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Adaptive Bending of Aluminium Extrusions Using an Automated Closed-Loop Feedback Approach

T. Welo[1], K. Sætertrø[1], O.P. Søvik[2]

[1] NTNU-Dept. of Engineering Design and Materials – Rich. Birkelands v. 2B, N-7491 Trondheim, Norway
URL: www.ntnu.no *e-mail: torgeir.welo@ntnu.no; kristian.satertro@simulix.com*

[3]Hydro Aluminium Structures, Design & Engineering - Building 5, Industriv. 1, N-2831 Raufoss, Norway
URL: www.hydro.com *e-mail: odd.perry.sovik@hydro.com*

ABSTRACT: A new rotary, compression bending set-up with automated closed-loop feedback control is being developed. The overall goal is to improve the dimensional accuracy of formed shapes using elastic springback compensation. In-process measurement data are transferred into an algorithm (steering model) for prediction of springback and bend angle prior to unloading. Emphasis was placed on developing a physically-based steering model. More than 150 bending tests of AA6060 extrusions were conducted to demonstrate the capability of the technology. Prior to forming, the material was exposed to different heat treatments to provoke a range of stress-strain behaviours, which are known to affect elastic springback. An optical measurement procedure was established to determine key dimensions and their associated statistical distributions. When using traditional compression bending, the results show that the variability in springback of a selected reference point was in the range of 10 % of the nominal springback. Using the closed-loop feedback system, the corresponding variability in springback was in the range of 3 %, representing a factor-three improvement in terms of dimensional process capability (C_p). It is concluded that the present technology has a high industrial potential, in particular for volume components with tight dimensional requirements.

Key words: Adaptive, Bending, Closed-loop Feedback, Dimensional Accuracy, Springback, Aluminium, Extrusions

1 INTRODUCTION

1.1 Motivation and objective

European manufacturers are currently facing increased competition from companies based in low cost countries. Hence, future competitiveness is strongly related to their capability in developing and integrating new technology, followed by commercialization into a stream of products that provide additional customer value in terms of reduced cost, improved quality as well as increased features and functionality.
One strategy to meet this challenge is developing more automated production technology, providing reduced labour cost while improving product quality. Adaptive processing is one of several technologies that support the desire of creating competitive advantages by offering improved products in the market place. It is applicable to numerous manufacturing processes that require high-quality parts. Moreover, adaptive processing may be executed at different levels of sophistication. For example, conventional stretch bending may be considered as a low-level adaptive process since simultaneous stretching and bending are known to reduce springback, hence improving the dimensional accuracy caused by variability in mechanical properties and geometric dimensions of incoming parts. The next level of sophistication may be associated with the method of manually adjusting the settings of a tool or machine, using data from a few test trials (of a new batch) and experience data from previous production batches. The highest level of sophistication in connection with adaptive processing is to integrate an automated closed-loop feedback scheme for instantaneous process control. Hence, in-line measurements are utilized in order to correct settings and process parameters while the component is being processed [1].
Development of automated, closed-loop feedback

control, applied to rotary compression bending, is the primary focus in this paper. The objective of the work is to establish a method for in-process control of profile bending, focusing on springback compensation, along with the associated steering model.

1.2 Closed-loop adaptive control strategies

There are multiple strategies for springback compensation in a bending operation, see the principles in Figure 1. One method (A) is (i) to unload the part at an intermediate forming stage, (ii) record springback characteristics, (iii) use the measured data to estimated stop position using a predetermined algorithm, (iv) reload the part to the predicted stop position, and finally (v) unload the part. A second strategy (B) is to (i) form the part to a prescribed stop position that would normally result in an under-bent part, (ii) unload the part and measure the springback, (iii) utilize the data for predicting a new stop position using a predetermined algorithm, (iv) reload the part to a new stop position closer to the nominal one, (v) repeat the procedure until the part geometry meets the desired part geometry. Both these strategies are mainly suitable to small-batch production of customized products since the loading-unloading scheme increase cycle time.
A third strategy (C), which is more applicable to high volume production, is to run the operation as a one-hit, conventional process. Rather than measuring springback directly, other more indirect (underlying) parameters such as bending moment, stretch and section dimensions need to be measured instantaneously. A successful outcome, however, presumes the existence of an accurate steering model. Moreover, the measurement technology and equipment must be robust, accurate and reliable to provide reliable input to the steering model.

