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Mechanisms for controlling springback and strength in heat-assisted sheet forming

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A R T I C L E   I N F O

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A B S T R A C T

The recently developed multi-step sheet forming technology with inductive in-situ heating serves to increase the productivity and to reduce costs compared to hot stamping with furnace heating. The paper reveals the mechanisms for the flexible setting of geometric and mechanical properties such as the bending angle and strength in terms of a closed loop control. The air and die bending as representative forming processes are analyzed with respect to the mechanisms overbending, springback and thermal distortion by experimental, numerical, and analytical investigations. The mechanisms for controlling strength in carbon steels by grain refinement, grain growth and cooling rate are described.

1. Introduction

Hot forming has become an essential technology for the production of high-strength and safety-relevant components. The application of this technology is driven by the paradigm change from shaping a component to setting the mechanical properties for lightweight and component safety [1]. To enhance the productivity, increase the flexibility, and reduce the investments compared to the classical hot stamping of boron-manganese steel with furnace heating, new technologies are currently being developed. Examples are the shortened process chains for reduced investments by the contact heating within the handling system [2] or by a conductive heating, forming and blanking in one stage [3]. The design flexibility and processing speed depends on the number of tool stages and is treated e.g. by a new multi-step forming approach [4]. Further concepts are based on the rapid heating by laser or induction systems, the servo-technology to adapt the stroke velocity, or the fast convective cooling inside or outside the tool [5]. These developments require new alloys and coatings, so that the short-term soaking, and the forming in a larger temperature-time window become possible. Examples therefore are the air-hardening chromium steels [6], rolled-bonded plates [7], or zinc coatings for the direct hot stamping process [8].

Recently a rapid process with inductive heating in progressive or transfer tools has been introduced [9]. By separating the forming (here: bending) and cooling over several stages, a higher stroke rate proportional to the number of stages results (Fig. 1). Product properties are monitored by laser and micro-magnetic sensors for controlling the process. So far, the springback compensation has been demonstrated [10], which was based on an empirical off-line control according to the classification of Allwood et al. [11]. To qualify the technology for adjusting the properties by rapid austenitization and quenching, low-carbon steels have been studied [12]. The design of the heat supply and the heat removal for different process parameters were derived [13].

Depending on the requested material and initial condition, the local heating is used for setting the geometrical or mechanical properties. Hence, the prevailing mechanisms during forming (here: bending) of annealed high-strength metals (e.g. Mg-, Al- and Ti-alloys, high strength steels) must be clarified. On the other hand, the investigation of the heat treatment is required to improve the formability during processing (e.g. MS steel) or to set tailored properties. When those effects are mathematically described, the application in terms of the closed loop control (e.g. off-line feed-forward or feed-back control) becomes feasible. Yanagimoto et al. [14] have disclosed the temperature sensitivity during bending, but could not separate the influences of the thermal strains, the work hardening and the strain rate on the bending angle. Overbending during loading, which is dependent on the material behavior and tool design, has not yet been differentiated from springback. In terms of the rapid annealing, the short austenitization time and fast heating lead to a fine grain structure [15] and undissolved carbides [16]. For the quenching, however, a distinct grain size and carbon content are required.

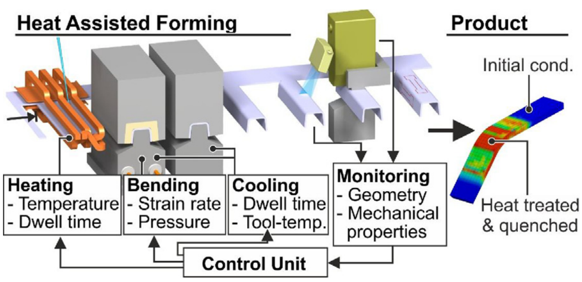

Fig. 1. Heat assisted sheet metal forming in a progressive tool.

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In this paper, all mechanisms influencing the geometrical and mechanical properties of the products after heat-assisted sheet forming processes are investigated and revealed. In Section 2, a study of air-bending is presented to differentiate the effects of **overbending** and **springback** mechanisms. The mechanism of **thermal distortion** on the bending angle is disclosed by an analysis of a die-bending process. In Section 3, the mechanisms in the in-situ heat treatment to facilitate the quenching and adjusting the strength by the **grain refinement**, **grain growth** and **cooling rate** have been explored.

2. Overbending, springback and thermal distortion

In the sheet bending process, the curvature, the angle and the residual stresses are influenced by many parameters, e.g. the tool, the process parameters, and the material. As shown by Dannemann [17] in the late 60s, depending on the strain hardening and tool dimensions, the achieved angle can be either positive or negative in relation to the nominal value due to dominant overbending or springback. Yanagimoto et al. [14] discovered that the temperature itself leads to a similar effect with a changed sign of the angle deviation. While this important observation could not be modeled by means of elastic-plastic FEM, the phenomenon was explained by relaxation and creeping. In the following, those effects are characterized and related to the mechanisms overbending, springback and thermal distortions.

The set-up of the bending process enabled by an induction coil and transport unit is shown in Fig. 2a. Fig. 2b and c shows the tools and parameters for the air- and die-bending, respectively. After the heating ($dT/dt \approx 75$ K/s), the specimen is immediately transported and deformed. To measure the bending angle during forming and unloading, an on-line laser line triangulation sensor (LLT 2910-50/BL, Micro-Epsilon) captures one bending leg.

