CIRP Annals - Manufacturing Technology 65 (2016) 573–596

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Closed-loop control of product properties in metal forming

J.M. Allwood (1)[a,*], S.R. Duncan[b], J. Cao (1)[c], P. Groche (1)[d], G. Hirt (1)[e], B. Kinsey[f], T. Kuboki[g], M. Liewald (3)[h], A. Sterzing[i], A.E. Tekkaya (1)[j]

[a] Department of Engineering, University of Cambridge, Cambridge, United Kingdom
[b] Department of Engineering Science, University of Oxford, Oxford, United Kingdom
[c] Mechanical Engineering Department, Northwestern University, Chicago, IL, USA
[d] Institut für Produktionstechnik und Umformmaschinen, Technische Universität Darmstadt, Darmstadt, Germany
[e] Institut für Bildsame Formgebung, RWTH Aachen, Aachen, Germany
[f] Department of Mechanical Engineering, University of New Hampshire, Durham, NH, USA
[g] Department of Mechanical Engineering and Intelligent Systems, University of Electro-Communications, Tokyo, Japan
[h] Institut für Umformtechnik, Universität Stuttgart, Stuttgart, Germany
[i] Fraunhofer-Institut für Werkzeugmaschinen und Umformtechnik, Chemnitz, Germany
[j] Institut für Umformtechnik und Leichtbau, Technische Universität Dortmund, Dortmund, Germany

ARTICLE INFO

Keywords:
Metal forming
Product properties
Control

ABSTRACT

Metal forming processes operate in conditions of uncertainty due to parameter variation and imperfect understanding. This uncertainty leads to a degradation of product properties from customer specifications, which can be reduced by the use of closed-loop control. A framework of analysis is presented for understanding closed-loop control in metal forming, allowing an assessment of current and future developments in actuators, sensors and models. This leads to a survey of current and emerging applications across a broad spectrum of metal forming processes, and a discussion of likely developments.

1. Motivation

The technology of metal forming has evolved over 7000 years, from the earliest ornaments and tools, through the mediaeval blacksmith and armourer, to today's rapid mass production in rolling mills and presses. This development, supported by parallel developments in the science of plasticity [133] and the understanding and prediction of product properties [177], has led to extraordinary world-wide benefit. The global industrial system currently produces 200 kg of steel [39] and 7 kg of aluminium [38] per person per year and transforms them into buildings, vehicles, equipment and final goods [5] of universal familiarity at unprecedentedly low cost.

Unlike ceramic or composite materials, the properties of metal components are a consequence both of their composition and of the history of thermo-mechanical processing that was used to convert the as-cast material into a final form. The properties of interest include both the overall geometry of the component, mechanical properties such as strength and ductility, surface properties such as roughness and micro-structural properties such as texture which influences almost all mechanical properties.

The technological developments that have led to today's production allow rapid and precise application of deformation and temperature change to metal workpieces. New technologies aim at increasingly refined product states, for example with a distribution of strength and ductility through components such as the B-pillar in cars, to optimise their performance in service and in a crash. Increasing the speed of production of these tightly specified components depends primarily on the elimination of variability through ever more precise control of material composition, temperature history and geometry. Decades of effort have improved tolerances in metal forming so they are now more sensitive to smaller uncertainties which are beyond the reach of even the most advanced production systems. These include uncertainties related to the as-cast microstructure, contact surfaces, post-processing and process interruptions.

When metal is cast and first solidifies, even though its composition is tightly controlled, the pattern of nucleation that defines the grain structure of the solid cannot be controlled. The distribution of grain sizes and their composition, phases and orientation are therefore subject to stochastic variation as illustrated in Fig. 1. This variability creates an uncertainty about the outcome of downstream processing and hence properties.

The geometric precision, surface quality and microstructure of a product in metal forming depends on the tools, the elastic deflection of the equipment and the heat transfer between tools and workpiece. In turn, these interactions depend on lubrication, surface oxidation, and tool wear. However, these mechanisms vary across the contact surface and throughout processing. For example, Fig. 2 shows how the coefficient of friction between tool and workpiece varies even under the highly controlled conditions of a laboratory strip drawing test, and as yet cannot be fully predicted.

* Corresponding author.
E-mail address: jma42@cam.ac.uk (J.M. Allwood).

http://dx.doi.org/10.1016/j.cirp.2016.06.002

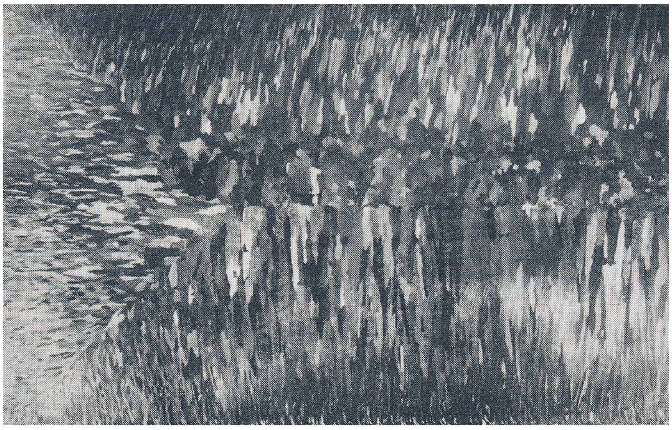

Fig. 1. Uncertainties related to the material: grain size distributions in cast steel. From [153], p120.

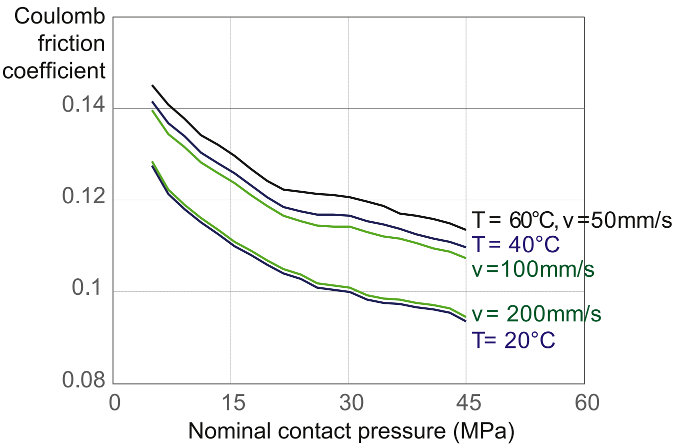

Fig. 2. Variation of friction coefficient with temperature and speed during a strip drawing test [183].

In many metal forming operations, the product properties continue to evolve after the main action of processing is complete, for example due to post-process cooling, and these post-processes have a high-degree of uncertainty. Fig. 3 illustrates the variability in springback of samples of the same material.

Unanticipated interruptions to processing may change process conditions away from their expected state, particularly for processes that operate above ambient temperature. For example the incoming material to a hot rolling mill will cool more than expected if there is a delay between its release from the pre-heat furnace and mill entry and equally the 'thermal crown' of the work rolls (their thermal expansion) will evolve between strips. This uncertainty is particularly acute when equipment operation is re-started after an idle period, or during switchover between different products.

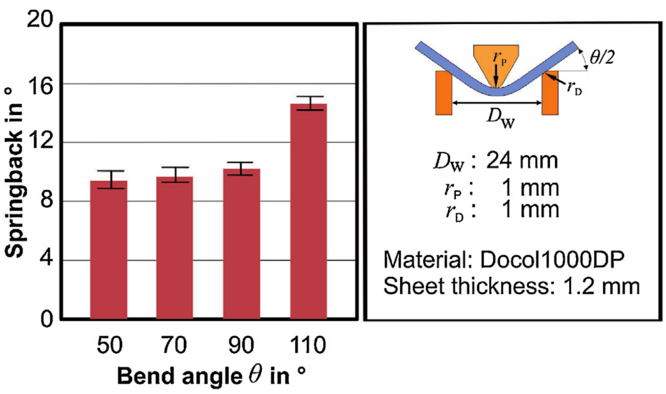

Fig. 3. Variation in springback during the air bending of sheets of the high-strength steel Docol100DP to different bend angles [49].

These examples of uncertainty in metal forming can usefully be separated into two categories in anticipation of the exploration of closed-loop control in this paper:

- *Model errors* include all uncertainties related to use of a process model. For example, a model used to predict roll force and torque in strip rolling might fail to predict the values accurately due to the use of inaccurate material models, or failure to characterise friction variations such as those shown in Fig. 2.
- *Disturbances* include all uncertainties beyond what should have been predicted by the process model. For example, a process model in rolling that assumed the incoming material would be of constant thickness and at ambient temperature would be disturbed – its output would be inaccurate – if the incoming material in fact had thickness variations and was at a raised temperature. Similarly, vibration of the equipment might change the outcome of processing.

Within the community of metal forming researchers, these two forms of uncertainty look rather similar: disturbances would become model errors if the scope of the model were expanded to cover the disturbing phenomenon. However, from within the community of control engineers, the two forms of uncertainty are quite different – because one (the model error) is affected by the control signals applied to the process, while the other (the disturbances) is not.

Fig. 4 presents a schematic illustration of metal forming processes which shows the relationship between the physical process and any model used to describe it. The figure demonstrates the challenge of achieving product quality in the face of the two forms of uncertainty. The process is operated according to a schedule of planned actuator inputs, $\mathbf{u}$. Any errors in the model, Δ, will influence the schedule and degrade the product state, $\mathbf{z}$. However, even were the process model perfect, un-modelled disturbances, $\mathbf{d}$, will also drive the state away from its reference target.

Uncertainties in metal forming downgrade product quality which must be compensated by additional downstream manufacturing, increasing cost and reducing productivity. This is particularly important in small batch runs, which are subject to the highest uncertainties, but where the cost of compensating for uncertainties cannot be shared over a long production run. Furthermore, as the science of product property prediction improves and while the range of actuation and sensing that can be applied in metal forming increases, there is a growing opportunity to add more value through metal forming, to tailor product properties more precisely [177]. As well as component geometry, metal forming processes in future can aim to deliver other specified product properties.

Today's metal forming processes operate at levels of product quality and overall productivity beyond any possible imagining of the mediaeval blacksmith. However, the blacksmith could compensate for uncertainties and still produce a product of the required quality. This opportunity, which is only available to a very limited extent in today's mass production equipment, provides a further motivation for this paper: given emerging insights into product properties [177] and 20 years of innovation to increase process flexibility [6,65,88], could metal forming processes of the future be designed to compensate for a wide range of uncertainties and still achieve today's excellent productivity? Specifically, is it possible to add feedback to the schematic diagram of Fig. 4 that allows compensation for the unavoidable uncertainties that arise in metal forming operations?

