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Closed Loop Springback Control in Progressive Die Bending by Induction Heating

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Large springback of high strength steels in progressive dies hinders accurate manufacturing because a proper prediction of elastic unloading is not possible due to material variations, tool wear, and varying ambient conditions. In order to compensate springback and enhance the forming limit when brittle materials are bent, a warm bending technology for progressive dies through inline induction heating is developed. Within a certain temperature range, there is a linear relation to the springback angle, which allows a direct influence on the final bending angle. Based on this principle, a closed loop control with a feedback of the angle after unloading is implemented, which adjusts the sheet temperature before bending. With the developed discrete controller, finally a stable and fast control mode is achieved so that an initial deviation from the target value is reduced to less than $\Delta\theta = \pm 0.30°$.

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NOMENCLATURE

c = Settling cycles
d = Damping factor
e = Error
f = Frequency
f_s = Stroke rate
n = Number of dead cycles
T = Temperature
v_r = Stroke velocity
θ = Bending angle
θ_n = Nominal angle
Θ = Springback angle

1. Introduction

Today, advanced high strength steels (AHSS), multiphase and press-hardenable steels offer a high potential for lightweight construction and energy savings in the automobile industry.[1] However, a direct substitution of conventional steels is limited due to the increasing springback, decreasing formability, and additional necessary process heat.

The literature offers a huge number of models to describe springback in relation to various stress states, material behaviors, and boundary conditions,[2] but the accurate prediction of shape deviations is restricted. In general, batch fluctuations, the tool condition, errors in the flow curve and friction model, the increasing temperature due to forming work, and other error sources require the application of compensation methods. To overcome the increasing springback deviations, the closed loop control for bending processes is of rising interest. Here, a direct control with geometrical feedback, an indirect control with stress or force feedback, or combined control is applied to act on geometrical errors.

Since the 1970's, different process controllers have been developed, which use force-displacement curves to estimate the springback deviation.[3] Further attempts adopted the main idea of indirect control integrated strain hardening effects[4] and developed extensions for small bending angles[8] as well as the true bending line in the forming area.[6]

A simple approach to compensate springback in die bending through a direct control is given by Gerritsen,[7] where intermediate unloadings are employed to measure the current stress-free status and adapt the final stroke position. Advanced approaches for air and die bending processes include empirical, analytical, or numerical models to calculate the springback in relation to measured forces, whereby a full unloading becomes unnecessary.[8]

Welo and Granly[9] elaborated an indirect closed loop control for the more complex tube bending. During forming, the elastic shape deviation is calculated with a theoretical model and the measured moment. Subsequently, the process parameters are updated to compensate deviations, by which also the ovality can be adapted.

For roll forming, Groche et al.[10] developed actuators to adjust a rolling stage and an in-situ measuring system of the profile angle after unloading. To achieve a nominal angle in the running process, the feedback of the unloaded angle and a process model are implemented into the online controller so that a stable control behavior is achieved despite the dead time between actuating and identifying the reaction.

Although the summarized methods allow springback control in established processes, a direct application of ultra-high strength materials is not possible due to the small elongations. A common method to enhance the process window is the usage of additional process heat.[11] Through warm or hot bending, not only the formability of brittle materials, e.g., AZ31B can be increased,[12] also the springback behavior changes and can be reduced significantly.[13]

Despite the high potential of forming at elevated temperatures, it is restricted to special applications due to a complex process design and a cost intensive heating apparatus. This article discloses a new progressive die with local induction heating for the large scale production with the objective to enhance the formability and to compensate springback. In order to control the angle after unloading, a closed loop control with a measuring system to feed back the formed angle has been developed.

2. Experimental Setup

The experimental setup is used to characterize the springback at elevated temperatures and validate the closed loop control of the bending angle. To analyze the innovative bending process with a direct induction heating before forming, a prototype progressive die was designed.

The new principle is shown in Fig. 2 and is characterized by the heating of the specimen by an inline induction coil (2), the forming procedure directly after heating (3), the cooling afterwards (4), and a final geometry check (5). Through the integrated arrangement of the heat source, the transportation time and heat losses due to radiation, convection, or conduction within the workpiece material become minimal and only the forming area exhibits a high temperature.

Fig. 1 depicts the example experimental parameters, i.e., the induction coil (a), the bending tool (b), and the arrangement in the machine (c) for the closed loop control application. Depending on the arc length of the bending specimen, the number of conductors and heating stations vary. For the heating of sheet metal with a thickness s = 4 mm, a nominal radius r_n = 6 mm, and a nominal angle θ_n = 45°, an optimal inductor geometry was found by an electromagnetic simulation in Ls-Dyna. Here, the two-turn induction coil overlaps two stations in feed direction, whereby a gap to the sheet metal (a_{Sheet} = 5 mm) and between both conductors ($a_{Conductor}$ = 2 mm) are absolutely necessary. A generator frequency of f = 20…100 kHz was selected as a function of the sheet thickness, whereby the power is limited to P_{max} = 40 kW. In this tool setup, after two heating stations, there is a dummy station before the bending takes place. Subsequently to forming, several air cooling stations are arranged, the second of which is used to feed back the bending angle via a measuring device.

