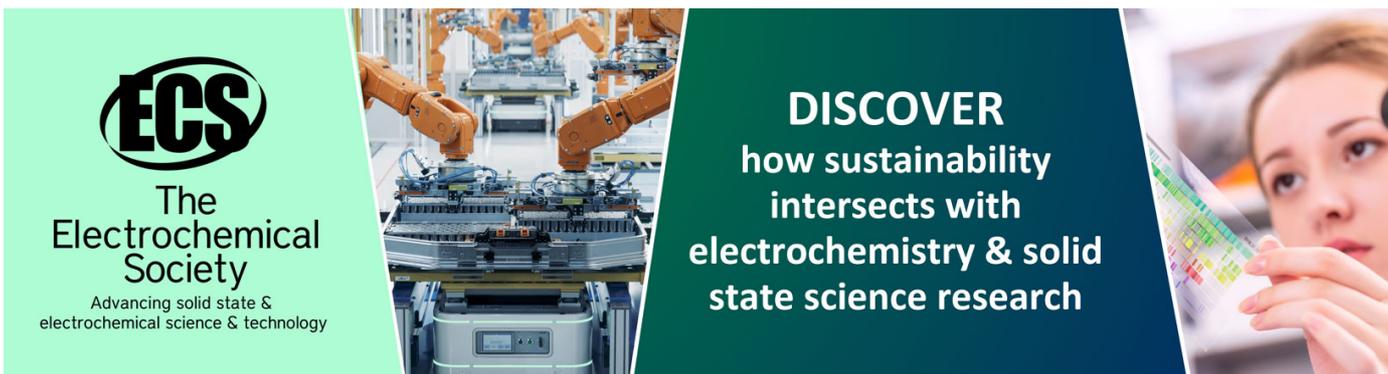
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A springback energy based method of springback prediction for complex automotive parts

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Abstract: Springback prediction and control of complex automotive parts is a critical issue in industrial practical application. In this study, a method is proposed for characterization, prediction and control of springback based on the springback energy, which is the driving energy causing springback after stamping. A theoretical model was established and experimentally verified. A case study was conducted on the basis of an automotive part formed using aluminium alloy AA6016 sheet, and finite element method was used to obtain the necessary variables of the theoretical model. Springback energy was calculated using the theoretical model and visualized using Matlab. Results show that the magnitude of springback distortion increases with the release of springback energy. It further indicates that in addition to the average level, the distribution of springback energy has an obvious effect on the form and amount of springback. Both the reduction and homogenization of springback energy can effectively reduce springback of the part. This study facilitates the understanding, prediction, and control of springback using a new approach with springback energy that is especially applicable to complex automotive parts.

1. Introduction

Springback of a stamped sheet metal panel is the change in shape or distortion that occurs under the forces of residual stresses after the part is released from the die and all constraints are removed. This distortion of the drawn panel is caused by elastic recovery within the material and is inherent in the die stamping process. Springback has a deleterious effect on dimensional accuracy and precision of the formed part. Springback predictions are largely based on FEM simulations which must incorporate complex standards of springback assessment [1]. Various models and test methods are used to calibrate or validate springback predictions such as the draw-bend springback test [2] and U-channel FEM models [3]. Approaches of springback prediction accuracy are different depending on the various definitions of springback magnitude (e.g. angles between experiments and simulations) [4-6]. On the other hand it is unfortunate that many previous simulations or analytical approaches may only be suitable for simply deformed shapes (e.g. U-shaped). It is necessary, therefore, to develop some simple but efficient methods to improve the springback prediction of complex parts.

With this goal, a new corresponding assessment procedure has been proposed [7] that is very efficient in evaluating defects of parts such as springback. Hirotec in Japan has developed a system of assessing defects of parts based on the tension distribution, by which it was noted that the tension in the standard axial direction induced the springback of the part. By calculating different energy components, the main cause of the overall springback of the part can be determined. Measures are taken to improve the uniformity of the energy distribution to achieve the purpose of controlling the springback. Vratislav Kafka [8] analysed the nature of the physical phenomenon with the method of internal elastic energy



based on a microscopic approach. The author explained the essence of elastic modulus attenuation and nonlinear unloading behaviour which cause springback, but the theory is based on complex constitutive Equations.