The topic of closed-loop control of properties in metal forming has had relatively little attention, with just one review of the major applications to date [144]. However, in other areas of manufacturing technology, the topic has attracted wider attention. Reviews have been published on closed-loop control of electro-discharge machining [166], machine tool feed-drives [169], machine tools [96], machining [104], robotic welding [197], drilling fibre-reinforced

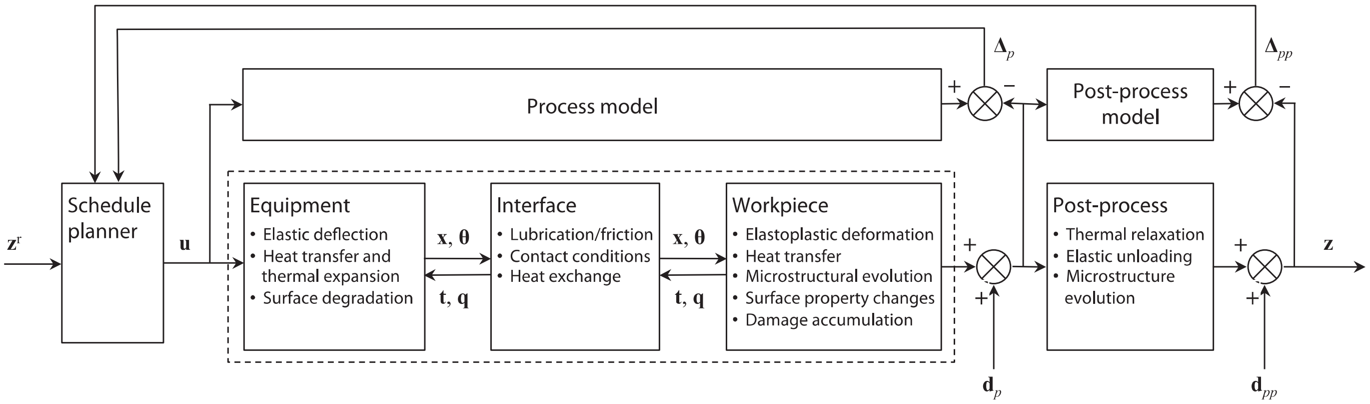

Fig. 4. The influence of uncertainties on the outcome of metal forming processes and examples of the physical phenomena involved (**z** is the state of the product, $\mathbf{z}^r$ is the target state requested by the customer, **u** are the scheduled actuator settings, **x** is the current geometry of the equipment or workpiece, θ is the current temperature of the equipment or workpiece, **t** are surface tractions, **q** is the rate of heat transfer between equipment and workpiece, Δ_p, Δ_{pp} are the model errors of the process and post-process respectively, and $\mathbf{d}_p$, $\mathbf{d}_{pp}$ are un-modelled disturbances).

plastic composites [165] and additive manufacturing with metal [175]. These reviews raise common themes which translate to the challenge of controlling properties in metal forming: because process behaviour is non-linear, the simplest applications of proportional–integral–derivative (PID) control can act only over a restricted range of actuator settings; the sensors are typically indirect, for example temperatures can be measured only at component surfaces and often at some distance from the region of interest, so are usually interpreted via an 'observer' model; because of the non-linearity of the processes, the success of the control system is strongly dependent on the process model available to it, and this must trade-off accuracy against solution speed.

2. Classification of control systems in metal forming

All contemporary metal forming machines are equipped with closed-loop control systems, to ensure that the actuators fitted to the equipment lead to the anticipated response *of the equipment*. This form of closed-loop control is illustrated in Fig. 5 for a subset of Fig. 4 and is *not* the focus of this paper: in Fig. 5, the feedback relates to the state of the equipment, where this paper considers feedback related to the state of the workpiece.

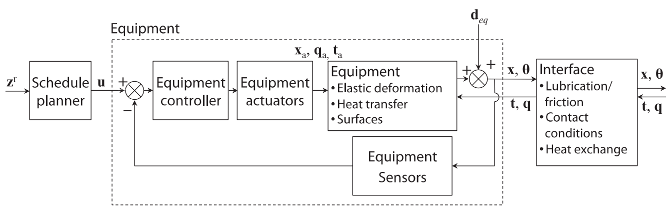

Fig. 5. Conventional closed-loop feedback control of the state of the equipment ($\mathbf{x}_a$ is the current location of any geometrical actuators, $\mathbf{t}_a$ are tractions created by actuators, $\mathbf{q}_a$ is the rate of heat transfer between the actuators and the equipment, $\mathbf{d}_{eq}$ are external disturbances).

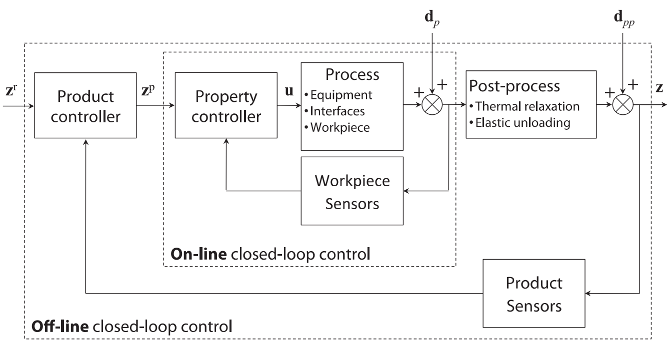

Fig. 6. On-line and off-line closed-loop control of product properties ($\mathbf{z}^p$ is the modified reference state, before the uncontrolled post-process).

The closed-loop control of equipment in Fig. 5 is of course essential, but is here assumed to be part of the 'equipment' box in Fig. 4: if an actuator request is submitted by the schedule planner to the equipment, it will be assumed that the equipment is so actuated. Instead, Fig. 6 illustrates two further forms of closed-loop control that could be introduced to the system of Fig. 4, if sensors were available to assess the state of the *workpiece* (in contrast to the sensors on the equipment in Fig. 5).

Fig. 6 uses the notation 'workpiece sensors' to indicate sensors that measure the state of the product during processing and 'product sensors' to measure the state after both process and post-process are complete which may involve some time delay. Off-line product sensors such as those illustrated in Fig. 6 remain part of a closed-loop (i.e. not open-loop) system, if the system is making a series of similar parts, and the feedback of product information can be used to improve the production of later products in the same series.

Perhaps surprisingly, although to production technologists the on-line and off-line approaches to closed-loop control illustrated in Fig. 6 are quite different, they look identical to control engineers. In practice, on-line sensing allows adjustment to a planned schedule during the production of a particular part, where off-line sensing allows adjustment only between parts in the same batch. However, in tuning the planned schedule of actuation settings, the same questions must be addressed in both cases: what is the best estimate of the current product state that can be made from current and past sensor outputs? Based on this estimate and its comparison to the reference state, how should the planned schedule be adjusted, taking account of model errors and external disturbances?

Section 3 introduces a framework of analysis for closed-loop control of properties in metal forming. In order to retain a connection between the analysis and the realities of metal forming in practice, the analysis is referred to three exemplar processes which are introduced below.

2.1. Control of sheet metal bending geometry

The process of V-bending [60,90] aims to deliver a target angle of bend after the elastic recovery of material upon unloading. This springback is controlled by the inhomogeneous plastic deformation over the thickness of the workpiece which creates a residual stress distribution in the bend. Closed loop control of V-bending has thus been developed to control residual stresses in the face of uncertainty about incoming material properties and thickness. Most implementations of V-bending, as illustrated in Fig. 7, have one actuator. However, additional actuators could be introduced for heating or stress superposition [15]. Similar processes to V-bending include air bending [188], L-bending [200] and U-channel forming [185], where additional control parameters and actuators, such as binder force, can be incorporated.

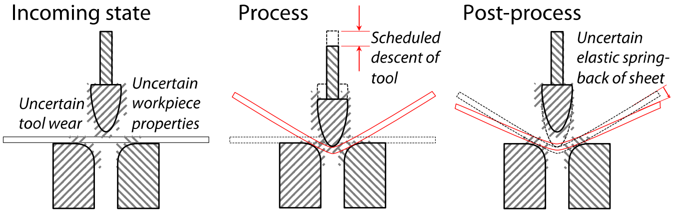

Fig. 7. Schematic of V-bending.

2.2. Microstructure control in hot strip rolling processes

Fig. 8 is a schematic of the hot rolling process, incorporating pre-heating of the as-cast slab, reduction by rolling in a reversing 'roughing' mill, finish rolling in a tandem mill, cooling by water sprays on a run-out table and finally coiling.

Process metallurgists plan a target schedule of reduction and temperature for this process to control the phase and grain size distribution in the finished coil. However, the temperature at exit of the finishing mill may vary by ±100 °C [138] due to variability in the exact sequence of events after the slab is removed from the re-heating furnace, and because the tail of the rolled strip has cooled in air for longer than the head prior to finish rolling. The problem created by this uncertainty is shown in the illustrative continuous cooling transformation diagram of Fig. 9.

The planned temperature path shown in Fig. 9 would lead to a fine pearlitic microstructure and high strength. If the starting material is cooler than expected, application of the same cooling activity on the run out table would lead to a lower pearlite content, but as shown a lower rate of cooling could be used to compensate for the lower initial temperature and allow more transformation before quenching. Prediction of the eventual microstructure arising from this process is made more difficult by the exothermic release of heat during the pearlite transformation, which may continue within the coiled strip if it is insufficiently cooled. Operators, and therefore closed-loop control systems may attempt to control the microstructure by changing the pattern of cooling on

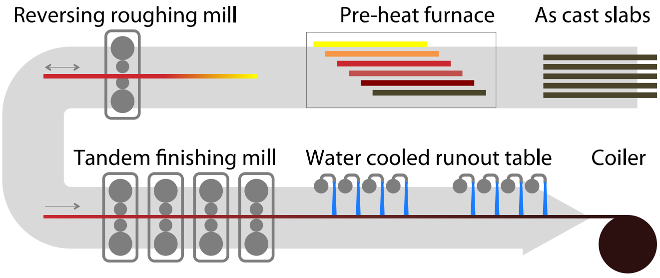

Fig. 8. Schematic of hot rolling from as-cast slab to coiled strip.