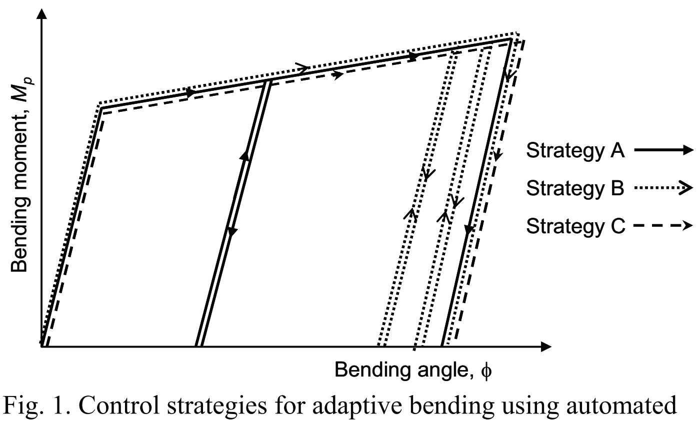

Fig. 1. Control strategies for adaptive bending using automated closed-loop feedback.

2 EXPERIMENTS

2.1 Set-up

The lay-out of the (rotary) compression bender is shown in Figure 2. The assembly consists of an electric power unit that is connected to a gear box. A torque transducer is placed between the exit of the gear box and the entry shaft of the upper bending arm. The rotation of the bending arm is measured directly using a rotational transducer connected to the gear. A drawback arrangement is mounted at the underside of the bending arm to eliminate friction as the profile slides towards the upper bending tool during bending. The drawback is hinged locally at the bending arm to ensure free rotation of the front end of the profile. A device (not shown in the figure) that is operated with air pressure clamps the rear end of the profile, constraining rotation and translation in the length direction. The lower tool has a constant radius and is fixed. The tool's contact surface is made with a protruding ridge to make a local imprint along the inner flange of the profile during bending.
During forming and unloading, both torque and rotation are continuously recorded and fed into a PC-operated control system, which automatically calculates and updates the stop position using a pre-determined steering model. The process is entirely controlled by the control system, without any human interference other than specifying desired bend angle of profile, loading the part, click the 'go-button', and removing the finished part. Due to the control strategy adopted (C), the cycle time of the bending machine is the same as for conventional compression bending technology.

2.2 Calibration and test procedures

Since the torque ($M(\varphi)$) and rotation (φ) are measured directly on the shaft that connects the gear and the bending arm, the effects of gravity forces ($M_g(\varphi)$) and bearing friction ($M_\mu(\varphi,\Delta_i)$) have to be reset to zero, hence

$$M(\varphi) - M_p(\varphi) = \pm M_\mu(\varphi,\Delta_i) - M_g(\varphi) \qquad (1)$$

where $M_p(\varphi)$ is the bending resistance of the profile.
Readings obtained by running the machine without profile for $0 \le \varphi \le 90^\circ$ were used to calibrate the

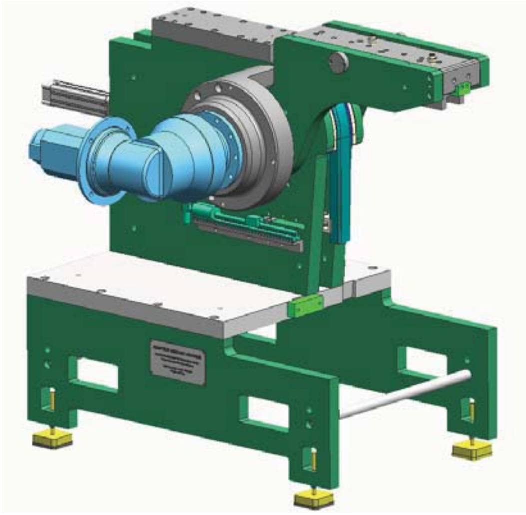
Fig. 2. Outline of bending machine and tooling.