In the present paper, a new analytical procedure of springback evaluation is developed with an energy method and extended to springback predictions of complex parts. The overall springback of parts such as bending springback and torsion springback occur more frequently and are difficult to solve in real production processes. Therefore, the integral springback of a part is explored with this new evaluation idea in order to control springback of complex parts.

2. A proposed analytical model of springback energy

In order to study springback prediction based on the new energy method, the definition and analysis of springback energy must be defined. The analytical method based springback energy is subjected to different springback forms. In this paper, the contribution of two different springback forms to integral springback of parts is analysed.

2.1 Material mechanical properties

Mechanical properties of 6016 aluminum alloy input for the analytical model and the FE model are summarized in Table 1. The standard tensile test data displayed in Table 1 were carried out according to ASTM E8-08 at a crosshead speed of 3mm/min.

Table 1. Mechanical properties of AA6016.

UTS ^a (MPa)	0.2% YS ^b (MPa)	E(MPa)	et ^c (%)	eu ^d (%)	n ^e	k ^f
224	128	68900	17	15	0.26	406

^a ultimate tensile strength.

^b yield strength.

^c total elongation(engineering strain).

^d uniform elongation(engineering strain).

^e working hardening exponent.

^f working hardening coefficient.

2.2 Determination of in-plane springback and bending springback

Springback of the sheet results from in-plane tension springback (such as strip length variation) and bending springback (such as bending angle variation). Zhang et al.[9] proposed an iterative function to evaluate the springback amount which is a result of the displacement and rotation of nodes on the sheet surface. Figure 1 shows the springback iterative method that was incorporated in determination of two types of springback. $S(P_i)$ refers to the springback magnitude of node P_i and represents the accumulation of rotation and displacement magnitude of the sheet element $P_i P_{i+1}$. P_0 does not incur springback deflection and P_1 represents the springback node. The iterative Equation for $S(P_i)$ which is the springback amount of node P_i can be expressed as follows

$$S(P_i) = \sum_{j=0}^{i-1} R(P_j) + \sum_{j=1}^i D(S_j) \quad (1)$$

where R and D represent the springback resulting from angle and length variation, respectively.

Equation (1) shows that the displacement caused by springback is the accumulation of angle variation and length variation of the elements between node P_0 and node P_{i+1} . In order to verify the theoretical analysis of springback length and angle variation, a metal sheet was formed into a U-shape part. The system is shown in Figure 2, where material properties and tooling geometry (taken from the Numisheet 2011 benchmark) are given in Tables 1 and 2, respectively. Figure 3 illustrates that the length of the sheet element is constant when springback occurs.

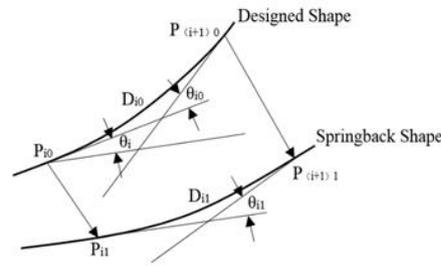


Figure 1. Illustration of springback iteration [9].

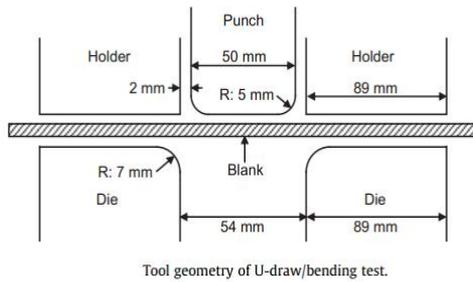


Figure 2. Experimental apparatus of metal U-shape forming.