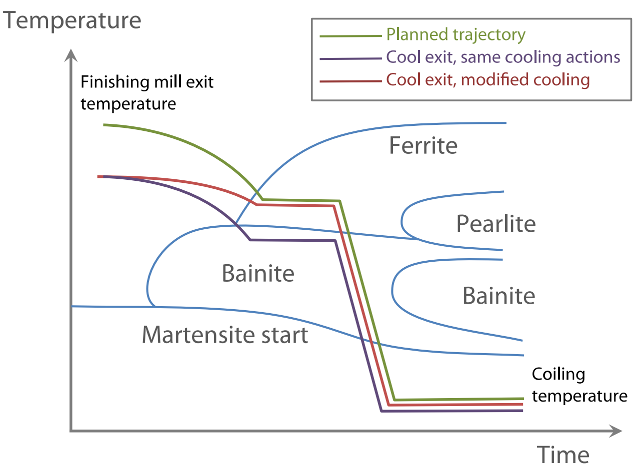

Fig. 9. Schematic continuous cooling transformation diagram for a high carbon high strength steel.
Adapted from [138].

the run out table. However, an alternative compensation is to accelerate the finishing mill along the length of the strip, to increase heating within the deforming strip, aiming to achieve the planned temperature prior to the run out table.

2.3. Flatness control in strip rolling

The problem of microstructure control in Section 2.2 has been described as a scalar variation in properties along the length of the strip, but also occurs across the width of the strip, as the strip edges will always be cooler than the centre-line. A related spatial problem in cold strip rolling arises from the deflection of the rolls. As the strip is deformed plastically, the mill deflects elastically, with the rolls bending away from the strip at the centre line. If uncompensated, this leads to a greater reduction in strip thickness towards the strip edges. In hot rolling this leads to manifest waviness in the strip known as a flatness defect. However, in cold rolling where the yield stress is higher, the strip may remain flat with the profile variations converted into a residual stress distribution, also called a 'flatness' or sometimes 'shape' defect.

Fig. 10 shows a range of actuators that have been added to cold rolling strip mills to compensate for this effect, and two downstream sensors (for profile and residual stress) that provide on-line monitoring of the finished strip. During process operation, mill operators or on-line closed-loop controllers adjust the actuators to reduce the measured defects.

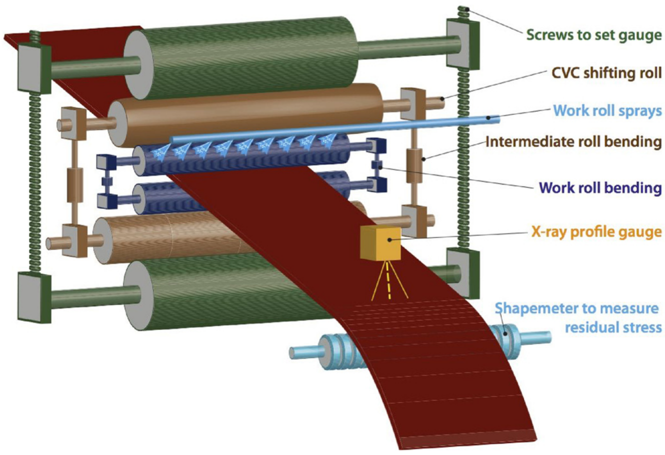

Fig. 10. Schematic of the actuators and sensors available in a cold strip rolling mill to compensate for flatness defects.

2.4. Key features of controlling product properties in metal forming

The three exemplar processes described in this section illustrate the key features of product property evolution in metal forming which are distinct from other control problems:

- The actuators of metal forming processes have a distributed influence on the workpiece in both time and space, and there are constraints on how actuators can be configured;
- Today's sensors cannot measure all product properties and their positioning is constrained. Properties vary throughout the product, but are usually measured only at the surface.
- Most metal forming processes are non-linear, some properties have not yet been characterised, and process behaviour is usually dependent on the current state of the product. As a result process models are currently slow and imperfect.

The next section presents a consistent framework for analysing the particular challenges of controlling product properties in metal forming. The following three sections will use this framework to explore the three features mentioned here, and Section 7 will present a survey of applications to date.

3. The design and specification of control systems for closed-loop control of product properties in metal forming

This section starts from the most general statement of the problem of closed-loop control as a non-linear optimisation problem. For most metal forming processes, solution of this problem would be too time consuming to be of practical use, so it will be simplified in stages, to the point that practical control systems can be designed and implemented. The full derivation of the analysis in this section has been supplied as a supplementary information file, available on-line.

The developments in this section could, with reference to Fig. 6, apply either to off-line or on-line closed-loop control, and will use the following definitions (with the convention that italics indicate scalar variables while vectors are in bold):

- The state of the system $\tilde{z}$ will be described as a scalar function of space $\mathbf{x}$ and time t to simplify the notation, although the analysis extends naturally to states with several parameters.
- The inputs to the actuators are denoted by $\mathbf{u}(t)$.
- The measurements from sensors are represented by $\mathbf{y}(t)$
- The disturbances affecting the state are $d(\mathbf{x}, t)$
- The sensor noise is $\mathbf{e}(t)$.

3.1. Process model

The behaviour of the metal forming process in Fig. 6 can at its most general be described by equations with the form

$$\begin{aligned} &\dot{\tilde{z}}(\mathbf{x},t) = f(\tilde{z},\tilde{\mathbf{u}},t) + \tilde{\Delta}^{\mathrm{f}}(\tilde{z},\tilde{\mathbf{u}},t) + d(\mathbf{x},t) \\ \text{subject to}\quad &\mathbf{g}(\tilde{z},\tilde{\mathbf{u}},t) + \tilde{\Delta}^{\mathrm{g}}(\tilde{z},\tilde{\mathbf{u}},t) \le 0 \end{aligned} \tag{1}$$

where f is a model of the process, $\mathbf{g}$ are constraints (such as forming limits or actuator limits), and Δ are model errors. The control system aims to find a set of inputs, so that the process reaches a reference state $\tilde{z}^{\mathrm{r}}$ by solving the minimisation problem,

$$\begin{aligned} &\min_{\tilde{\mathbf{u}},t}\max_{\tilde{\Delta}^{\mathrm{f}},\tilde{\Delta}^{\mathrm{g}}}\left\{\|\tilde{z}^{\mathrm{r}}(\mathbf{x},t_{\mathrm{f}})-\tilde{z}(\mathbf{x},t_{\mathrm{f}})\| + \int_0^{t_{\mathrm{f}}}[\lambda_1\|\tilde{z}^{\mathrm{r}}(\mathbf{x},t)-\tilde{z}(\mathbf{x},t)\| + \lambda_2\|\tilde{\mathbf{u}},t\|]\mathrm{d}t\right\} \\ \text{subject to}\quad &\dot{\tilde{z}}(\mathbf{x},t) = f(\tilde{z},\tilde{\mathbf{u}},t) + \tilde{\Delta}^{\mathrm{f}}(\tilde{z},\tilde{\mathbf{u}},t) + \hat{d}(\mathbf{x},t) \\ &\tilde{z}(\mathbf{x},0) = \tilde{z}_0(\mathbf{x}) \\ &\mathbf{g}(\tilde{z},\tilde{\mathbf{u}},t) + \tilde{\Delta}^{\mathrm{g}}(\tilde{z},\tilde{\mathbf{u}},t) \le 0 \end{aligned} \tag{2}$$

where $\hat{d}(\mathbf{x},t)$ is a prediction of the disturbances, and λ_1 and λ_2 allow a balance between matching the trajectory of the state to a target and minimising process inputs.

Finding actuator schedule, $\mathbf{u}$, that solves the optimisation in Eq. (2) would require hundreds of solutions of the complete process model. For many metal forming processes even one solution may take weeks of computing time, so while Eq. (2) is easy to state, it cannot be used in practice in most cases. However, using a simplified model will increase model error and thus increases the vulnerability of the process to disturbances, and this reduces the value of the planned schedule.

Two approaches allow schedule design in practice: firstly, the time-horizon over which the schedule is planned can be reduced by introducing feedback into the system; secondly, the model can be simplified. These are explored in the next two sections.

3.2. Feedback

The optimisation of Eq. (2) must be solved over the whole period of process operation. This is an 'open loop' approach to control relying solely on the model to predict system behaviour. An alternative is to use measurements from the system to estimate the current state of the product. If the measurements obtained from process sensors are denoted by $\mathbf{y}$ and are a function $\mathbf{h}$ of the state and the inputs, then an estimate of the product's state can be obtained using an observer, ℓ.

The solution of Eq. (2) can thus be simplified to the task of finding the optimal inputs over the period from t_1 to t_{f} using

$$\begin{aligned} &\min_{\mathbf{u}(t)}\left\{\|\tilde{z}^{\mathrm{r}}(\mathbf{x},t_{\mathrm{f}})-\tilde{z}(\mathbf{x},t_{\mathrm{f}})\| + \int_{t_1}^{t_{\mathrm{f}}}[\lambda_1\|\tilde{z}^{\mathrm{r}}(\mathbf{x},t)-\tilde{z}(\mathbf{x},t)\| + \lambda_2\|\tilde{\mathbf{u}}(t)\|]\mathrm{d}t\right\} \\ \text{subject to}\quad &\dot{\tilde{z}}(\mathbf{x},t) = f(\tilde{z},\tilde{\mathbf{u}},t) + \hat{d}(\mathbf{x},t) \quad \text{for } t_1 \le t < t_{\mathrm{f}} \\ &\tilde{z}(\mathbf{x},t_1) = \hat{z}(\mathbf{x},t_1) \\ &\mathbf{g}(\tilde{z},\tilde{\mathbf{u}},t) \le 0 \\ \text{and where}\quad &\tilde{\mathbf{y}}(t) = \mathbf{h}(\tilde{z},\tilde{\mathbf{u}}(t),t) + \tilde{\Delta}^{\mathrm{h}}(\tilde{z},\tilde{\mathbf{u}},t) + \mathbf{e}(t) \\ &\hat{z}(\mathbf{x},t) = \ell(\hat{z}(t),\tilde{\mathbf{y}}(t),\tilde{\mathbf{u}}(t),t) \quad \text{for } 0 \le t \le t_1 \\ &\hat{z}(\mathbf{x},0) = \hat{z}_0(\mathbf{x}) \end{aligned} \tag{3}$$

This is a form of model predictive control subject to uncertainty, but the solution remains challenging because the models and constraints are non-linear. To avoid this problem, most control designs are based on a linearised model, which can then be reduced to a finite dimensional model using basis function expansions.

3.3. Linearised model

If one complete solution of the non-linear process model is known, based on a schedule of actuator operation similar to that required for the target product, then the model can be linearised about this solution and solved rapidly.

