Intelligent Manufacturing Systems: Controlling Elastic Springback in Bending

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Abstract. A rotary compression bending system with automated closed-loop feedback control has been developed. The overall goal is to improve the dimensional accuracy of formed shapes by transferring in-process data into a steering model for instant springback compensation. An analytical method based on the deformation theory of plasticity was employed to develop a physically-based steering model. Unlike alternative control strategies, the present control strategy is attractive for volume production since the approach does not impact cycle time. More than 150 tests of AA6060 extrusions were conducted to determine the capability of the technology. Prior to forming, the material was exposed to different heat treatments to provoke different stress-strain characteristics. The results show that the springback-angle standard deviations were improved from ±0.41° to ±0.13° by activating the closed-loop feedback system. Since the dimensional process capability is improved by a factor of three, it is concluded that the technology has high industrial potential.

Keywords: Forming, machine system, adaptive control, dimensional accuracy.

1 Background

European manufacturing companies are currently facing increased competition from low cost countries. One strategy to meet this challenge is developing more automated production technology, providing reduced labor cost while improving product quality. Hence, the future competitiveness of European manufacturing companies is strongly related to their capability in developing and integrating new technology, followed by commercialization of new products that provide superior value to customers.

Despite its long history [1-7], adaptive processing is still a technology that may create competitive advantages in the market place. In bending operations, for example, adaptive control strategies can be used for elastic springback compensation and dimensional control of the final

product. One control strategy (A), [8], is to unload the part at an intermediate forming stage and use recorded data to estimate stop position using a predetermined algorithm. A second strategy (B) is to repeat procedure A multiple times until the part geometry meets the desired specifications. Both these strategies are suitable for low-volume production only since the approach increases cycle time. A third strategy (C) is to use a closed-loop feedback scheme and measure parameters such as bending moment, stretch, bend angle and section dimensions, using a steering model for instant prediction of springback. Its main advantage is producing high-quality parts in one single step without intermediate unloading, making it suitable for volume production. Successful application, however, is strongly dependent on the capabilities of the steering model and the measurement technology used to record instant input data. Automotive product examples where adaptive forming has high value creation potential are shown in Fig. 1. The reader is advised to [9] for more applications and to [10] for research outlook.
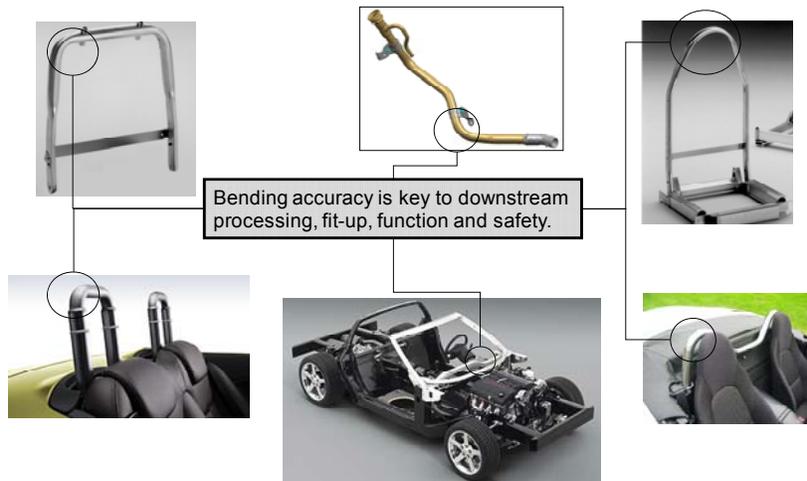
Fig. 1. Application examples where springback control in bending is key to product quality.