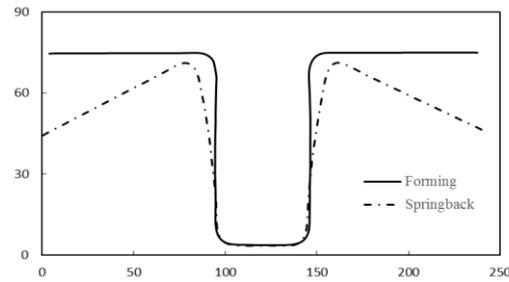


Figure 3. Scanned profiles of sheets after springback and sheet length is 370.017 mm.

Table 2. Tooling geometry.

Sheet thickness(mm)	Rp(punch) (mm)	Rd(die) (mm)	Sheet length(mm)	Punch displacement(mm)	Blank holder Force (kN)
0.8	5	7	360	71.6	100

2.3 Springback energy analysis

According to the law of conservation of energy, the springback energy for describing springback of sheet during unloading is defined as the difference of deformation energy of each point before and after unloading. The deformation energy represented in the form of strain and stress is based on the potential energy in the sheet. In the course of a physical process, the increment of the deformation energy is equal to the integration of the load displacement path of sheet to the displacement axis

$$U = W = \sum_0^{\delta_1} Pd\delta \tag{2}$$

Therefore, springback energy density is equal to the integral of the stress-strain path corresponding to the variable axis in the unloading process. The calculation of springback energy can be simplified. Assuming that the unloading process is a linear stress-strain curve, the springback energy is the integral of the unloading curve to the coordinate axis, namely, the shadow area in Figure 4.

An assumption made in this section is that the material undergoes non-linear strain-hardening and its stress-strain relationship is governed by $\sigma_{es} = k\varepsilon_{es}^n$, where σ_{es} and ε_{es} represent the effective stress and the effective strain, respectively, k is the strength coefficient and n is the strain-hardening exponent, both of which are constants. A sheet with a thickness of t can be divided into $2m_1 + 1$ layers through the thickness, and the thickness of the each layer is $t_1 = t/(2m_1 + 1)$. The strains at point q_i on the q th layer from the mid-surface are $\varepsilon_{\theta iq}$ and ε_{riq} .

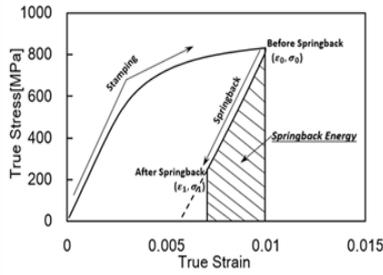


Figure 4. Definition of springback energy in the uniaxial tensile state.

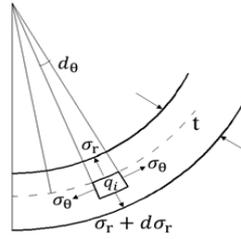


Figure 5. Schematic diagram of a bending sheet along the thickness

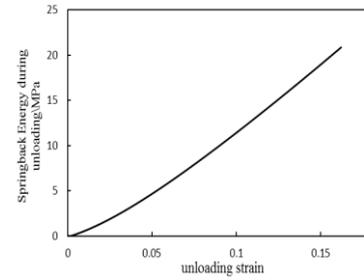


Figure 6. Relationship between springback energy and unloading strains

Based on the assumption that with the elastic deformation being neglected the material is regarded as incompressible so that the mean strain is

$$\varepsilon_{\text{avg}} = \frac{(\varepsilon_{\theta} + \varepsilon_r + \varepsilon_z)}{3} = 0 \quad (3)$$

The effective stress and strain are determined by

$$\sigma_{\text{es}} = \frac{\sqrt{2}}{2} \sqrt{(\sigma_{\theta} - \sigma_r)^2 + (\sigma_r - \sigma_z)^2 + (\sigma_z - \sigma_{\theta})^2} \quad (4)$$

$$\varepsilon_{\text{es}} = \frac{\sqrt{2}}{3} \sqrt{(\varepsilon_{\theta} - \varepsilon_r)^2 + (\varepsilon_r - \varepsilon_z)^2 + (\varepsilon_z - \varepsilon_{\theta})^2} \quad (5)$$

respectively, while

$$\sigma_{\text{avg}} = \varepsilon_{\text{avg}} (1 - 2\nu)^{-1} = 0 \quad (6)$$

Substituting Eq. (3) into Eq. (5) results in

$$\varepsilon_{\text{es}} = \frac{2}{3} \sqrt{\varepsilon_{\theta}^2 + \varepsilon_r^2 + \varepsilon_{\theta} \varepsilon_r} \quad (7)$$