The known solution is notated with inputs $\bar{\mathbf{u}}$ and process state evolution $\bar{z}$ which thus satisfies

$$\dot{\bar{z}}(\mathbf{x},t) = f(\bar{z},\bar{\mathbf{u}},t) \quad \text{for } 0 \le t \le t_{\mathrm{f}} \tag{4}$$

Using the notation that z and $\mathbf{u}$ are small deviations about this trajectory, the process model f, the constraints g and the measurement equation h can be expanded as a Taylor series, whose first order terms $\mathcal{A}(t), \mathcal{B}(t), \mathcal{P}_1(t), \mathbf{P}_2(t), \mathcal{C}(t), \mathbf{D}(t)$ respectively give the process model

$$\begin{aligned} &\dot{z}(\mathbf{x},t) = \mathcal{A}(t)z(\mathbf{x},t) + \mathcal{B}(t)\mathbf{u}(t) + \tilde{\Delta}^{\mathrm{f}}(z,\mathbf{u},t) + d(\mathbf{x},t) \\ &\mathbf{y}(t) = \mathcal{C}(t)z(\mathbf{x},t) + \mathbf{D}(t)\mathbf{u}(t) + \tilde{\Delta}^{\mathrm{h}}(z,\mathbf{u},t) + e(t) \\ \text{subject to}\quad &\mathcal{P}_1(t)z(\mathbf{x},t) + \mathbf{P}_2(t)\mathbf{u}(t) + \tilde{\Delta}^{\mathrm{g}}(z,\mathbf{u},t) \le \mathbf{p}(t) \\ &z(\mathbf{x},0) = z_0(\mathbf{x}) \end{aligned} \tag{5}$$

This is a time varying, linear model of the process, which could be calculated in advance of process operation once the target product and process state are known. If the model is time-invariant, the terms $\mathcal{A}, \mathcal{B}$, etc. in Eq. (5) are constant.

3.4. Actuators and sensors

For a forming process with M actuators at locations $\mathbf{x}_m^a$, the linearised process model of Eq. (5) can be written as

$$\dot{z}(\mathbf{x},t) = \mathcal{A}(t)z(\mathbf{x},t) + \sum_{m=1}^{M}\beta_m(\mathbf{x}-\mathbf{x}_m^a)u_m(t) + d(\mathbf{x},t) \tag{6}$$

where β describes the change in the value of a particular property throughout the workpiece in response to a (small) change in the setting of the mth actuator. By analogy with conventional time-domain control, the function β can be described as a spatial impulse response. Experimental trials show that for some processes, such as the English Wheel and the Power Hammer, this spatial impulse response is remarkably consistent throughout processing [127]. In this case the process model of Eq. (5) could be solved as a convolution integral.

Following a similar logic for the sensors monitoring the process, the measurement signal obtained from the pth sensor (in a set of P) can be modelled as

$$\begin{aligned} y_p(t) &= \iint_S \gamma_p(\mathbf{x}-\mathbf{x}^s)z(\mathbf{x},t)dS + \mathbf{D}(t)\mathbf{u}(t) + \tilde{\Delta}^{\mathrm{h}}(z,\mathbf{u},t) \\ &\quad + e_p(t) \quad \text{for } p \\ &= 1,2,\ldots,P \end{aligned} \tag{7}$$

where S denotes the surface of the workpiece and γ_p is the spatial 'footprint' of the sensor, i.e. the region of the surface over which the sensor takes its measurement. As with the actuators, the terms $\mathbf{x}$ and $\mathbf{x}^s$ may be functions of time if the workpiece or sensor are moving.

3.5. Basis function expansion

The discussion above provides a framework for describing the operation of all components of the closed-loop system. However, a further step is required in order to assess its performance and to design a control algorithm to cope with external disturbances and internal model errors. Control engineers examining time-domain systems make this assessment through use of Fourier transforms: the time domain signals of the control system are transformed into the frequency domain and the system is assessed by its capacity to reject disturbances of various frequencies and magnitudes, for example by use of Bode plots as illustrated in Fig. 11.

However, in addition to such time domain performance, for most metal forming systems of interest, the state z also varies in space. Thus an extension to the conventional Fourier transform is required.

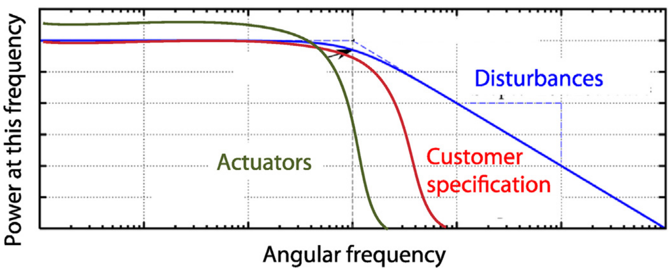

Fig. 11. Magnitude component of a Bode plot used to compare customer requirements against disturbances and actuator capability. In this case, the specification above the bandwidth of the actuators cannot be met.

The state of the process z can be expressed in terms of a spatial basis function expansion as

$$z(\mathbf{x},t) = \sum_{n=1}^{\infty} q_n(t)\phi_n(\mathbf{x}) \tag{8}$$

where ϕ_n are a suitable set of orthogonal basis functions, such as a Fourier series or Legendre or Chebyshev polynomials. Fig. 12 demonstrates how on-line measurements of flatness defects in cold-strip rolling can be expressed as the coefficients q_n of an expansion using first order Chebyshev polynomials in Eq. (8).

The same basis can be used to expand the spatial impulse response of the actuators and sensors, which in practice will be 'band-limited' in the sense that the coefficients of the expansions in Eq. (8) will approach zero above some 'bandwidth' N.

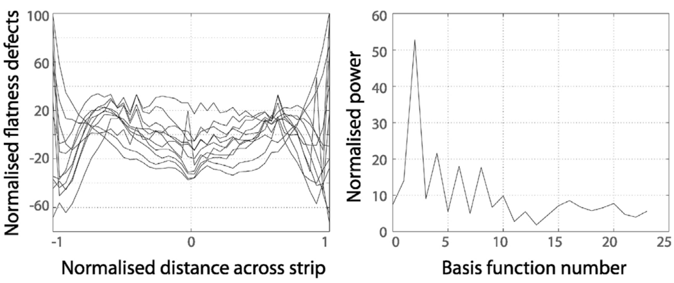

Fig. 12. Flatness defects in cold strip rolling and their expression as the coefficients of a series of first order Chebyshev polynomials [46].

Using this approach, the model of Eq. (5) can be expressed as

$$\begin{aligned} &\dot{\mathbf{q}}(t) = \mathbf{A}(t)\,\mathbf{q}(t) + \mathbf{B}(t)\,\mathbf{u}(t) + \Delta^{\mathrm{f}}(t) + \mathbf{d}(t) \\ &\mathbf{y}(t) = \mathbf{C}(t)\,\mathbf{q}(t) + \mathbf{D}(t)\,\mathbf{u}(t) + \Delta^{\mathrm{h}}(t) + \mathbf{e}(t) \\ \text{subject to}\quad &\mathbf{P}_1(t)\,\mathbf{q}(t) + \mathbf{P}_2(t)\,\mathbf{u}(t) \le \mathbf{p}(t) \end{aligned} \tag{9}$$

in which the state is now described by the coefficients of its basis function expansion $\mathbf{q}$, as are the inputs $\mathbf{u}$, disturbances $\mathbf{d}$, measurements $\mathbf{y}$ and errors $\mathbf{e}$.

3.6. Control strategies for linearised models

The control strategy in Eq. (3) aims to minimise the difference between the current state and a reference or target value. Using the linearised model, the reference state can also be expressed in terms of the orthogonal basis functions of the form of Eq. (8) so the minimisation of Eq. (3) can be restated as

$$\begin{aligned} &\min_{\mathbf{u}(t)}\left\{\|\mathbf{q}^{\mathrm{r}}(t_{\mathrm{f}}) - \mathbf{q}(t_{\mathrm{f}})\| + \int_{t_1}^{t_{\mathrm{f}}} [\|\mathbf{q}^{\mathrm{r}}(t) - \mathbf{q}(t)\| + \lambda\|\mathbf{u}(t)\|]\mathrm{d}t\right\} \\ &\text{subject to}\quad \dot{\mathbf{q}}(t) = \mathbf{A}(t)\,\mathbf{q}(t) + \mathbf{B}(t)\,\mathbf{u}(t) + \hat{\mathbf{d}}(t) \quad \text{for } t_1 \le t < t_{\mathrm{f}} \\ &\qquad\qquad\quad \mathbf{q}(t_1) = \hat{\mathbf{q}}(t_1) \\ &\qquad\qquad\quad \mathbf{P}_1(t)\,\mathbf{q}(t) + \mathbf{P}_2(t)\,\mathbf{u}(t) \le \mathbf{p}(t) \\ &\text{where}\qquad\ \mathbf{q}^{\mathrm{r}}(t) = \mathbf{q}^{\mathrm{t}}(t) - \overline{\mathbf{q}}(t) \\ &\text{and}\qquad\quad\ \dot{\hat{\mathbf{q}}}(t) = \mathbf{C}(t)\hat{\mathbf{q}}(t) + \mathbf{D}(t)\mathbf{u}(t) \\ &\qquad\qquad\qquad + \mathbf{L}(t)[\mathbf{y}(t) - \mathbf{C}(t)\hat{\mathbf{q}}(t) - \mathbf{D}(t)\mathbf{u}(t)] \quad \text{for } 0 \le t \le t_1 \end{aligned} \tag{10}$$

This form of control design is a model predictive control scheme, applied over a finite horizon. Eq. (10) define a constrained quadratic optimisation problem, which can be solved by a number of standard approaches, and in many cases solution will be fast enough for use in on-line closed-loop control of metal forming.

For time-invariant linear systems that do not consider either uncertainties or constraints, the state space model of the system in Eq. (10) reduces to

$$\begin{aligned} \dot{\mathbf{q}}(t) &= \mathbf{A}\mathbf{q}(t) + \mathbf{B}\mathbf{u}(t) \\ \mathbf{y}(t) &= \mathbf{C}\mathbf{q}(t) + \mathbf{D}\mathbf{u}(t) \end{aligned} \tag{11}$$

Taking Laplace transforms, this can be expressed in terms of a (multi-input, multi-output) transfer function from $\mathbf{u}$ to $\mathbf{y}$,

$$\begin{aligned} &\mathbf{Y}(s) = \mathbf{G}(s)\mathbf{U}(s) \\ \text{where}\quad &\mathbf{G}(s) = \mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B} + \mathbf{D} \end{aligned} \tag{12}$$

In this case, classical control methods can be used to design a controller that performs the minimisation in Eq. (10). If the constraints $\mathbf{P}$ in Eq. (10) are ignored and the time horizon is infinite, the minimisation is achieved optimally by a Linear Quadratic Gaussian controller obtained from the algebraic Ricatti equation with a Kalman filter used to estimate the current state of the process. In the simplest case, if the system can be described by a scalar transfer function and approximated by a first order time constant τ and a delay τ_{d}, so that

$$\mathbf{G}(s) = e^{-s\tau_{\mathrm{d}}}\frac{g}{\tau s + 1} \tag{13}$$

where g is the gain of the system, then it can be controlled using a proportional plus integral plus derivative (PID) controller. A key benefit of approximating the system using this transfer function is that the Ziegler Nichols rules can be used to tune the PID controller without knowledge of the values of the coefficients in the transfer function.