In order to reach a target temperature T_i, a temperature PID controller brings the actual temperature into alignment with the demanded value. Here, a short-wave pyrometer with a wavelength λ = 1.6 μm and a measurement range $T_{Pyrometer}$ = 300…1200°C is used to determine the temperature of the second heating station. The later introduced angle measurement device to feed back the bending angle is implemented into a superordinate process controller. For the closed loop control, the desired temperature of a single stroke to compensate the springback will be determined by this process controller and transferred written to

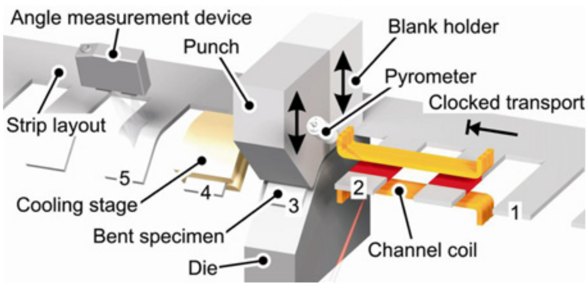

Fig. 2 Principle for bending at elevated temperatures through induction heating in progressive dies: 1: Precut specimen, 2: Heating station, 3: Bending station, 4: Cooling station, 5: Measuring station[14]

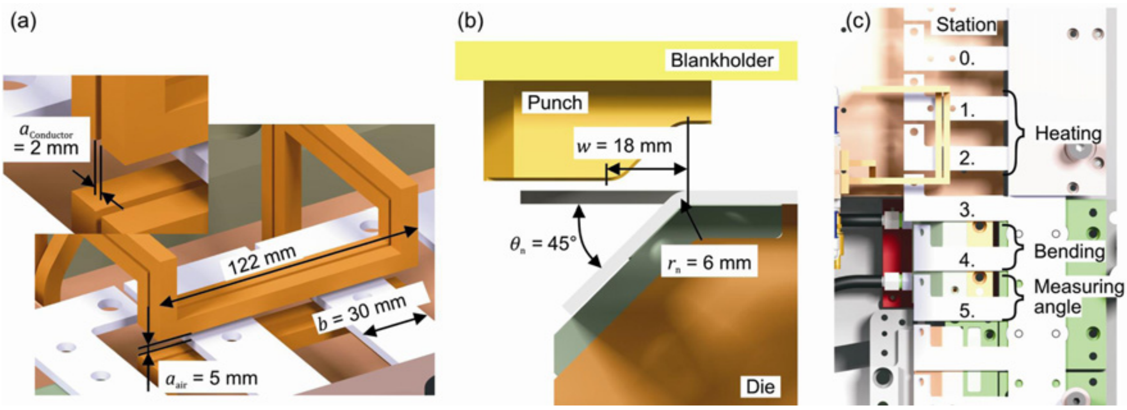

Fig. 1 Experimental setup: (a) Induction coil (b) Bending station (c) Stations in progressive die

the temperature controller.

In this investigation, the steel S500MC is applied, which is widely used in progressive die processes. Beside the temperature, also strain rate effects are considered. To avoid any secondary effects from the heating and cooling stations, the whole process runs at the constant stroke rate f_s = 15 1/min and only the ram velocity is alternated. For this purpose, a servo press allows for this stroke rate a variable ram velocity at contact point v_r = 10…140 mm/s.

3. Characteristics of the Warm Bending Process

To clarify the basic function of the innovative progressive die, an experimental investigation illustrates the effect of temperature on springback. Later, the experimentally achieved data is applied to set up the closed loop controller, so that an adjustment of springback will be obtained. Also other product properties such as the residual stresses, hardness, and microstructure are influenced in the warm bending process. Analogous to the springback, these properties could be the objective of the closed loop control. For this purpose, only a suitable measurement method to return the current status is necessary.

Fig. 3(a) reveals springback results from experiments with varying temperature T and stroke velocity v_r for the example tool parameters. Within the temperature interval 300…850°C to, firstly the positive springback angle Θ decreases. For higher temperatures above 350°C, each strain rate is combined with a significantly linear decreasing springback angle, whereby the gradient $\delta\theta/\delta T$ is increasing for higher strain rates. After the springback has reached a minimum value, higher temperatures lead to reversed characteristics with a slightly rising angle. Fig. 3(b) shows the calculated strain rate corresponding to the experiments. While the winding of the specimen around the die takes place, a constant angular velocity of the press drive leads to a decreasing strain rate. Finally, when the stroke reaches the bottom dead center, the strain rate becomes zero.

The reversed springback through alternating tool dimensions and material parameters is already detected for room temperature[15] as well as for high temperatures[13] and can be explained by overbending, which is schematically shown in Fig. 4. Due to elastic strains, strain hardening, an inhomogeneous temperature, and tool tolerances, the true bendline differs from the ideal bendline. These effects are expressed in a displacement of the forming zone, a vertical and horizontal mismatching punch position, and a lifting of the sheet between die radius and blank holder. Finally, these effects lead to larger angles during bending. When the sheet metal is formed at low temperatures with relatively high flow stresses, in addition to overbending, a high springback occurs during unloading so that a positive springback angle exists ($\theta_n > \theta$). For higher temperatures, the springback driving ratio flow stress to Young's modulus decreases,[14] whereby the overbending prevails and an absolute negative springback occurs ($\theta_n < \theta$).