As stated in the abovementioned assumption, the work hardening law of the material is taken as

$$\sigma_{\text{es}} = k \varepsilon_{\text{es}}^n \quad (8)$$

Taking the above Equations into account, the strain energy per unit volume can be expressed as

$$u = \int \sigma_{\text{es}} d\varepsilon_{\text{es}} = \frac{k}{n+1} \varepsilon_{\text{es}}^{n+1} \quad (9)$$

Substituting $\varepsilon_{\theta i q}$ and $\varepsilon_{r i q}$ and Equation (8) into Equation (9), the springback energy of the q th layer after springback can be expressed as

$$U_q = \sum_{i=1}^m \frac{4k}{3(n+1)} \left(\Delta(\varepsilon_{\theta i q}^2) + \Delta(\varepsilon_{r i q}^2) + \Delta(\varepsilon_{\theta i q} \varepsilon_{r i q}) \right)^{\frac{n+1}{2}} \quad (10)$$

The springback energy corresponding to the unloading strain at a certain point can be calculated by Equation (10). Springback energy during unloading increases with strain and reaches a linear trend gradually as shown in Figure 6.

Therefore, the springback energy of the sheet can be defined as the integral of the springback energy density at all layers along the thickness. In the process of bending and springback, the neutral layer will move inward, so two analytical modes exist according to the position of the neutral layer. On the one

hand, the neutral layer is between the inner and middle layer as shown in Figure 7, that is $U_q^m < U_q^i < U_q^o$ or $U_q^m < U_q^o < U_q^i$. On another hand, the neutral layer moves outwards, as shown in Figure 8, that is $U_q^i < U_q^m < U_q^o$ or $U_q^o < U_q^m < U_q^i$. Springback energy can be calculated by Equations (11) and (12) respectively in terms of two kinds of neutral layer states.

$$\Delta U = \frac{1}{4} \cdot t \cdot (U_q^i + U_q^o - 2U_q^m) \tag{11}$$

$$\Delta U = \frac{1}{2} \cdot t \cdot |U_q^i - U_q^o| \tag{12}$$

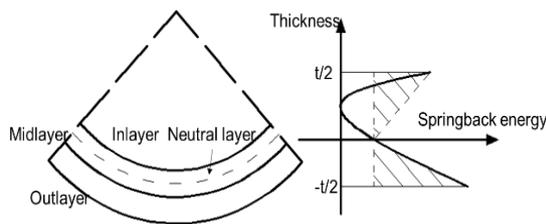


Figure 7. Distribution of springback energy along the thickness of sheet in terms of neutral layer between in-layer and mid-layer.

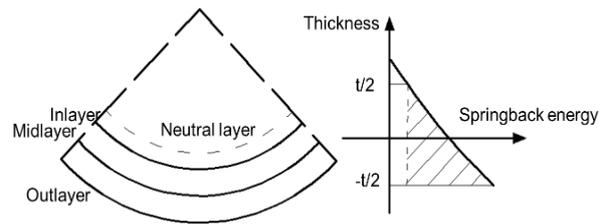


Figure 8. Distribution of springback energy along the thickness of the sheet in terms of neutral layer outside.

3. Results and discussion

In order to verify the springback energy method, the corresponding relationship between springback energy and springback of a part is studied on the two aspects of springback energy, which are springback energy values and springback energy distribution.