3.7. Spatial and dynamic bandwidths

Expanding the state in terms of basis functions has shown that N spatial modes can be changed by the actuators and observed by the sensors. This means that although the disturbance entering the process may include components in the spatial modes above N,

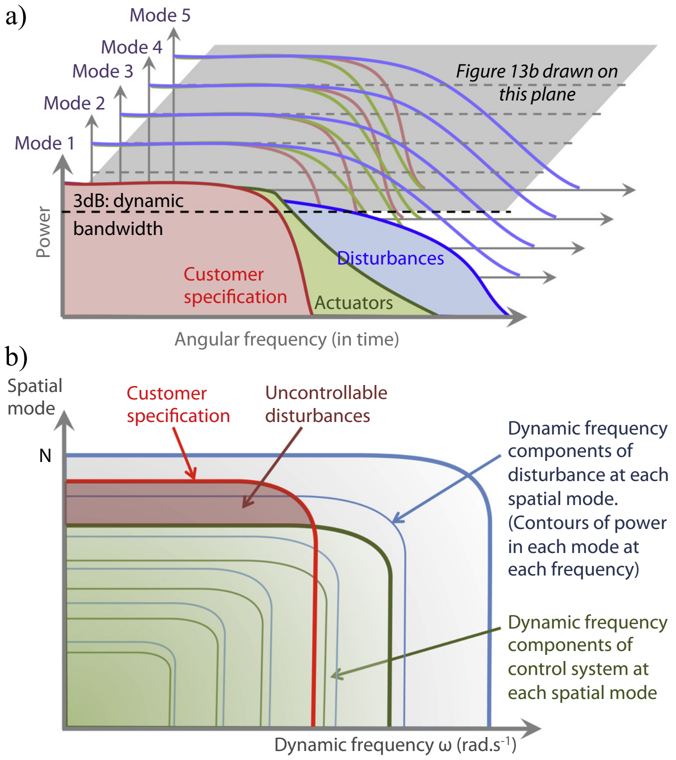

Fig. 13. Map of spatial modes and dynamic bandwidths for the disturbances, control system, and customer specification: (a) bode magnitude plots for each mode and (b) contour plot of dynamic bandwidths of each mode showing uncontrollable area.

these components are effectively uncontrollable, so N can be regarded as the 'spatial bandwidth' of the process. Each spatial mode of the process has a dynamic bandwidth, generally defined as the frequency at which the system response is 3 dB below the steady state gain. This is illustrated in Fig. 13a which shows the dynamic frequency range for several modes of the disturbance. Only frequency components below the dynamic bandwidth can be controlled for each spatial mode. The combined spatial and dynamic bandwidths can be represented on a 2-dimensional map, as illustrated in Fig. 13b. The spatial and dynamic range of the actuators forms a region on this plot and only those components of disturbance that lie within this region can be controlled.

For processes that have stationary actuators, in order to control all N spatial modes of the disturbance, the spatial responses of all actuators must be linearly independent and $M \geq N$, where M is the number of actuators in the process. If $M < N$, the N modes cannot be controlled separately. Similarly, to observe N spatial modes, $P \geq N$ where P is the number of sensors.

The design of the controller has been based on a continuous time model of the process but in practice, it is not possible to update the optimal control inputs continuously. The optimisation of Eq. (10) must therefore be solved at discrete times, and the required form is in the electronic supplementary information.

One final insight created by the combination of spatial and dynamic bandwidths shown in Fig. 13 is to specify the requirements of the process model: if only N spatial modes are controlled, the model need only predict the evolution of these modes, and must do so sufficiently quickly to allow the discrete form of Eq. (10) to be minimised within one sample period.

3.8. Parameter identification and model adaptation

The previous sections have discussed how to design a control system that is robust to uncertainties in the model, but an alternative approach is to estimate the values of the model parameters directly from the process. The approach of learning the dynamic response from data collected from the process is known as system identification and is well developed for linear systems [110,167]. These methods can be extended to non-linear systems using approaches such as neural networks, fuzzy systems, and more recently, Bayesian methods, but there is not yet, an underlying unified theory to back up these approaches.

Once system identification has been carried out, the estimates of the parameters are used to design a control system that remains fixed until the system identification is repeated. An alternative approach is taken by adaptive or self-tuning systems [11,193] where the results of the system identification are used to update the parameters of the control system while the process is running in closed loop. In principle, this is attractive, but in practice, because the controller is continually changing, it is difficult to guarantee stability.

3.9. Key features of controlling product properties in metal forming

Section 2.4 raised three issues about the challenge of implementing closed-loop control for product properties in metal forming, and this section has demonstrated an approach to each. In summary:

- to cope with non-linear process mechanics, the system model can be linearised around an expected trajectory of operation as in Eq. (5), so the controller addresses deviations from this path. The controller can be designed to cope with model errors;
- the derivation here has assumed a scalar state variable, so some weighting function would be required to balance competing objectives in a multivariable state;
- the spatial and temporal distribution of responses can be addressed by decomposing the spatial response using basis functions as in Eq. (8) allowing the definition of spatial and temporal bandwidths in Fig. 13, which in turn creates a specification for actuators, sensors and models.

4. Actuators

V-bending at its simplest requires a single actuator whose motion follows a simple down-and-up path. This actuator could be a mechanical, electromagnetic, thermal or hydraulic mechanism, including servo-hydraulic mechanisms which would allow control of the deformation path. In addition, a coining force can be applied to the bending region at the end of the process to decrease the springback angle [101]. Temperature may also be controlled to improve the deformation of the material [26,91,124,157]. Related processes may have additional actuators, such as the binder force in U-channel forming, that can be used to control springback [171].

Three features of this narrative set the agenda for this section:

- The performance of the controlled system depends on the characteristics of the actuators including their dynamic response, power limits and precision.
- The response of the workpiece to a control signal depends not just on the actuator, but also on the 'transfer function' of the equipment and workpiece. In the bending example, the mass of the punch limits its acceleration, and its stiffness changes the distribution of force along the length of the bend.

The quality of the resulting workpiece – the bandwidth of the disturbances that can be controlled – depends on how the actuators interact as well as on their separate performance.

These features are also present in the two rolling examples. In hot strip rolling: the maximum cooling rate on the run-out table depends on the rate at which cooled water can be supplied; the response of the strip depends on its temperature; the effect of sprays at the exit of the run-out table is influenced by the actions of those earlier on. In cold strip rolling: the speed of response to an error in strip flatness depends on the speed at which oil can be pumped into the hydraulic jacks; the actuator response changes with the diameter of the roll and the width of the strip; actuation that separates the work roll bearings may counter that which separates the backup roll bearings. In this section, these three features are explored leading to an outlook on the potential for adding actuation to processes in future.

4.1. Actuator characterisation

The yield stress of a metal depends on its temperature, while its microstructure evolves with the history of temperature, strain and strain rate. The actuators used in metal forming processes therefore either add or remove heat, or apply force or displacements at the workpiece surface.

Table 1 presents a survey of common actuators organised in these two categories, and gives indicative characteristics of their performance. These characteristics determine their selection during process design. For example, in selecting a main drive for a rolling mill, motor torque will be the primary design requirement, but in the V-bending example, many of the characteristics of Table 1 will be relevant.

A small body of work has developed to support the selection of actuators by designers. For any two of the characteristics on the right side of Table 1, the range of available performance of every actuator on the left side of the table can be assessed, leading to actuator selection charts of the type illustrated in Fig. 14.

Table 1
Actuators used in metal forming and their characteristics.

	Actuator type	Characteristics
Force/ displacement	Motor + ball screw	Stiffness
	Hydraulic	Maximum force/pressure
	Piezo-electric	Torque
	Electromagnetic/plasma pulse, explosion	Power
		Stroke (range)
	Pneumatic (+switching valves)	Resolution/accuracy
		Resonant frequency
		Speed and acceleration
Heating/cooling	Power supply/DC converter: conductive heat	Maximum temperature
		Maximum power
	High current switch mode – resistance heat	Frequency
		(induction heating)
	Laser	
	Gas furnace	
	Electric furnace	
	Induction heating	
	Spray cooling	

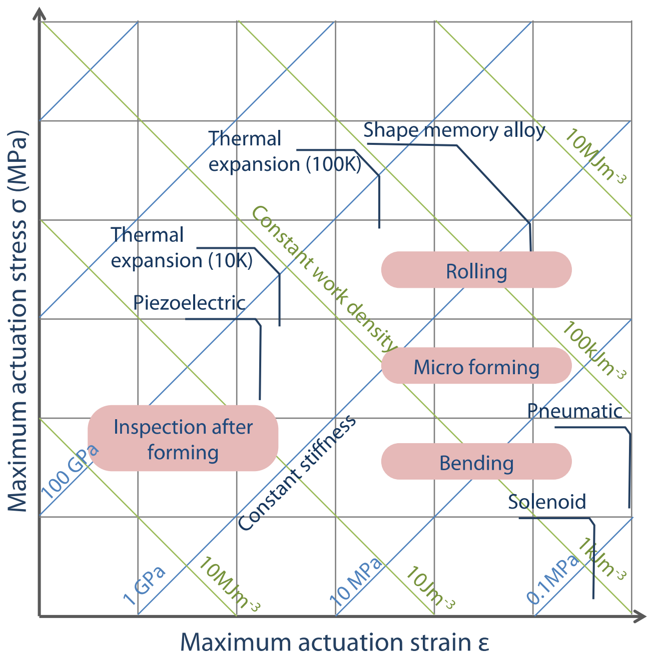

Fig. 14. Illustrative ranges of actuator performance organised by the characteristics of maximum stress and strain.
Adapted from [79,85].

The chart in Fig. 14, presents a survey of a wide range of mechanical actuators, including several that are not generally applicable within metal forming, but excludes electric motors as their design can cover the whole span of the chart. Any other pair of characteristics from Table 1 could be used to create a similar map of options.

An important limit on the degree of actuation that can be applied in metal forming is created by the workpiece material itself. In particular, for actuation that adds heat to the workpiece, the heat can only be applied at the surface (via radiative, conductive, or convective transfer) or at a short depth into the workpiece (via induction heating). This boundary heating then diffuses into the core material at a rate determined by the thermal conductivity of the workpiece. Forming processes will generally be most productive if heating is as rapid as possible. However, the temperature at the workpiece surface must be constrained to avoid melting or unwanted changes in microstructure. Even if sufficient power is available in the actuator, the rate at which it can be applied may often be constrained by such limits.