Besides the temperature itself, also the strain rate affects the springback significantly. While forming takes place at a lower strain rate, the characteristic springback curve is displaced to lower temperatures. This is a result of time and temperature dependent recovery and recrystallization effects, which lead to simplified dislocation motions and lower flow stresses.

Within the temperature range from 350°C up to 750°C, microalloyed steels manifest advantageous ductility, while an undesired change of mechanical properties and microstructure is avoided through the inline induction heating with a short dwell time.[14] Thus, the closed loop control through varying the temperature in a huge range can be well applied. Depending on the actual strain rate, for this current example a

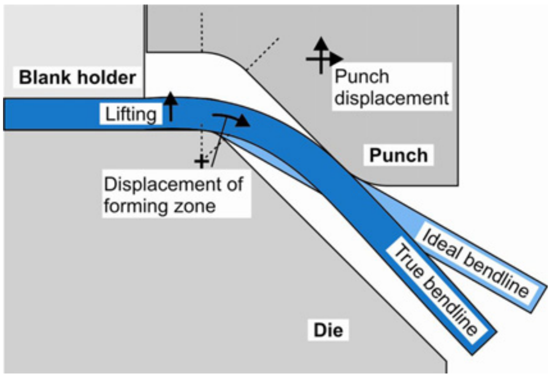

Fig. 4 Die bending of sheet metal: Deviation from ideal bendline caused by punch displacement, displacement of forming zone and lifting lead to overbending before unloading

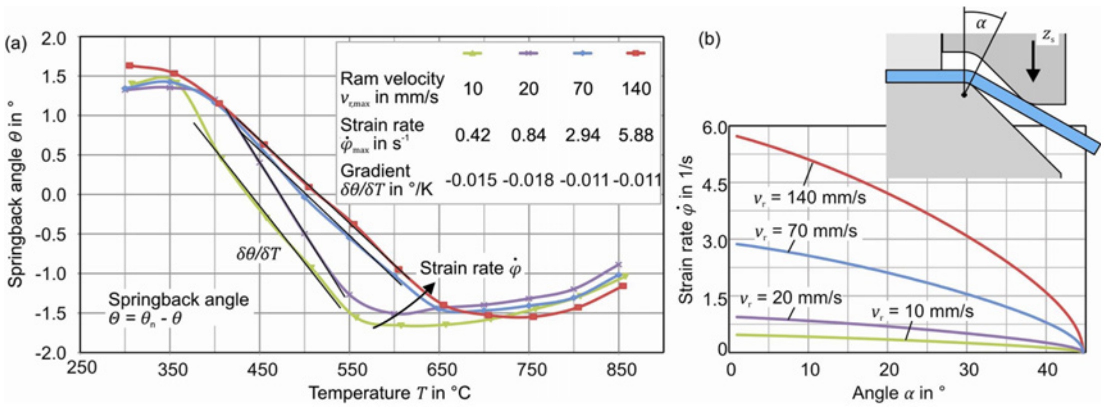

Fig. 3 Bending of S500MC (s = 4 mm) at elevated temperatures: (a) Springback angle after unloading (b) Calculated strain rates for varying maximum ram velocity

temperature range from 350°C up to 550°C (low strain rates) or 650°C (low strain rates) with a linear relation between springback and temperature is very suitable to adapt the angle after unloading. For this example bending tool, a maximum variation of $\Delta\theta = \pm 1.25°$ around the nominal angle θ_n = 45° can be achieved.

4. Discrete Controller for Springback Compensation

The innovative technology for warm bending in progressive dies offers not only an advantageous forming behavior but also a new principle to influence the springback after unloading. As long as the material and bend geometry requires no special temperature in order to keep an ideal ductility or certain product properties, the temperature is freely adjustable. With this method, not only errors of angle generated by the bending itself but also errors from heating and cooling can be compensated. Through the inline induction heating within one or a few strokes, the heating reveals a very short response time to act on a current error. Thus, only an error feedback is necessary to set up a closed loop control.

4.1 Design of discrete controller

Because, in this process design, the correction of the bending angle requires a change of the temperature before bending, and a measurement feedback is not possible before unloading, only a discrete control system process is feasible. Here, the stroke rate fs directly predetermines the sample time of the control system. A major challenging factor in the control process with the very low sample rate is the dead time. This dead time is equal to the number of intermediate strokes between heating and measuring n divided by the stroke rate f_s and describes the time gap between action and response. Generally, to overcome the dead time, a model of the process is implemented to estimate the system response for a current control value. The next control value will be adjusted with the predicted, but not delayed response of the model. An additional delayed feedback of the real system serves to suspend errors due to model failures. The PI-Controller with a Smith-Predictor is based on this principle so that a very aggressive and fast control reaction becomes possible.[16] Nevertheless, this controller type requires an accurate model function and is sensible to errors like nonlinear transfer functions. As Fig. 5 reveals, already a moderate PI-Controller setting with a relatively long response time cannot prevent the system from exceeding a defined angle. Thus, smaller PI-Controller constants are necessary to achieve a stable control mode, which is accompanied by a long settling time and a huge number of pieces with deviations from the target value.