2 Technology Brief

The overall goal is to improve the dimensional accuracy of formed shapes using a physically-based steering model for elastic springback compensation. A new rotary draw bending machine system with automated closed-loop feedback control is being developed. In-process

measurement data are transferred into an algorithm for instant prediction of springback and bend angle prior to the unloading sequence. The bending system, Fig.2, consists of an electric power unit that is connected to a gearbox. A torque transducer is placed between the gearbox and the entry shaft of the bending arm. The rotation of the bending arm is measured using a rotational transducer connected to the gear. A drawback (sleigh) is mounted underneath the bending arm to eliminate friction as the profile slides against the tool during bending. The drawback is hinged locally at the bending arm to ensure free rotation of the front end of the profile. A pneumatic clamp is used at the rear end of the profile, constraining rotation and translation in the length direction. The lower tool has constant radius and is fixed. The tool's contact surface is made with a protruding ridge to form a local imprint along the inner flange, hence preventing uncontrolled local buckling. During forming, torque and rotation are continuously recorded and fed into a PC-operated control system, which automatically calculates stop position using a steering model. The process is entirely managed by the control system, without any human interference other than specifying the desired bend angle. Due to the control strategy (C) adopted, the cycle time of the bending machine is the same as for conventional draw bending.
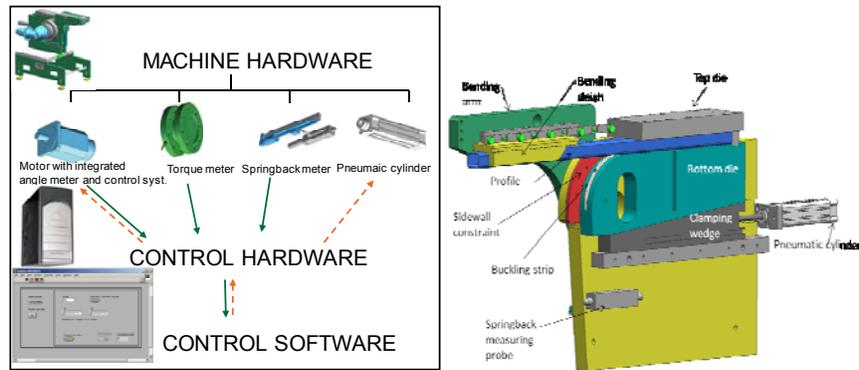

Fig. 2. System for automated closed-loop feedback control (left). Mechanical details (right).

3   Steering Model

Establishing a continuum-based steering model for springback compensation is a tedious matter, see [11], whose details will be omitted herein. In general, it is essential that the model is capable of capturing the main

sources to variability in the bending process, including material parameters such as yield stress and strain hardening as well as dimensional characteristics of the profile. The analytical method used was based on the theory of plasticity using beam theory in combination with a non-linear, closed-form moment-curvature relationship as basis for the predictions. The kinematics and structural scheme of the process are interpreted in Fig. 3. Since elastic springback is essentially a result of the instant moment-to-stiffness ratios, i.e. elastic curvature $\kappa^e(s) = \frac{M(s)}{EI(s)}$, in the entire region A-D prior to unloading, it is important to establish a model that reflects the actual bending moment distribution. Here it is assumed that the bending moment varies linearly from zero at point A to M_B at point B, attaining a stationary, maximum value M_C over a transition angle $\Delta\theta_B$ from the profile's first contact point with the die and vanishing over a distance $2 \cdot D$ (depth) inside the clamped region C-D. The bending moment is a function of instant material properties and the shape of the cross section, while stiffness is only a function of the latter since Young' modulus (E) is assumed unaffected by (pre-)deformation.
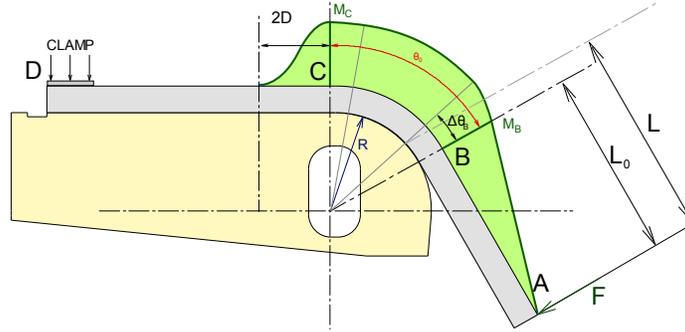
Fig. 3. Kinematics and moment distribution used as basis for development of steering model.