4.2. Transfer functions between actuators and workpieces

All actuators have some dynamics in time. The delivery of force or power by the actuator lags behind the control signal requesting it, due to mechanical or thermal inertia. Furthermore, many actuating devices (motor, heater, cooling spray) act either on the workpiece surface or on components of the equipment. In turn the equipment influences the workpiece surface, via contact conditions, and eventually some region of the workpiece interior is actuated. This chain of connections between physical actuator and the workpiece response is described by a 'transfer function'. For example, in the case of a robot, the transfer function describes the dynamic response of several flexible connections each of which has their own inertia. This function may relate to dynamics in time (as in the robot example) but may also relate to spatial effects: for example an actuator acting at a point may lead to a distributed effect along the length of the component.

Fig. 15 shows an example of a set of spatial transfer functions arising in cold strip rolling. Each of the actuators acting on the rolling mill shown in Fig. 10, causes a different spatially distributed change to the residual stress distribution in the workpiece.

The analytical framework developed in Section 3 allows for characterisation of these spatial and temporal transfer functions. Fig. 16 illustrates the disturbances of Fig. 12a and the same actuator responses as shown in Fig. 15 but now expressed as the coefficients of a set of basis functions (first order Chebyshev polynomials.) These are the spatial modes on the y-axis of Fig. 13b. In this case the response of the actuators is fast compared to the

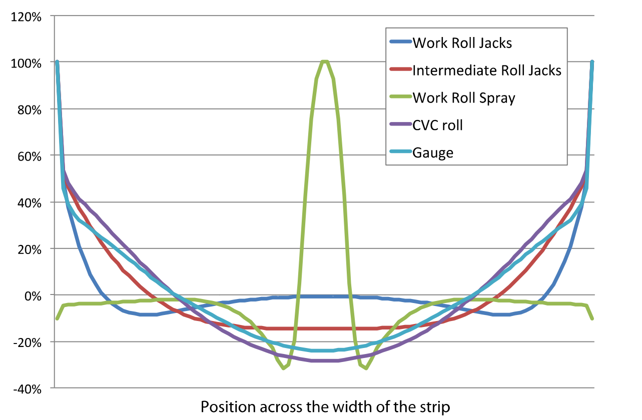

Fig. 15. Spatial response of residual stress in cold strip rolling of aluminium to small changes in several different actuators.
From [46].

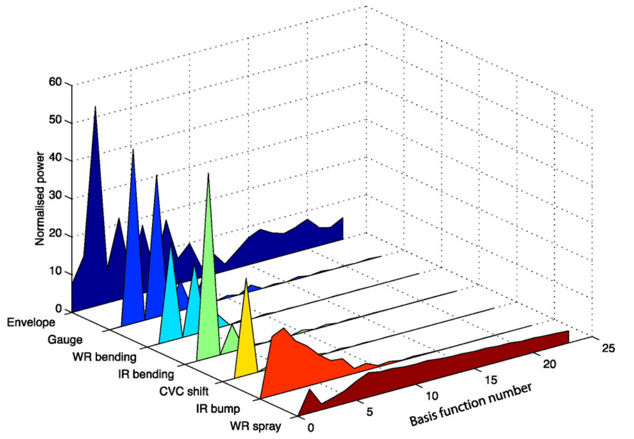

Fig. 16. The power of a set of actuator responses in cold strip rolling, expressed as the coefficients of a Chebyshev polynomial series [46].

rate of change of incoming disturbances (the variations in incoming strip profile, residual stress, and yield stress) so the response remains virtually constant across all dynamic frequencies of interest. Fig. 16 illustrates the limits to the quality of control that can be achieved by this system: most of the available actuator power is in the second and fourth basis functions – the quadratic and quartic components of the residual stress distribution; for higher order disturbances, only the distributed cooling sprays across the work roll have any actuated influence, and these have limited power.

The examples used in this section have been mechanical, but similar discussion would apply to any heating or cooling actuators, where the effect of a control action is distributed in both space and time.

4.3. The design of multiple actuator systems

Fig. 13 provides a basis for designing closed-loop control systems in metal forming with multiple actuators. The customer specification and process disturbances must be characterised by the components of their dynamic and spatial modes and this defines the requirement for actuation. The sensor signal can also be transformed into power in each frequency and mode, as a result of which the relevant actuation can be applied to remove the error. If two or more actuators influence the same mode, the control system can be designed to share the work between them to avoid conflict, and the controller must also account for practical limits (such as non-negative contact forces, or avoiding surface temperatures close to melting) discussed above.

The control of residual stress or profile in strip rolling is generally achieved by several actuators, as illustrated in Fig. 16, but the figure also illustrates two key challenges to designing multiple-actuator systems.

- The most convenient location for positioning actuators in strip rolling is at the roll bearings. Typically these are hydraulic jacks that separate the bearing blocks of the rolls, but the power of these actuators is concentrated in the same low order modes. The fact that many actuators have similar responses leads to potential redundancy in the system, and also a form of 'instability' in the control system, where one actuator may cancel out the effect of another.
- It is mechanically difficult to create actuators with significant power in the higher spatial modes.

These design problems are a challenge for all mass production metal forming processes, and there remains space for innovation in finding more local actuation to augment the higher power actuators that respond to lower spatial modes. Processes in which the workpiece is deformed incrementally such as spinning, the English Wheel or hammering naturally use higher order spatial modes. This increases the opportunity to control disturbances, at the cost of increased production times.

4.4. Outlook for actuation in metal forming processes

In metal forming, all actuation will be filtered through some form of transfer function related to the tooling, equipment and workpiece characteristics, and good design can help in providing more precise responses. Of the example processes running through the paper, the control of profile and residual stress in strip rolling has been given more attention, and generally is subject to more actuation. This suggests that the quality of strip bending processes could also be improved by addition of more actuation: actuation to adjust the die during the punch stroke might help to reduce sheet springback; local actuation at the edges of the workpiece could compensate for the distributed stiffness of the sheet; distributed actuation along the punch could compensate for punch wear, misalignment or curvature.

Until the customer specification represented in Fig. 13 is fully under control, more actuation will general give higher quality products. However, this may not be the case if the same process is used over a diverse range of products, for example if actuators intended to be at the edge of a part are misaligned for smaller parts, or if the response of the workpiece to the actuator varies with different materials. An interesting opportunity for future research is to design processes that have more predictable actuator responses to simplify the challenge of process modelling. This is illustrated in [127] for the English Wheel which causes similar deformation in a sheet, regardless of location or current curvature, in contrast to the incremental sheet forming process in which the response is strongly dependent on both history and location.

5. Sensors

The description of spatial and dynamic bandwidths in Fig. 13 proved central to the specification of actuators in the previous section, and similarly sets the agenda for sensor system design. Regardless of actuator availability, the closed-loop control system will be able to remove only those components of the error signal that can be detected by the sensors. If the sensors can detect a wider bandwidth than can be controlled by actuators, this is redundant.

V-bending will typically have simple product property sensing. Within the equipment, the linear distance descended by the working punch and the force acting on it, will be monitored, but this is only to ensure that the equipment follows the target schedule. The key final product property is the bend angle after springback. Fig. 17 illustrates several methods to measure this parameter that could be incorporated in a closed loop control system. The figure demonstrates that the measurement can be obtained visually (i.e., optical) or via contact with the specimen (i.e., tactile). Of these methods, measuring pins have been used most frequently [57]. For example, interrupted bending experiments were performed using a linear variable displacement transducer towards the end of the V-segment to assess variations in the material properties and thickness [188]. Three interrupts during the tests allowed improvements in accuracy of the bend.

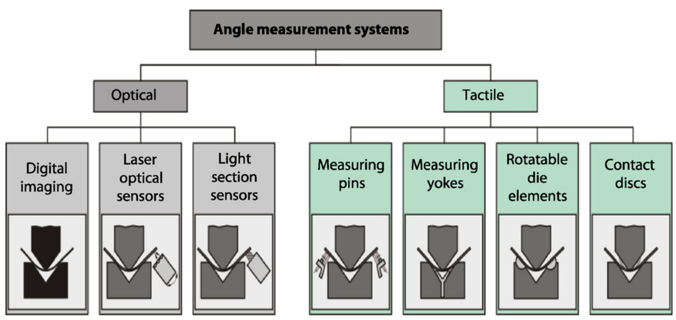

Fig. 17. Various springback angle measurement methods.

The sensors in Fig. 17 cannot detect variations of the bend angle along its length. Other product properties of interest include the residual stresses in various locations in the final part as well as cracking and surface roughness at the bend region. Sensors exist for these properties, but generally cannot operate at on-line speeds so off-line closed-loop control as in Fig. 6 is required.

In contrast, the sensing applied to strip rolling may include a scanning gauge measuring strip profile, some measurement of flatness (such as the 'shapemeter' [168] illustrated in Fig. 10) and optical temperature measurement. However, the microstructure in hot rolling, which is of critical importance to customers, cannot be measured on-line so must be inferred by an appropriate model and validated by off-line sensors.

As before, this discussion sets the agenda for this section:

- What sensors are available, and how do these correlate with the properties of interest in the metal forming?
- What influences the transfer function between the physical reality of the workpiece and the signal reported by the sensor?
- To what extent can process models be used to create 'observers' of properties that cannot be measured directly?
- How should an array of sensors be designed to match customer requirements and be consistent with available actuation?

5.1. Sensor characterisation

An indicative mapping between process parameters and product properties is given in Fig. 59 of [177]. This is expanded in Fig. 18 to demonstrate the long chain of connections that may exist in metal forming process between actuation and the eventual determination of product properties. The explicit inclusion of the interface conditions in Fig. 18 is a reminder of the two-way interaction between equipment and workpiece, in determining how the product properties evolve with new actuator settings. For example, if the workpiece is already hotter, an increase in tool temperature may cause less change, than if the workpiece were originally cool.

The consequence of Fig. 18 for closed-loop control, is that there may be a significant disconnect between what sensors can detect, and what actuation may be applied. In controlling the speed or direction of a vehicle, sensors can measure directly the variable under control, and actuators act directly to change it. Many of the properties in metal forming (particularly those to do with the microstructure) cannot be measured directly, or cannot easily be measured non-destructively or on-line. The sensing of metal forming processes is thus linked to the provision of process models (or 'observers').