To achieve an aggressive and simultaneously accurate control mode for this specific system with a relatively long dead time, a discrete controller on the basis of a simple P-Controller was designed (see Fig. 6). In order to bridge the known dead time nf_s^{-1}, a hold function ensures a constant setpoint $T(k)$ until a new corresponding result θ is measured and feed back into the controller. In this model, the recorded angle θ contains a process error $e_{Process}$, which consists of

- a heating error $e_{Heating}$,
- a bending error $e_{Bending}$,
- a cooling error $e_{Cooling}$ and
- a sensor error e_{Sensor}.

After the first result related to the current setpoint reaches the bending angle sensor, a new setpoint will be calculated and finally the hold function counter starts from the beginning.

In the bending model, the change of the setpoint $\Delta T(k)$ is determined through the strain rate dependent gradient $\delta\theta/\delta T$ and the current bending angle error $\Delta\theta(k)$:

$$\Delta T(k) = \left(\frac{\delta\theta}{\delta T}\right)^{-1}\Delta\theta(k) = \left(\frac{\delta\theta}{\delta T}\right)^{-1}(\theta_n(k) - \theta(k)) \quad (1)$$

In the second step, the new setpoint $T(k)$ is determined by the previous setpoint $T(k-1)$, whereby an additional damping factor d is used to avoid overshooting:

$$T(k) = T(k-1) + d\cdot\Delta T(k) \quad (2)$$

To adjust the control performance, only knowledge about the gradient $\delta\theta/\delta T$ and an adjustment of the damping factor d is necessary. The strain rate dependent gradient $\delta\theta/\delta T$ can be derived from experiments (see Chapter 3), whereas a suitable damping factor d can be determined by simulations.

4.2 Simulation of discrete controller

The control mode and stability of the designed discrete controller can be tested during the process or, otherwise, through simulations. The application of standard design procedures is not suitable because the representation of a partial non-linear system response and a dead time is quite challenging. Thus, a simulation is used to test the control behavior. Here, the discrete controller is implemented into a routine and the real bending process is substituted by a function which puts a certain bending angle in relation to an input temperature by interpolating the experimental data. Afterwards, the calculated bending result is indexed with the corresponding delay time.

To find a controller setting which facilitates in favor to a fast response and accurate setting, the simulation is used to match the damping factor d. Fig. 7 shows the simulated temperature and system response for the example bending case with at a ram velocity v_r = 70 mm/s. According to Fig. 4, the gradient $\delta\theta/\delta T$ is set to –0.011°/K. Furthermore, the implemented hold function keeps the setpoint constant as long as

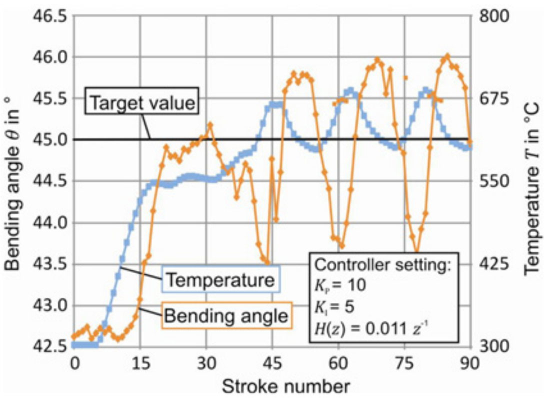

Fig. 5 Closed loop control of bending angle with PI-Controller and Smith-Predictor

additional four strokes are completed so that the whole dead time is exceeded. Besides the non-linear relationship in the bending process over the full range, an error $e_{Simulation}$ is included for the representation of the process error $e_{Process}$ and ensures realistic deviations from an ideal model. In the simulation this error function is assumed to have a random value within the range $e_{Simulation} = \pm 0.15°$.

As Fig. 7(a) indicates, despite the introduced damping, a significant swinging up occurs. Already after stroke number 10, the bending angle overruns the target value and overshoots up to 46.3°. Subsequently, further oscillations within approximately 24 strokes occur, whereby the bending angle oscillates nearly in the full range and no settling can be perceived. As a result the damping factor is reduced to $d = 0.6$, whereby the oscillation amplitude decreases below $\Delta\theta_{Error} = \pm 0.5°$ and a slight fade away is detectable (see Fig. 7(b)). Nevertheless, the control mode is still not suitable to achieve smallest deviations within a short reaction time. Therefore, an additional reduction of the damping factor to $d = 0.4$ (see Fig. 7(c)) is performed, which leads to a fast settling, although the response time is quite short. After the target value is exceeded and the bending angle reaches its maximum at stroke number 19 the amplitude continually declines and, after the stroke number 26, only error deviations within the range $\Delta\theta_{Error} = \pm 0.2°$ occur.

As the simulation of the closed loop controller for the discrete bending process indicates, through this simple proportional controller, a precise adjustment of the temperature in order to compensate springback can be achieved. To tune the control mode for a particular bending case, besides the gradient $\delta\theta/\delta T$ next to the target angle, only the damping factor has to be adjusted, which can be derived from a simulation.

To allow the closed loop control during the progressive die bending process, a method to derive the bending angle directly after forming is introduced in the next section.

5. Feedback of Bending Angle

In this section, a new measurement principle for the inline feedback of the bending angle is introduced. Subsequently, the derived information is used to compare the set- and actual-value in terms of the closed loop control.