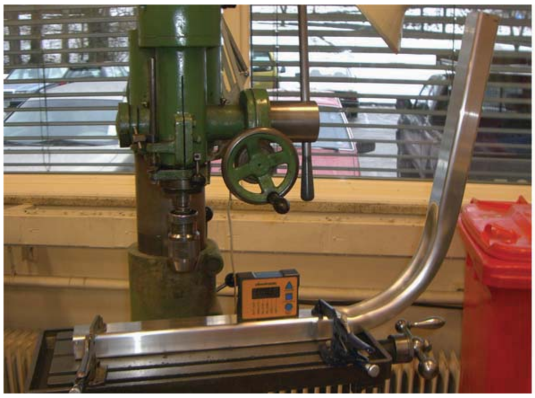
Fig. 3. Bent part clamped in fixture and ready for dimensional measurements.

transducer such that only the contribution from the profile would be measured in the tests. After resetting the moment readings, an additional ten tests were run without profile to determine variability (from Δ_i). The results showed that the recorded torque's standard deviation was in the range of 1.2–2.0 Nm within one cycle, and that the mean value increased slightly from the first to the last test (1.4–5.0 Nm), reflecting the overall variations from friction and measurements.

The measurements procedure included clamping the profile loosely to a fixture and measuring the angle made up by the fixed and the free ends. A digital protractor, Clinotronic-Wyler (resolution of 1/60°), was used to measure the final bend angle. The repeatability of the procedure was checked by performing a number of consecutive measurement trials on the same profile.

A thin-walled, rectangular hollow AA 6060-T1 profile was used in the tests. In order to provoke different material characteristics, the profiles were aged to different temper conditions, including 'as is'(T1), and, respectively, 60 minutes and 120 minutes at 175 ºC, providing a ± 17 % range in yield stress. The test overview is given in Table 1.

Table 1. Test overview.

Series no.	Control model	Material	# of profiles
1	Manual	"As is"	25
2	Manual	175ºC / 60min	25
3	Manual	175ºC / 120min	25
4	Adaptive	"As is"	25
5	Adaptive	175ºC / 60min	19
6	Adaptive	175ºC / 120min	20

3 STEERING MODEL

Establishing a physical steering model for springback compensation is a tedious matter, whose details cannot be reported in detail within the scope of this article. The procedure was based on beam theory using a non-linear, closed-form moment-curvature relationship as basis. The result may be converted into a steering model on the form:

$$\tilde{\varphi} = \frac{\Theta_0 + \Delta\varphi_0 - \frac{L_0}{R} f_1(n) + \frac{1}{2}\frac{f_2(n)L_0}{EI_0}\left(f_3(n) + \frac{2R\Delta\varphi_0}{\beta L_0} + \frac{2D}{L_0}\right)\tilde{M}(\tilde{\varphi})}{\left(1 - f_2(n)\frac{R}{\beta EI_0}\tilde{M}(\tilde{\varphi})\right)} \quad (2)$$

Here $\tilde{\varphi}$ is the die rotation at end of forming, $\tilde{M}(\tilde{\varphi})$ is measured torque, n is strain hardening parameter, EI_0 is initial bending stiffness, and Θ_0 and $\Delta\varphi_0$ are the part's desired bend angle and the difference between the initial rotation of the die and the profile, respectively. Some other geometrical parameters are illustrated in Figure 4. If the measurements are limited to the die rotation and torque, the above equation may be simplified:

$$\tilde{\varphi} = \frac{\Theta_0 + \hat{c}_0 + \hat{c}_1\tilde{M}(\tilde{\varphi})}{\left(1 - \hat{c}_3\tilde{M}(\tilde{\varphi})\right)} \quad (3)$$

4 RESULTS

A summary of the results obtained from more than 140 tests is given in Table 2. For the adaptive process, the targeted angle (Θ_0) was 80°, whereas the traditional process was run with a pre-specified bend angle (φ) of 85° without any attempts made to hit the same nominal. The dimensional capabilities can be evaluated by considering the process capability index :