Figures 9 and 10 show the shape of the U-shaped part after springback in simulations and the springback energy distribution diagram of the U-shaped part which illustrates how the springback energy is distributed along the length direction of the strip (calculated according to the springback energy method). As shown in Figures 9 and 10, angle variations at points A and D are larger than those at points B and C; and the springback energy curve indicates that springback energy at points A and D is larger. In view of the springback energy method, the springback angle increases as the springback energy increases and has a simple corresponding relationship to the energy. The main reason for springback obtained is that the springback energy of at four points drove larger springback angles based on the analysis method previously discussed. Angle variation then extended the relative state change of flange and side wall as shown in Figure 9.

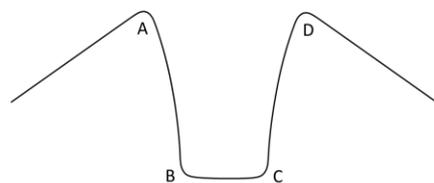


Figure 9. Springback profile in simulations.

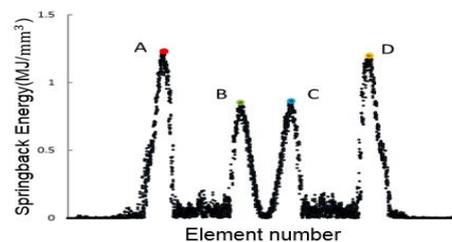


Figure 10. Distribution of springback energy.

In order to verify the corresponding relationship between springback energy and overall springback of the part further, simulations were carried out with different blank holder forces by the AutoForm software. The mean values of springback energy distributed along the entire U-shaped part are calculated as shown in Figure 11.

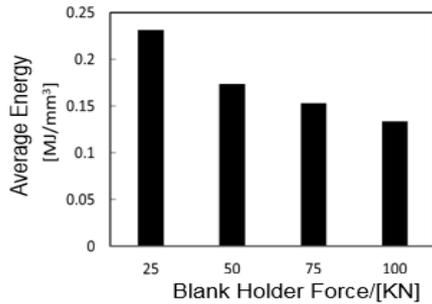


Figure 11. Bending springback energy under different holder forces.

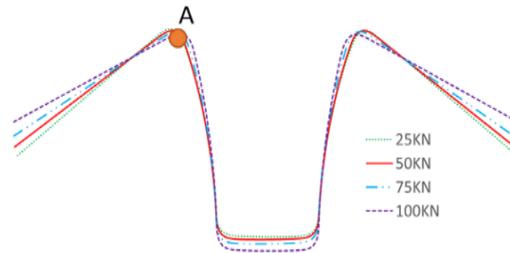


Figure 12. Profiles of U-shaped parts under different holder forces.

It is revealed that the mean springback energy decreases with the increase of the blank holder force, resulting in a reduction of springback of the part. Therefore, the greater the blank holder force, the smaller the overall springback of the U-shaped part. It is further confirmed that the reliability of the springback energy method and the corresponding relationship between the springback energy and the springback energy method can be used to evaluate the springback amount.

The relationship between springback energy distribution and torsion springback of the part was investigated. Torsion springback is a common form of springback in stamping. Based on the finite element method with incorporated energy method, the relationship between springback energy distribution and springback was explored by adjusting blank holder forces distribution. In the simulation of the U-shaped part, different draw beads were distributed along the width direction of the specimen as indicated by the force curves in Figure 13.

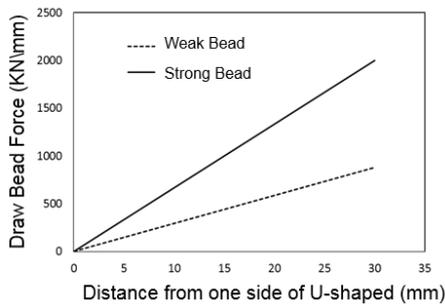


Figure 13. Drawbead forces distribution along the width of sheet.

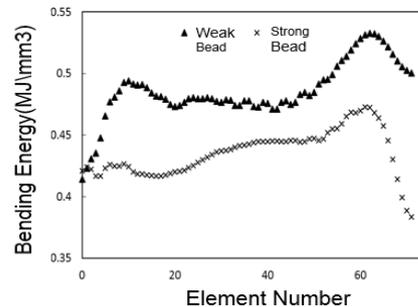


Figure 14. Springback energy distribution in the section of sheet.