Fig. 4 shows an overview of the sequential steps included in the calculation strategy to obtain the steering model. In its general form, the solution includes instantaneous input from multiple parameters, including geometrical ones, which would surpass the measurement capabilities of the current system. If the measurements are limited to die rotation and bending moment only, however, the above equation may be converted into a simplified algorithm on the form:

$$\tilde{\varphi} = \frac{\Theta_0 + \hat{c}_0 + \hat{c}_1 \widetilde{M}(\tilde{\varphi})}{1 - \hat{c}_3 \widetilde{M}(\tilde{\varphi})}$$

Here $\tilde{\varphi}$ is the die rotation at end of forming, $\tilde{M}(\tilde{\varphi})$ is the measured moment, Θ_0 is the desired bend angle, and the parameters $\hat{c}_i$ are calibration constants. $\hat{c}_0$ reflects an offset factor due to elastic springback within region *C-D,* while $\hat{c}_1$ reflects the elastic springback contribution from regions *A-C*, which is the reciprocal of the cross-section's bending stiffness EI_0. The constant $\hat{c}_3$ may be interpreted as a correction factor, making springback response non-linear due to inelastic material behavior, shifting contact conditions and cross-sectional distortions.
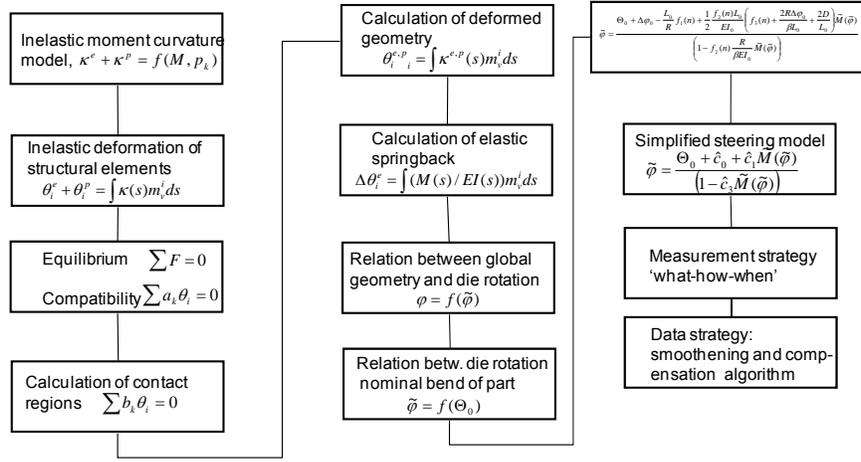
Inelastic moment curvature model, $\kappa^e + \kappa^p = f(M, p_k)$	Calculation of deformed geometry $\theta_i^{e,p} = \int \kappa^{e,p}(s)m_v^i ds$	$\tilde{\varphi} = \dfrac{\left(\Theta_0 + \Delta\varphi_0 - \frac{L_0}{R}f_1(n) + \frac{1}{2}\frac{f_3(n)L_0}{EI_0}\left(f_3(n) + \frac{2R\Delta\Theta_0}{\beta L_0} + \frac{2D}{L_0}\right)\tilde{M}(\tilde{\varphi})\right)}{\left(1 - f_2(n)\frac{R}{\beta EI_0}\tilde{M}(\tilde{\varphi})\right)}$
Inelastic deformation of structural elements $\theta_i^e + \theta_i^p = \int \kappa(s)m_v^i ds$	Calculation of elastic springback $\Delta\theta_i^e = \int (M(s)/EI(s))m_v^i ds$	Simplified steering model $\tilde{\varphi} = \dfrac{\Theta_0 + \hat{c}_0 + \hat{c}_1\tilde{M}(\tilde{\varphi})}{(1 - \hat{c}_3\tilde{M}(\tilde{\varphi}))}$
Equilibrium $\sum F = 0$ Compatibility $\sum a_k\theta_i = 0$	Relation between global geometry and die rotation $\varphi = f(\tilde{\varphi})$	Measurement strategy 'what-how-when'
Calculation of contact regions $\sum b_k\theta_i = 0$	Relation betw. die rotation nominal bend of part $\tilde{\varphi} = f(\Theta_0)$	Data strategy: smoothening and compensation algorithm

Fig. 4. Calculation strategy for development of steering model for springback compensation.