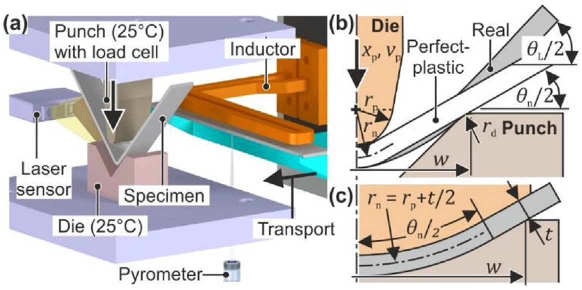

Fig. 2. Heat assisted bending: (a) set-up (b) air-bending (c) die-bending.

2.1. Air-bending — viscoplastic and thermal influence

To differentiate the overbending and springback, two parameters are introduced: The **overbending** ratio M represents the enlarged angle in the loaded state θ_L in relation to the nominal angle θ_n, and the **springback** ratio S describes the angle θ_R due to elastic unloading with respect to the loaded state:

$$M = \theta_L/\theta_n \quad \text{and} \quad S = \theta_R/\theta_L\,. \tag{1}$$

The nominal angle θ_n is derived from the geometrical parameters such as h the punch travel and t the sheet thickness under idealized conditions for a rigid-perfect plastic material as (Fig. 2b):

$$h = \left(r_d + \frac{t}{2}\right)\cdot(1 - \cos\theta_n) - \cos\theta_n\cdot\left(r_p + \frac{t}{2}\right) + \sin\theta_n\frac{w}{2} - \sin\theta_n\cdot\tan\theta_n\left(r_p + r_d + t\right). \tag{2}$$

Fig. 3 depicts the experimentally and numerically determined overbending-ratio and springback-ratio for a micro-alloyed (MA) steel. The basis for the elastic-viscoplastic FEM simulation (Solver: Abaqus implicit) is a table-based description of the temperature- and strain rate-dependent flow curve, which was determined from tensile tests in 100 °C increments at three different rates. The alternating bending ratio r/t is defined by the nominal radius r_n to the sheet thickness t (Fig. 2). Due to the blue brittleness and the decreasing Young's modulus over temperature, the springback S initially decreases before the flow stress drops drastically at higher temperatures so that the trend reverses.

The overbending is affected by the change of flow stress σ_f due to the strain hardening and the strain rate sensitivity. Both effects are described by the Swift equation for the strain hardening with the hardening exponent n, the strength value K and the initial strain ε_0, and, the Cowper–Symonds equation with the parameters C and p, respectively, for the strain sensitivity:

$$\sigma_f = K\left(\varepsilon_0 + \varepsilon_{pl}\right)^n\left(1 + \frac{\dot{\varepsilon}^{pl}}{C}\right)^{1/p}. \tag{3}$$

While at room temperature (RT) the initial strain-hardening exponent is comparably low due to the Lüders strain, slightly higher temperatures manifest a strongly pronounced strain-hardening because of the steady flow onset. Hence, the increasing strain hardening is contributing to the overbending. At higher temperatures, the increasing strain rate sensitivity causes the higher flow stress instead of the strain hardening, which is finally completely abolished by the recrystallization (see Table 1). Another contributing factor to both overbending and springback is the heat loss due to the tool contact. In consequence, the plastic zone expands around the circumference. This effect is relatively small as shown by the adiabatic simulation (dashed line) in Fig. 3a.

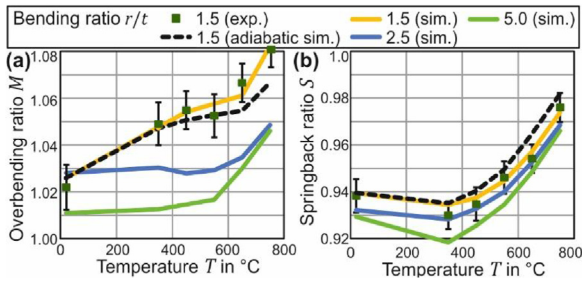

Fig. 3. (a) Overbending (b) springback (thickness t = 4 mm; die width ratio w/t = 10; nominal angle θ_n = 82°; punch velocity v_p = 10 mm·s^{-1}).

Through the rectified evolution of both ratios, the relative angle deviation to the nominal value θ_n (product $M\cdot S$) is distinguished by a change from negative to positive values. In order to adjust the bending angle, two independent mechanisms overbending and springback are thus active, both of which are controlled by the geometric parameters, the punch speed and the temperature.

Table 1
Coefficients of the micro-alloyed (MA) steel ($\sigma_{y,0}$ = 600 MPa at 25 °C): Strain hardening exponent n, Cowper–Symonds parameters C and p.

T in °C	20	(...)	350	450	550	650	750
n	0.117		0.116	0.090	0.061	0.042	–
C	–		–	59.4	5.23	4.13	0.49
p	–		–	2.90	2.85	2.48	2.61

The accountability of the described mechanisms has been observed for other process relevant high-strength alloys such as the AlMg4.5 Mn (EN AW-5083) and the Ti6Al4V (Gr. 5). The pure Al- and Ti-grades (EN AW-1050A and Gr. 1) are considered for comparison. Fig. 4b reveals a decreasing springback, which is in accordance to the characterized ratio σ_f/E of tensile tests.

While the grades Al99.5 and Ti6Al4V are characterized by a low strain hardening at RT, the overbending is small compared to the grades AlMg4.5 Mn and Ti99.9. At higher temperatures with lower initial yield stress due to vanishing strengthening effect of alloy elements and increasing strain-hardening exponent, the overbending is increasing for all alloys (for Ti99.9 already at RT due to the distinct strain rate dependency).

The analysis of the tool dimensions shows that a broader die, a smaller bending ratio as well as reduced nominal angles lead in