Today, numerous principles for the online measurement of workpiece geometries are available. Besides tactile and laser optical principles, the application of CCD cameras with image processing technologies to measure the springback angle has become increasingly important. Most approaches are implemented in order to feed back the angle after unloading. For the swing folding process, Fait[17] integrated two tactile sensors onto a cheek, which captures the straight part in relation to the mounting during bending or in an unloaded status and allows high precision measurements in a stressless status. Rothstein[18] developed a technique to obtain the angle in three point bending with rotary tools, in which the angle is directly derived from the tool rotation. Another principle of three point bending, also with the integration of the tool geometry is introduced by Müller-Duysing,[19] where laser triangulation sensors are applied on the unformed flange outside the tool. More flexible implementations are designed for die bending and for draw bending. Here, a CCD sensor is used to recognize the global workpiece

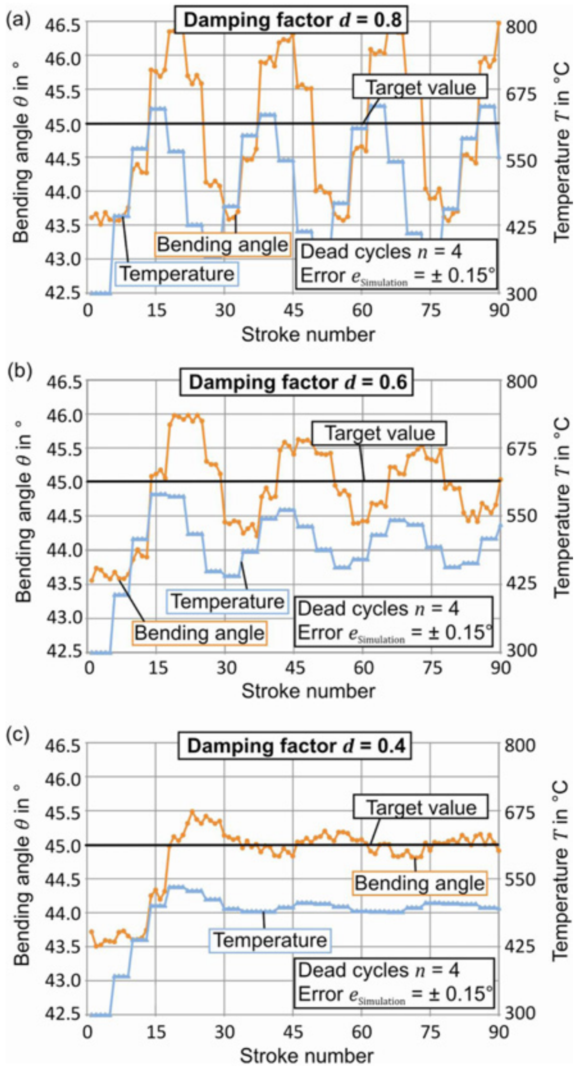

Fig. 7 Simulation of discrete controller on the basis of experimental data (ram velocity v_r = 70 mm/s) for different damping factors: (a) d = 0.8 (b) d = 0.6 (c) d = 0.4

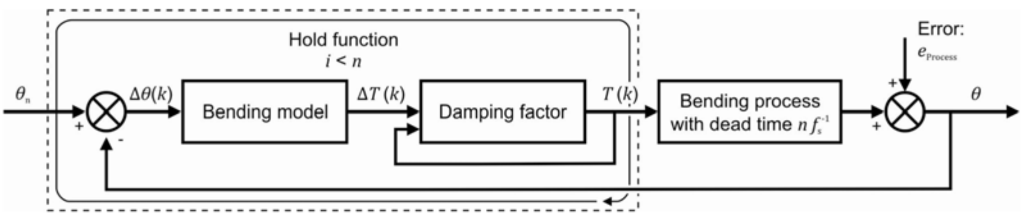

Fig. 6 Schematic of discrete controller for bending with dead time

geometry.[8] Dependent on the surface conditions, the image processing can be quite challenging and error-prone so that additional laser light or special filters are of major importance.

In the frame of this work, a measurement principle similar to tactile angle feedback in swing folding[17] is developed for a progressive die process is developed, which is based on two laser triangulation sensors (see Fig. 8). This principle can only receive a signal after forming, i.e., in a subsequent position (see Fig. 1(c)). Because the forming process is only adaptable via the temperature before the bending starts, a signal generation during forming is not relevant. While the response of laser sensors is read, the opposite flange is clamped between upper and lower tool and thereby horizontally aligned. As Fig. 8 illustrates, the front of the laser sensors is mounted into the upper die with a reference angle α so that the laser beams are nearly perpendicular to the surface. If a deviation of angle of the final part geometry occurs, a difference between both signals s_1 and s_2 will be measureable.

The deviation of angle δ in relation to the reference angle α is specified by Eq. (3) so that the full bending angle becomes $\theta = \alpha + \delta$:

$$\delta = \tan^{-1}\left(\frac{s_2 - s_1}{l}\right) \tag{3}$$

In this arrangement, beside the reference angle α and the distance l between both sensors, only the clamping of the horizontal flange is a potential error source so that any other tool influences are excluded. In this investigation, short range laser triangulation sensors with a resolution of 1 μm and a repeatability of 3 μm are employed, from which an ideal sensor error of up to $e_{Sensor} = \pm 0.01°$ for the distance l = 17.8 mm results.