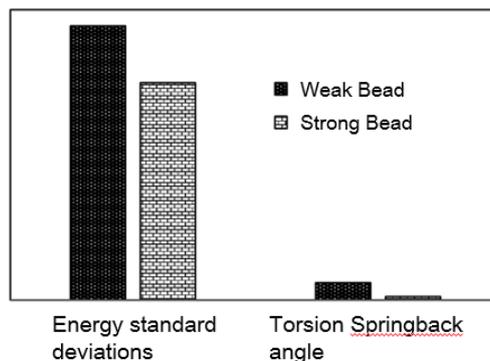


Figure 15. Standard deviation of springback energy and torsion springback angle at two types of draw bead conditions.

Figure 14 illustrates the springback energy distribution of the U-shaped section calculated by the method of springback energy. The uniformity of springback energy is evaluated by the standard

deviation. The standard deviation comparison diagram under two conditions of drawbeads is shown in Figure 15. As observed from Figures 14 and 15, the greater the standard deviation of springback energy distribution, the greater the torsion springback.

4. Application

Based on the above discussion and taking the typical automobile front cover part for an example, the springback characterization method was applied to springback prediction of complex parts with the application of energy visualization.

The springback energy method can be extended to visualization application, which enables observation of springback energy distribution on the surface of the part clearly and intuitively, and can identify the main locations where springback occurs. Springback energy was calculated according to springback energy model derived in Equations (11)-(13). Springback Energy cloud pictures of the part was plotted in Matlab software as shown in Figure 17 and magnitude of springback energy can be demonstrated by different colours.

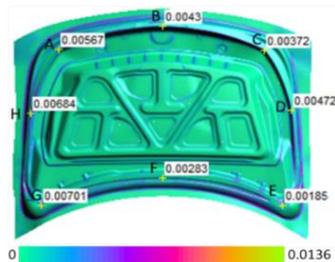


Figure 16. Curvature springback

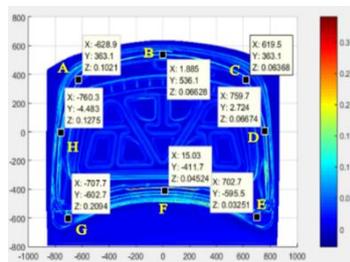


Figure 17. Springback energy distribution cloud of auto cover plate.

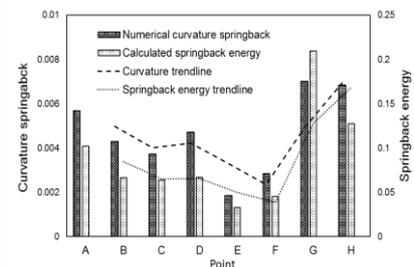


Figure 18. Comparison between curvature springback and springback energy

Comparison of Figures 16 and 17 suggests that curvature variation of the part is large corresponding to large values of springback in terms of the moving average trendline, and curvature variation is small relative to small results of springback. Therefore, it is known that the amount of springback energy has obvious correspondence with the size of curvature springback (z represents springback energy values in Figure 17). With analysis and summary, it is found that (Figures 16 and 17) springback energy distribution at the larger stiffness area adjacent to smaller stiffness area is uneven, and the springback amount at the smaller stiffness area (especially in the flange area) is easy to increase.

5. Conclusions

In order to develop an efficient method and considering the springback of complex parts in terms of bending springback and torsion springback, a springback energy approach formulated in generalized variables has been proposed. The efficiency of the proposed model is demonstrated by simulating a U-channel part in Autoform software. Results show that the magnitude of springback increases with the release of springback energy. It further indicates that both the distribution and the average level of the springback energy have obvious effects on the form and magnitude of springback. Both the reduction and homogenization of the springback energy can effectively reduce the springback of the part. This study facilitates the understanding, prediction, and control of springback from a new aspect of the springback energy, which is especially applicable to complex automotive parts.

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