Table 2, arising as with Table 1, from a survey of processes familiar to the authors, gives a representative set of sensors in current use in metal forming processes and lists some of the characteristics that are important in selecting between different available sensors for each application area. As with the classifica-

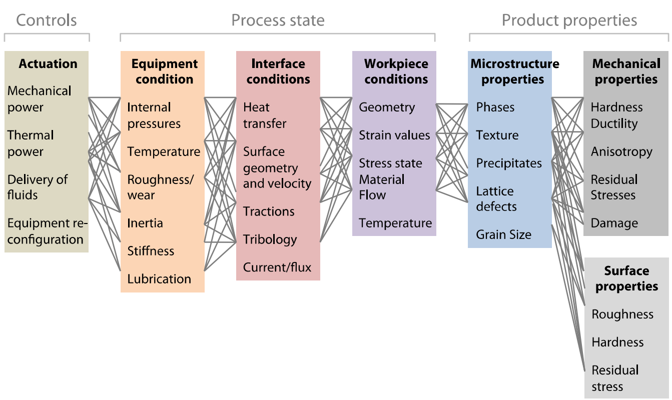

Fig. 18. Product properties in metal forming.

Table 2
Sensors in current on-line use in metal forming and their characteristics.

	Sensor type	Selection characteristics
Actuation and equipment condition	Strain gauges and load cells Linear/rotary distance encoders and transducers Voltage and current metres	Stiffness (or equivalently resistance or thermal inertia) Natural frequency
Interface conditions	Pressure and friction sensors	Range Resolution
Workpiece conditions	Surface temperature (infra-red camera, optical pyrometry, thermocouples) Surface strains/strain rates (digital image correlation, photon Doppler velocimetry)	Accuracy/Repeatability Linearity Sampling frequency (or frame rate, or speed) Spatial resolution Robustness to practical on-line conditions
Microstructure properties	Textures (electron backscatter diffraction)	
Mechanical properties	Hardness ductility (on-line hardness testing, X-ray diffraction, magneto-inductive tests) Damage (thermography, ultrasonics, radiographic inspection, vibrometry, acoustic emissions, eddy current techniques, magnetic leakage flux) Residual stress ("shapemeter")	
Surface properties	Surface morphology (white-light interference microscopy, tactile profilometer, photometry, laser triangulation, electronic speckle pattern interferometry)	

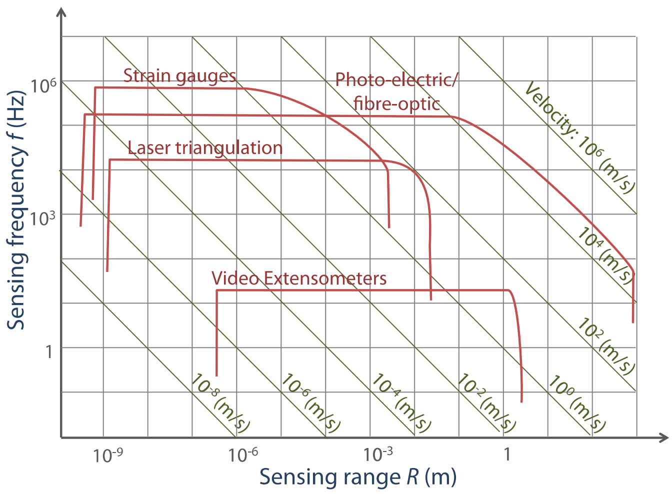

Fig. 19. An example sensor selection chart organised by frequency and range. Adapted from [156].

tion of actuators earlier, any two of the characteristics in the right hand column of Table 2 can be used to create maps to compare available sensors for particular applications. Fig. 19 shows an example.

Section 2 drew a distinction between on-line and off-line closed-loop control, which largely arises from the availability of sensors. Table 2 lists only sensors that can be used on-line, and many other forms of sensing such as microscopy or X-ray analysis can be used off-line. Innovations in sensor technology are gradually allowing more deployment of on-line sensors. However a key characteristic mentioned in Table 2 is the need for physical robustness. The forces required to deform metal are high, and many processes operate at high temperature and may use fluids, so the need for physical robustness is an essential – and currently limiting – requirement for many emerging sensor designs.

5.2. Transfer functions from workpieces to sensors

Section 4.2 introduced the idea of a transfer function for actuators. Similarly, most sensors act at some remove from the

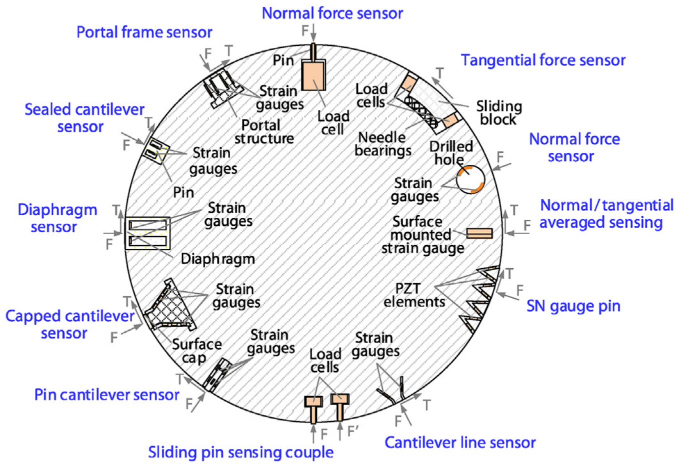

Fig. 20. Sensors for measuring contract tractions in rolling.
From [53] which gives further references for each different design.

workpiece. Between the sensor and the workpiece properties of interest, is some mechanical or thermal inertia or stiffness.

This form of transfer function associated with sensing is illustrated in Fig. 20 which shows several sensors designed to measure the surface contact tractions in rolling. The sensors would be damaged if making direct contact with the workpiece so are embedded some distance below the surface of the roll. In effect all designs respond to deflection, rather than stress, and by inspection it is clear that the deflection around the sensor depends both on the elastic deformation of the roll, and the whole distribution of contract tractions through the roll bite. This can be described by a transfer function, but limits the resolution of sensing. Even a hypothetical impulsive force acting on the surface of the roll would appear to be distributed over some area.

A second example of this form of transfer function in sensing product properties is shown in Fig. 21. Longitudinal residual stresses in cold strip rolling are measured on-line by deflecting the strip over a 'shapemeter' – a set of narrow rings, mounted coaxially on a stiff core. Each ring deflects in response to the component of residual stress normal to the axis of the rolls. As the figure shows, a theoretical impulse in residual stress would cause several rings to deflect. This is the spatial footprint γ in Eq. (7). If this footprint is known, the original signal can be recovered by solving Eq. (7).

The two examples of this section have demonstrated that even for a single sensor, a model is required to characterise the transfer function from workpiece properties to sensor output. The next section extends this use of models to consider the estimation of properties for which no direct sensor is available.

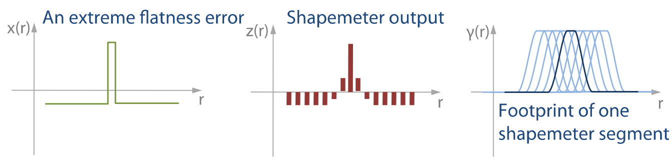

Fig. 21. The transfer function of a 'shapemeter' in cold strip rolling.

5.3. Observers: models to estimate what cannot be sensed

As yet, no sensors exist which in on-line conditions 'see' within the bulk of a metal workpiece: even X-ray sensing of residual stress penetrates only a few millimetres beneath the surface. Therefore, controlling properties in the interior of a workpiece can only be attempted if a model, an 'observer' in the language of control engineering, can predict the interior properties from those sensed at the surface. For bulk products, or in processes such as deep drawing where a sheet is closely contained within tooling and only a limited part of the workpiece is 'visible' to sensors, properties elsewhere in the workpiece must be inferred. Comparison of the product properties listed in Fig. 18 and the list of available sensors in Table 2 further demonstrates that many properties cannot yet be sensed during process operation. In particular, sensing of the distribution of microstructural properties and damage through the core of the material is only now being developed [177].

The precursor to this paper, Tekkaya et al. [177] suggests that it is possible to develop observers to predict many interior properties based on observations at the surface. For example, the widely adopted JMAK relationships [13] predict the evolution of grain size from an estimate of an initial microstructure, several material related parameters, and the history of temperature, strain and strain rate experienced by the workpiece. These variables could be inferred from measurements of surface temperature and position over time, and Table 2 lists several options for providing these measurements. A similar argument suggests that interior damage evolution could in future also be predicted from surface measurements.

5.4. The design of sensor systems

Section 4.3 revealed that actuators should be linearly independent and ideally orthogonal, to avoid a spatial instability with one actuator cancelling out another. For sensor array design this problem does not occur: if two sensors created essentially the same measurement, they could be used in tandem to estimate the uncertainty in the property under consideration. However, in order to monitor M spatial modes, the system must have at least M sensors whose spatial footprints are sufficiently independent to allow decoupling of each mode. This is the case for the shapemeter illustrated in Fig. 21: if there are M segments on the shapemeter, it will be able to report error signals up to the first M spatial modes.

Many of the sensors listed in Table 2 are scalar. However, some may scan across a workpiece, and those using imaging such as stereo-cameras or optical pyrometry for example, report images over a wide area. In this case, the spatial resolution of the sensor is likely to be much greater than that of the actuation available to the on-line control system, and the signal must be filtered to provide information only for those spatial modes which can be controlled. For line-scanning devices and imaging systems, the time between samples defines the maximum dynamic frequency that can be sensed with accuracy. Any variation in the error signal at higher frequencies will be unobservable.

5.5. Outlook for sensing in metal forming processes

A typical configuration of sensing for strip rolling was illustrated in Fig. 10, comprising a scanning profile gauge, a static thermal imaging camera, a shapemeter and force, torque and speed sensors on the rolls. With additional sensing on the temperature of the incoming strip prior to rolling, an observer could estimate changes in the grain size distribution in the strip.

Such observer based control has already been developed for the hot strip rolling problem in Fig. 8 and will be described in Section 7.4 below. In future, it is likely that new on-line sensors for example for hardness, or surface grain size will be developed, to allow a richer feedback into the observer model, and therefore a greater potential to eliminate unwanted deviations from customer requirements.

6. Models

The role of process models in closed-loop control systems for metal forming has permeated the discussion of this paper so far. Section 3 demonstrated that, except in the case of the simplest scalar systems with near linear behaviour (typically the slight variations of a single parameter around a known set-point) the application of control depends on a process model to allow the selection and optimisation of future actuator set-points. Section 4 introduced the idea of a transfer function between the controlled actuator and the response at the workpiece. Section 5 similarly discussed transfer functions associated with sensors, and has further demonstrated how interior product properties can only be controlled if they are predicted by an 'observer model'.