4 Calibration Procedure

Due to the low inelastic bending resistance of the profile and the use of its variation as input to the steering model, the accuracy of in-process moment readings is key to the success of this technology. Since the torque ($\tilde{M}(\tilde{\varphi})$) and rotation ($\tilde{\varphi}$) are measured directly on the shaft between the gear and the bending arm, the effects of gravity forces ($M_g(\tilde{\varphi})$) and bearing friction ($M_\mu(\tilde{\varphi}, \Delta_i)$) have to be eliminated. Hence

$$\tilde{M}(\tilde{\varphi}) - M_p(\tilde{\varphi}) = \pm M_\mu(\tilde{\varphi}, \Delta_i) - M_g(\tilde{\varphi})$$

where $M_p(\tilde{\varphi})$ is the bending resistance of the profile and Δ_i is a set of variables that may affect friction (temperature, lubrication, speed, position, bending force, etc). A calibration procedure was conducted to en-

sure that the transducer would measure the net contribution from the profile in the tests. After zeroing out signals from gravitation and friction, additional tests were run without profile to determine noise. The results showed that the torque standard deviation was 1.2–2.0 Nm within one cycle. The mean value drifted slightly from the first to the last test (1.4–5.0 Nm), reflecting mainly variations from friction.

5 Capabilities of Manual and Adaptive Bending

More than 150 bending tests of hollow AA6060 extrusions were conducted to determine the dimensional capability of the technology. In order to provoke different material behaviors, the profiles were aged to different tempers: 'as is'(T1), 60 minutes and 120 minutes at 175 ℃, providing initial yield stress range of ± 17%. After bending, the profile was clamped loosely to a fixture and the relative angle between the fixed and the free ends was measured. The repeatability was checked by performing several consecutive measurements of the same profile.

The dimensional capabilities can be evaluated by considering the process capability index, $C_p = B_t/(6 \cdot SD(\Theta))$, in which B_t is the tolerance band and $SD(\Theta)$ is the realized angle standard deviation. Inspecting the results in Fig. 5 shows that the manual process (steering model deactivated) creates three bend angle clusters, one for each heat treatment, with T1-profiles providing the least springback. With the steering model activated, the results merge together, indicating that the main parameters are taken into account in the steering model.

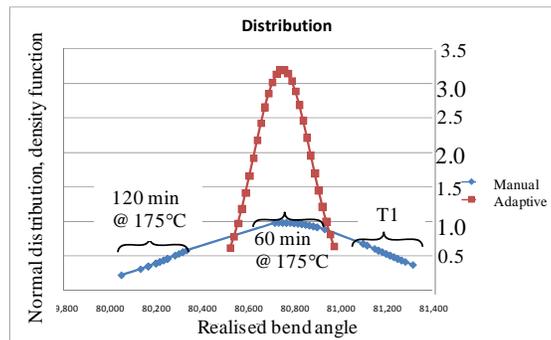Table 1 shows that the adaptive process is able to reduce the maximum

Fig. 5. Distributions of bend angle (adjusted to the same mean value) for the two methods.

variation from 1.27° to 0.45°. Assuming $B_t = 1.0°$, the adaptive process shows a process capability that is three times better than the manual one. If the bend angle is, say, a standard dimensional feature, C_p >1.33, the manual process would require a tolerance band of 3.26°, whereas the adaptive process would need a tolerance band of $\pm 0.53°$ to provide good parts. This result demonstrates that the technology has high industrial potential in terms of improved quality and reduced cost.