Furthermore, Fig. 9 shows manual measurements and the determined angles from laser sensors for bending at different temperatures. After an initial calibration step with a reference body, both measurements are very well in agreement. Not only for a constant bending angle the measurement error $e_{Measurement}$ is small, but also for higher temperatures the derived angles are in line with the tactile offline measurement. Over the total range, the maximum error becomes $e_{Measurement} = \pm 0.25°$ and is thus significantly higher than the ideal senor error ($e_{Sensor} = \pm 0.01°$). This relatively high measurement error $e_{Measurement}$ is caused by different mechanisms and is not only affected by the laser device itself:

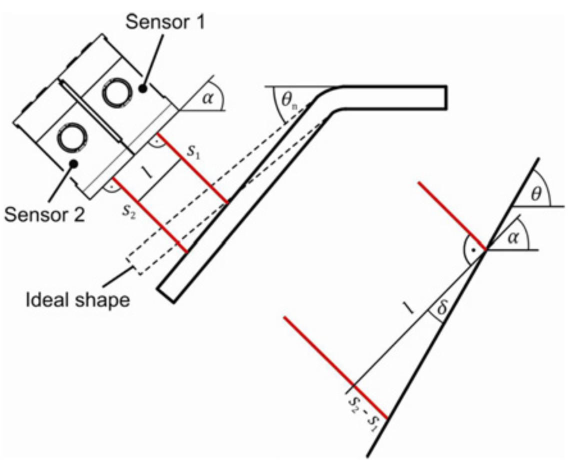

Fig. 8 Principle of bending angle measurement based on two parallel laser triangulation sensors

- Change of sensor temperature and dependent signal alternation
- Tactile measurement errors due to non-constant radius and angle over the whole width
- Regular deformation of angle through cooling after measurement
- Coupled influence of cooling error $e_{Cooling}$

Although these error sources are inevitable in this prototype progressive die, through a careful tool design, the magnitude of errors can be decreased. Therefore, the inline measurement must be implemented in a stage after total removal of heat so that the measurement is isolated from the cooling influences as the cooling error $e_{Cooling}$ and also temperature influences on the sensor are neglected. When these aspects are considered in the tool design, a significant reduction of the error can be reached.

In terms of the closed loop control, the introduced measurement method is implemented into the progressive die on station 5 (see Fig. 1). Here, the measurement of the free bending leg is conducted when the blank holder has pressed the strip layout onto the lower die completely. From this time on, the opposite bending leg is clamped in a horizontal orientation so that a relative measurement according to becomes possible.

6. Experimental Results and Discussion

In order to validate the closed loop control with the proportional transfer function, the controller is implemented into Labview and used to adapt the target temperature of the PID controller for temperature adjustment before bending. The temperature is controlled in station 2 (see Fig. 1(c)). Then bending is performed in station 4, followed by the final feedback of bending angle. As introduced in Chapter 5, a double laser sensor is used and mounted to the blank holder of the upper die. Accordingly, the feedback of angle begins when the blank holder reaches the strip layout and clamps the workpiece.

Fig. 10 depicts the process start with 35 strokes for the damping constant d = 0.4, which was simulated in section 4.2. Within the experiment, the moderate ram velocity of v_r = 70 mm/s at contact point is used, whereby a maximum strain rate $\dot{\varphi}$ = 3 s^{-1} at forming onset is generated. In accordance with the simulation results, the damping factor d = 0.4 is accompanied by a fast settling. After 15 strokes, the deviation becomes smaller than the final tolerance of $\Delta\theta_{Error} = \pm 0.3°$. In

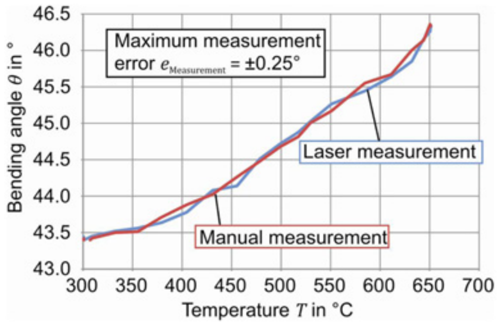

Fig. 9 Difference between manual tactile and automatic double laser sensor measurement of bending angle for varying temperature with ram velocity v_r = 70 mm/s

contrast to the fast settling of the deviations, other experiments revealed an unstable control mode for high damping constants above $d = 0.6$. In these experiments no settling occurred, which was expressed in temperature variations within the full range $T = 300…800°C$.

To enhance the control mode also for higher damping factors with an accordingly faster settling time, not only an improvement of the measurement technique (see Chapter 5) is necessary, but also a more precise bending model and an accurate temperature control are required. In this discrete controller, a proportional transfer function reflects the linear characteristic of the bending angle in relation to temperature within the medium temperature range. To achieve a fast springback compensation from the first stroke on, a numerical or empirical model which considers the nonlinear springback characteristic is required, whereby experimental knowledge for certain configurations (see Fig. 3) can be replaced.