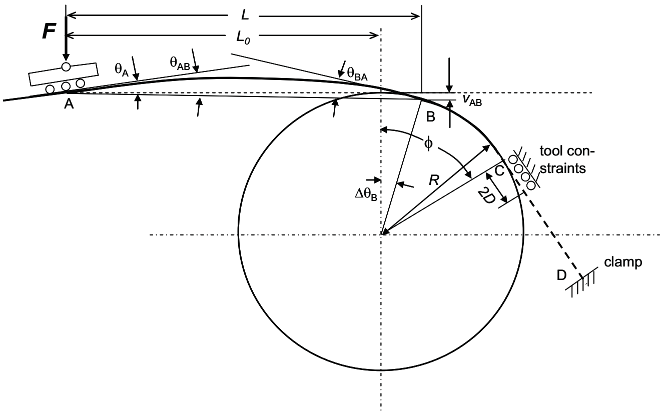

Fig. 4. Lay out of structural and kinematical model for segment A-B prior to unloading, including key dimensions.

$$C_p = \frac{USL - LSL}{6SD(\Theta)} \tag{5}$$

In which USL and LSL are the upper and lower specification limits, respectively, and $SD(\Theta)$ is the standard deviation of the realized bend angle. Assuming a tolerance band of 1.0°, the adaptive process shows a dimensional process capability that is more than three times better than the traditional process. If the bend angle is considered being a standard dimensional feature (with C_p >1.33) of a specific part, the traditional process would require a tolerance band of 3.26°, whereas the adaptive process would only need a tolerance band of ± 0.53° in order to provide good parts. This result clearly demonstrates that adaptive processing has a high industrial potential for improving part quality and reducing quality cost.

The statistical distributions of the two processes are shown in Figure 5. For illustration purposes, the distribution for the two processes is moved to have the same nominal bend angle (average). The traditional process shows three clusters, one for each heat treatment, with T1-profile results to the far right in the figure. The steering model does merge the results together, indicating that the main influential parameters are utilized in the steering model.

One can obviously argue that the heat treatment made to provoke different material characteristics resulted in a somewhat larger spread in properties than one would normally see in industrial practice for, say, T1 material. This is a correct statement if the manufacturer is capable of controlling the casting and extrusion processes as well as the shelf life of the material. Therefore, additional statistical analyses were made between batchs 1 and 2, and batches 2 and 3, for the two bending methods. The results showed that the traditional bending technology provided tolerance bands 2-4 times wider than those of the adaptive technology at the same process capability.

Table 2. Result summary.

	Traditional proc.	Adaptive proc.
Average angle, $\overline{\Theta}$	80.75	79.82
Max angle, Θ_{max}	81.32	80.05
Min angle, Θ_{min}	80.05	79.60
Std. dev. (Θ)	0.41	0.13
C_p (± 0.5°)	0.41	1.25
$USL - LSL$ (C_p =1.33)	3.26	1.06
Unit:	[°]	[°]

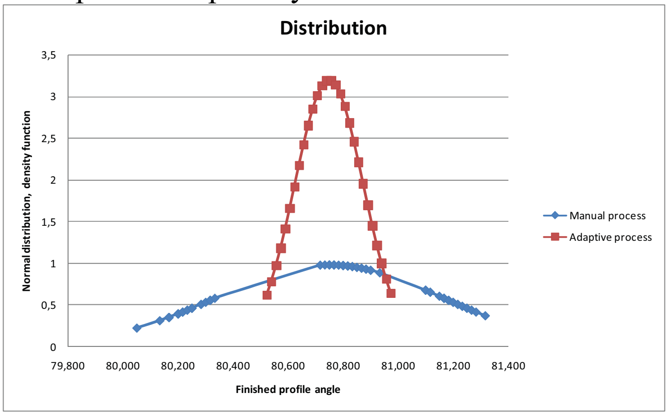

Fig. 5. Statistical distributions of bend angle with the two methods.

5 CONCLUSIONS

Based on the work presented herein, 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 a great industrial potential in terms of improved dimensional quality and reduced manufacturing costs.

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