Table 1. Result summary.

	Manual	Adaptive	Improvement
Average bend angle:	80.75°	79.82°	NA
Maximum variation:	1.27°	0.45°	282%
Standard deviation:	0.41°	0.13°	315%
C_p ($B_t = 1.0°$):	0.41	1.25	305%
B_t (C_p =1.33) :	3.26°	1.06°	307%

6 Conclusions and Lessons Learned

Based on this work, the following conclusions can be drawn:

- A new, adaptive bending technology with closed-loop feedback has been developed and validated using full scale experiments;
- The adaptive bending method has proven to dramatically improve the dimensional process capability;
- The technology has great industrial potential in terms of improved dimensional quality and reduced manufacturing costs.

Overall, the main challenge of this work was measuring the bending moment with sufficient accuracy. It turned out that the key was to reduce friction (variations) by replacing sliding bearings with roller bearings for the pivoting bend tool. Doing the machine design all over again, it would be beneficial to use lighter tool and die components to reduce sensitivity to variations since the bending forces are of the same magnitude as the gravity forces for the current concept. It was also a challenge to establish an in-process measurement strategy, relating the datum points of the tool to those of the profile since fit-up is dependent on dimensional accuracy of the incoming part. On the way to commercialization, its robustness and durability in a plant environment must be

tested. Finally, since the steering model may utilize additional instant geometry data, future work includes extending measurement capabilities to improve the accuracy of the bending methodology even further.

7   References

1. Hardt, D.E., Davis Webb, R., Suh, N.P. (1982), "Sheet Metal Die Forming Using Closed-Loop Shape Control", *CIRP Annals - Manufacturing Technology*, Volume 31, Issue 1, pp. 165-169.
2. Hardt, D.E, Roberts, M.A. Stelson, K.A. (1982) "Closed-loop shape control of a tool-bending process", *Journal of Dynamic Systems, Measurement, and Control*, Volume 104, Issue 4, pp. 317-323.
3. Jenne, C.J. (1986), "Closed loop control of roll bending/twisting: A shape control system for beams", Dep. of Mech. Engineering, *Massachusetts Institute of Technology*, MSc thesis, 166 pages.
4. Kwok, S.K., Lee, W.B. (1995) "The development of a machine vision system for adaptive bending of sheet metals*, Journal of Materials Processing Technology*, Volume 48, No. 1, pp. 43-49.
5. Lou, H., Stelson, K.A (2001), "Three-Dimensional tune geometry control for rotary draw tube bending, Part 2: Statistical tube tolerance analysis and adaptive bend correction, *J. Manufacturing Sci. Eng.,* Vol 123, Issue 2, pp.266-271.
6. Kuzman, K., Geiger, M. (2003), "Closed-loop control of the 3D bending process", *CIPR Annals - Manufacturing Technology*, Volume 52, Issue 1, pp. 204-208.
7. Ferreira, J.A., Sun, P., Gracio, JJ. (2006), "Close loop control of a hydraulic press for springback analysis", *Journal of Materials Processing Technology*, Volume 177, No 1, pp. 377-381.
8. Chu, H., Stelson, K.A. (2003), "Modeling and Closed-Loop Control of Stretch Bending of Aluminum Rect. Tubes", *J. Mnf. Sci. and Engn.*, Vol. 125, pp. 113-119.
9. Kleiner, M., Geiger, M., Klaus, A. (2003) "Manufacturing of lightweight components by metal forming", *CIRP Anneals – Manufacturing Technology*, Volume 52 , issue 1, pp. 521-542.
10. Welo, T. (2007), "Sheet Metal Forming", in: *Advances in Material Forming* (F. Chinesta and E. Cueto) , Springer, France pp. 175-192.
11. Welo, T., Granly, B. (2010), "A New Adaptive Bending Method Using Closed-Loop Feedback Control", *Trans Nonferrous Met. Soc China* (20), pp. 2111-2117.