Furthermore, in order to achieve a certain target temperature, a more precise temperature control is necessary. Fig. 11 depicts the final temperature after heating to the target $T = 750°C$. Here, over the complete longitudinal axis, the temperature fluctuates strongly and, in the center, an uncertainty in the range $\Delta T_{Heating} = \pm 10°C$ appears. According to Fig. 3(a), for the stroke velocity $v_r = 70$ mm/s, an approximate angle error $e_{Heating} = \pm 0.11°$ results from this temperature uncertainty. In order to improve the quality of the temperature control, the temperature observation during heating as well as changing the target temperature could be an optimization approach. To avoid an influence of varying surface conditions, additional pyrometers to average the measured infrared light intensity over a certain area could be applied. Moreover, when a temperature adaption is conducted, an existing interaction between both heating stations can affect the temperature control negatively. Depending on the actuating-value and the deriving generator power during the first step, the initial condition for the second step is not constant. For this reason, a differing heating power is necessary in order to reach a constant target value, and also the final temperature field before forming is determined by the temperature history of the heating process. From this point of view, a decoupling of the single heating station through separated induction coils could be beneficial.

When these error sources are considered in the design process of a progressive die, besides an aggressive control mode, also a short settling time will be reached with the consequence of less production waste.

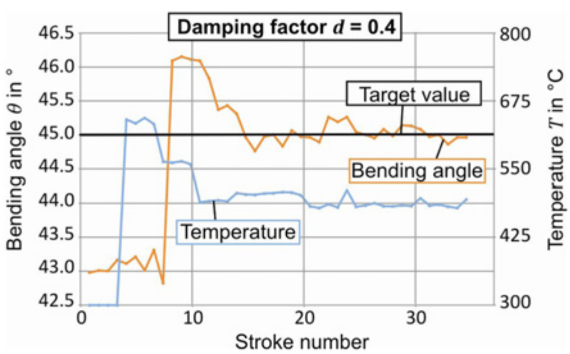

Fig. 10 Discrete control of bending angle in warm bending process (ram velocity $v_r = 70$ mm/s) for the damping factor $d = 0.4$

7. Future Perspective for Stable Response

The designed controller with a proportional factor and a damping constant overcomes the dead time through a hold function and is thereby capable to adjust the angle within the clocked bending process. Nevertheless, the damping factor limits the response time, a stable system response is not ensured for large model and system errors, and a change of the actuating-value in intermediate steps is not possible. Therefore, a fast reaction is inhibited, particularly when a small damping factor is used to handle large errors with regard to the temperature control, angle feedback, and deviations from the bending model. Some modifications lead to an improved controller design to avoid these disadvantages (see Fig. 13). Instead of holding a system response during the dead time, an adaption of the actuating-value is done after each stroke. For this purpose, the current setpoint is saved in a process history and later retrieved for an error comparison. Furthermore, the comparison of several earlier process results is used to eliminate the effect of single errors. Finally, through the adapted controller design with a mean value formation over m cycles, a damping factor becomes redundant.

In contrast to Eq. (1), from Eq. (4), the singular actuating-value $T^*(i)$ can be directly derived, which describes the corrected target temperature for an individual stroke:

$$T^*(i) = T(i) + \Delta T(i) = T(i) + \left(\frac{\delta\theta}{\delta T}\right)^{-1} \cdot \Delta\theta(i) \tag{4}$$

In this context, $T(i)$, $\Delta T(i)$, and $\Delta\theta(i)$ are the corresponding setpoint from the individual stroke i, the desired temperature change to overcome the measured error, and the measured error itself. Subsequently, from different actuating-values $T^*(i)$, an average actuating-value $T(k)$ is calculated in consideration of single setpoints is formed for the following stroke number k. When the bending process starts, as a function of the current stroke number k, the number of dead cycles n and the number of average values m, the new actuating-value $T(k)$ is calculated based on the process history:

$$T(k) = \begin{cases} \dfrac{1}{m} \displaystyle\sum_{i=k-n-m+1}^{k-n} T^*(i) & \text{for} \quad k > n+m \\ \dfrac{1}{k-n} \displaystyle\sum_{i=1}^{k-n} T^*(i) & \text{for} \quad n \le k \le n+m \\ T_{min} & \text{for} \quad k < n \end{cases} \tag{5}$$

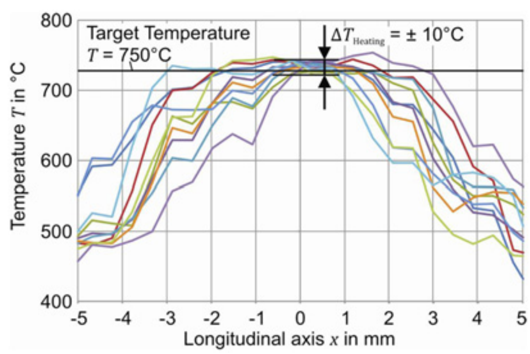

Fig. 11 Measured longitudinal temperature distribution of different specimens in second heating station directly before leaving

In the first strokes, the actuating-value $T(k)$ is set to the minimal temperature T_{min} because no reference data is available. According to section 4.2, the improved controller design was also tested in simulations (see Fig. 12).

For the constant simulation error $e_{Simulation}$, a stable control mode is achieved. Independent of the dead cycle number *n,* the initial deviation settles within a few strokes. When the number of dead cycles is $n = 4$ (see Fig. 12(a)), the number of settling cycles is decreased to less than $c = 12$ (see Fig. 10). Also a high number of dead cycles (see Fig. 12(c)) do not have a negative influence in form of swinging, even if the model does not match to the bending process, especially for large deviations from the target value. Also a small number of settling cycles is achieved for both high dead cycle numbers $n = 8$ and $n = 16$ ($c = 25$ and $c = 45$, respectively). As the simulations reveal, with the improved controller a ratio of settling cycles to dead cycles of approximately $c/n \approx 3$ is reached. In this way, also several concentrated forming operations can be controlled by a subsequent feedback of the generated product shape and a temperature adjustment prior to forming.

Finally, the improved controller design in combination with an advanced measurement technique to feed back the actual-value will be a powerful instrument in order to minimize geometrical errors, whereby, independent from a low or high dead cycle number, small deviations from the set-value are achievable.

8. Conclusion

In order to enhance the processing of high strength steels in the large scale production, a new warm bending technology with a closed loop control for progressive dies was introduced. Here an inline induction coil was used to allow a more ductile bending, whereby the absolute temperature was adjusted to compensate springback after unloading. From this investigation, the following conclusions can be drawn:

- Through heating before bending at temperatures between 300…850°C, the springback angle of microalloyed steel can be varied in the range of $\Delta\theta = \pm1.5°$. Here, a linear relation for medium temperatures depending on the strain rate is particularly useful to control the final bending angle.
- With the introduced double laser triangulation sensor an inline feedback of the generated angle is achieved. Measurements reveal a total error of $e_{Measurement} = \pm0.25°$, which is mostly the result of temperature influences on the sensor itself, and thermal distortion of bending parts can probably be significantly reduced by complete cooling before measuring.
- The conventional PID-controller with a Smith-Predictor is not suitable to overcome the large dead time and achieve a stable control mode through the faulty model function. As shown in an experiment, also decreasing K_p and K_i constants with a huge amount of strokes for reaction are not beneficial in order to settle down the initial deviation.
- On the basis of the introduced proportional controller with a hold function, a fast and stable control mode for the discrete warm bending process is achieved. Here, only a damping factor d has to be adapted for the certain bending case and current disturbances. For the example ram velocity $v_r = 70$ mm/s, a settling within 15 strokes and a total error $\Delta\theta_{Error} = \pm0.30°$ was obtained.
- In order to achieve a faster and more stable transient response, an improved control design was introduced. Here, the adaption of the actuating-value is based on the process history and occurs every stroke. As the simulation reveals, the controller is suitable to deal

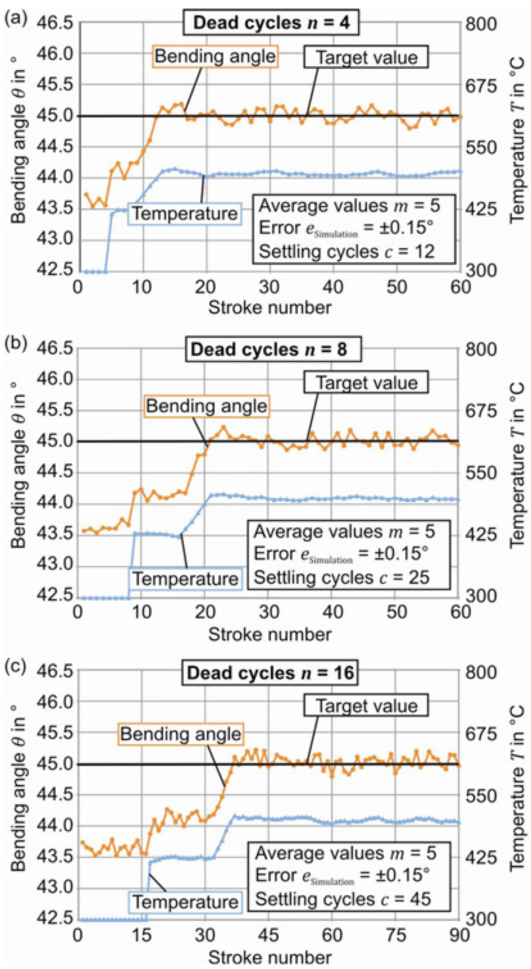

Fig. 12 Simulation of discrete controller with average function on the basis of experimental data (ram velocity $v_r = 70$ mm/s) for different dead cycles n

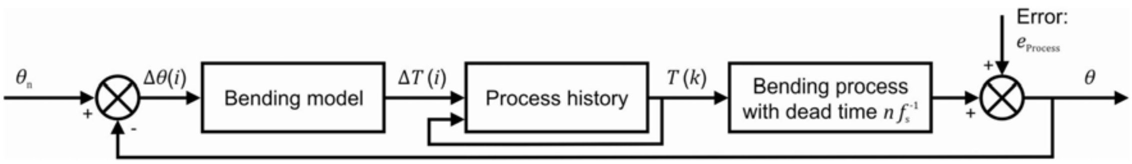

Fig. 13 Schematic of advanced discrete controller with averaging function

with low and high numbers of dead cycles.

Although a suitable controller design for the new warm forming technology was found, improvements in order to neglect failures of measurement and temperature control during heating are still outstanding. Here, the applications of complementary sensors as well as a complete cooling before measuring are key components in continuing investigations. A further approach for development is the implementation of the real bending characteristic so that a precise prediction of the springback angle serves for a shorter decay of initial errors. Therefore, a detailed numerical or analytical model of the warm bending process with different tools is required, which depicts strain rate, creep, and cooling effects.

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