Models are thus central to closed-loop control in metal forming, and developments in materials characterisation, in the theory of plasticity and damage, and the development of advanced numerical models are continuously enriching their predictive ability. However, the highly non-linear material behaviour associated with metal forming, the coupling of phenomena at different scales, and the large geometric changes experienced in deformation all mitigate towards the use of numerical models, in which variables are described by discretisation, usually involving a fine mesh of discrete values. Thus, as model sophistication has increased, despite the progress of computer speed according to Moore's Law, the solution times for metal forming process models have remained high. Increases in computing power have generally been absorbed by increasingly refined models, and for almost all practical processes of interest, model solution times remain much longer than process operation.

The challenge of modelling for closed-loop control is thus to find acceptable degrees of model approximation that reduce solution times so that optimisation methods can be applied on-line.

Applications of closed-loop control of V-bending to date have mainly used the most simplified modelling approach with a PID controller adjusting punch depth to compensate for springback in the bent angle. Several models have been used including neural networks or fuzzy logic [29,14,55,56,83], regression analyses [129] or a simple on-line database of punch force [199], to control springback. In another study, FEM along with Taguchi and analysis of variance (ANOVA) methods were used to assess the process parameter that had the most affected on springback, i.e., material thickness [179]. Alternatively, analytical models for predicting the bending angle and forces have been developed which could be used for closed loop control of the process [50,174,187], including curvature representation under the punch nose [42].

In strip metal rolling, models of property evolution have been widely used to design schedules of reduction and temperature history to create preferred grain size distributions through the strip. Early work in this area [19] has expanded significantly, as reviewed in [177]. Most of this work is applied off-line, but recent applications [138,141,192] have used on-line models. Simplified models of flatness defects have been developed since the 1970s [168] and are in regular use in mills both for on-line control systems, and for actuator setup as each new strip is presented at the entry of the mill.

The agenda for this section is therefore to identify what is required of process models to be useful for on-line control, and to evaluate how existing approaches meet these requirements.

6.1. Model requirements

Section 3.2 presented a generalised mathematical form for the closed-loop control of metal forming processes. If on-line solution of the optimisation problem takes a time T, then this defines the sample time of the controller, so the dynamic bandwidth of the control system is limited to variations which occur at frequencies lower than $1/2T$. In some processes this is useful. For example, in a large batch deep-drawing process producing the same product over many days, it may be useful to solve the optimisation problem and adjust the actuator settings during the batch. However, in general, full solution is too time-consuming, so some form of model approximation is required.

The term for model error Δ in Section 3.1 provides a basis for evaluating the trade-off between model accuracy and speed. Given a range of approaches to developing a process model, including different choices about model resolution and simplification, there will be some function that relates model solution time to model error, say, $T_{model} = S(\Delta)$. The sample time of the control actions T must be greater than this ($T > T_{model}$) so for each model design, it would be possible to solve a form of Eq. (2) to allow prediction of the maximum magnitude of the disturbances that can be controlled. Alternatively, given knowledge of the disturbances, it would be possible to specify the required trade-off between model solution time and error, S. As yet this analysis has not been developed, but would be a useful contribution to the design of future closed-loop control systems, and the approach could be extended to incorporate the value of increasingly accurate sensor feedback in improving the quality of model predictions at a given solution speed. Nevertheless, a broad range of modelling approaches are available, so the next section can at least describe qualitatively the development of the model quality function S.

6.2. Classification of models

A representation of existing approaches to modelling property evolution in metal forming is presented in Fig. 22. The x-axis indicates a qualitative description of resolution, from scalar description of a single measure to finely resolved numerical representations. The y-axis illustrates the degree of approximation used in modelling, from the simplest linear variation around a set point to the most detailed multi-scale representation of micro-structure. The curved contours are illustrative lines of constant solution speed, each showing a trade-off between resolution and approximation, with speed increasing towards the top right of the image.

As well as many PID control examples, the other common approach to process modelling for on-line property control to date has been the use of meta-models such as artificial neural network or response surface methods. These approaches draw on a database of past experience, acquired by numerical or experimental approaches, to interpolate a prediction of process behaviour at current operating points. This is efficient for behaviour in an operating region similar to that tested, but has little predictive capability. Future developments may allow the combination of these statistical approaches with analytic methods, to improve the probability of successful prediction in previously untested operating areas.

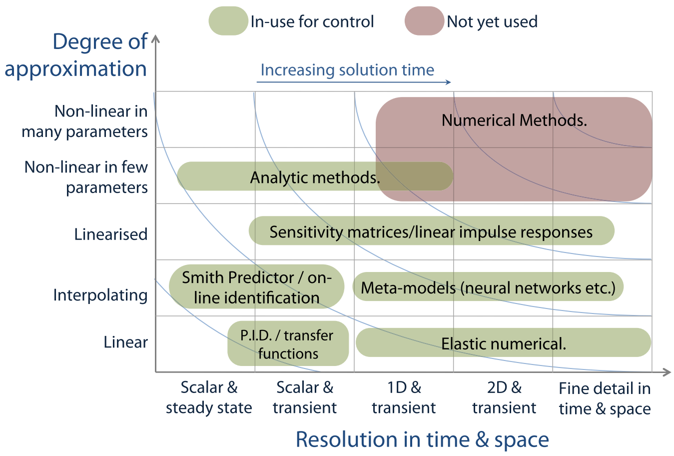

Fig. 22. The trade off between model solution speed and accuracy, illustrated for currently available modelling techniques, and their application to date for on-line closed loop control of product properties.

6.3. Outlook for on-line process modelling in metal forming

The need for rapid solutions to allow on-line control has driven the use of linearised models in most existing applications. Current applications in both V-bending and strip rolling typically use off-line non-linear modelling to predict the setpoint for some production run, and calculate sensitivities of the properties to variations in actuator settings around this setpoint to create a linear model for on-line use.

The plot of spatial and temporal bandwidth in Fig. 13 which was used in the previous two sections to describe requirements for the design of actuators and sensors also provides an interesting inspiration for future model development. If the control system is designed only to remove disturbances within a particular spatial bandwidth, then the required model needs only to deal with spatial modes below this threshold. Thus, although the non-linear behaviour of deforming metal and of the interaction between workpiece and equipment in forming processes is generally characterised with finely resolved numerical meshes, it may be possible to develop simplified process models in future which predict only the behaviour of those modes which are to be controlled. For example, if a rolling mill has only sufficient actuation to control parabolic and quartic components of disturbance to cross-directional properties (profile or flatness), for the purposes of control, there is no value in the model predicting higher order responses.

While the focus of this section has largely been on the trade off of speed and accuracy, future control of microstructural properties, depends on the development of new understanding. There is as yet no fundamental model able to predict for a general metal the evolution of microstructure with processing parameters, and ongoing improvements in metallurgical understanding will allow greater breadth of control in the future. The fact that this requires the coupling of phenomena at atomic scale (for example related to diffusion) with those at macro scale (the interaction between workpiece and equipment) illustrates how much future modelling development is required before the idealised optimisation model in Section 3.1 can be solved for every product property illustrated in Fig. 18.

7. Applications

The paper so far has been structured to present a framework for understanding present and future closed-loop control systems for product properties in metal forming. This section now returns to review current applications across the full range of metal forming processes.

7.1. Closed-loop control of properties in sheet bending

Sheet bending aims at a precise angle of bend, but must cope with uncertainties in incoming sheet geometry and properties. Several closed-loop control systems have been developed, with actuators that typically allow a variable punch depth, and sensors of many designs that measure the bending angle either between parts in a series, or between multiple punch strokes for one part.

In an early approach [199] the force–displacement relationship during the V-bending operation was monitored, and recorded in a database. A fuzzy-controller was then used to relate each new incoming material to all previous bending operations, and predict the depth of stroke required to achieve a required angle after springback.

Two control systems for air-bending have been developed with the form of Fig. 23 [81,188]. Both took an incremental approach to achieving a target bend angle: the punch descends to create a partial bend, then withdraws once [81] or three times [188] to allow measurement of springback. The force displacement curve, angle of bending and angle of springback are measured during the partial bending, and used to characterise the workpiece material. This allows calculation of the final stroke required to achieve a given angle. In contrast to the statistical approach of [199] the method of [81,188] can be used for any material, regardless of how many times it has been tested previously. Both studies report angle variability reduced to $\pm 0.5^{\circ}$, and the required calculation is sufficiently rapid to allow industrial application.

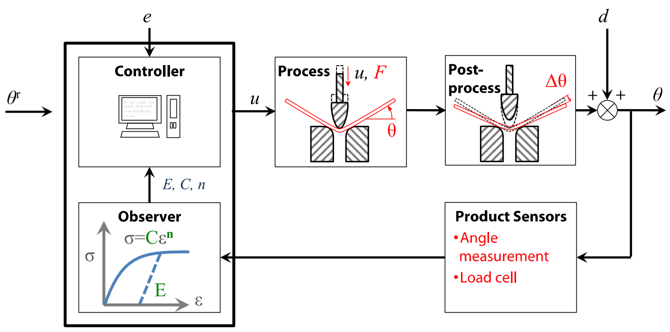

Fig. 23. Two-step bending for high precision angle.

A modification of the approach in Fig. 23, intended for mass production is to use a double sided punch, first over-bending, and then reverse bending to the target angle [184]. A regression model is used to predict the required strokes to achieve the target angle, based on samples over a long series of production. A different configuration designed for bending high strength steels, which have particularly high spring-back uses a progressive die set, with an induction heating station ahead of the bending station [111]. Closed loop control adjusts the temperature in the workpiece just prior to bending, to modify the final angle after springback.

7.2. Control of geometry in roll forming

Roll forming [69] is subject to the same uncertainties as sheet bending, but is a continuous process. The bend angle can thus be measured only after production has begun, for example by laser triangulation. Errors in the angle can then be compensated by adjusting the angles of the bending rolls as shown in Fig. 24.

A closed-loop control system has been developed with a Smith-Predictor to compensate for the (known) time delay between actuation and measured response. In trials with a high-strength steel U-profile part, the closed-loop calibration system showed springback reduced from up to $\pm 3^{\circ}$ with an open-loop model based design to a deviation of $\pm 0.2^{\circ}$ of the target angle [66].

A recent extension has been to roll-form Tailor Rolled Blanks with variable material thickness to allow weight minimisation. A tool and control concept to adjust the vertical and horizontal gap to track sheet thickness, is illustrated in Fig. 25.

Roll forming of dimensionally stable profiles from TRBs needs a local over-bending of the areas with lower sheet thickness and thus with higher springback potential [17] and can be used with a

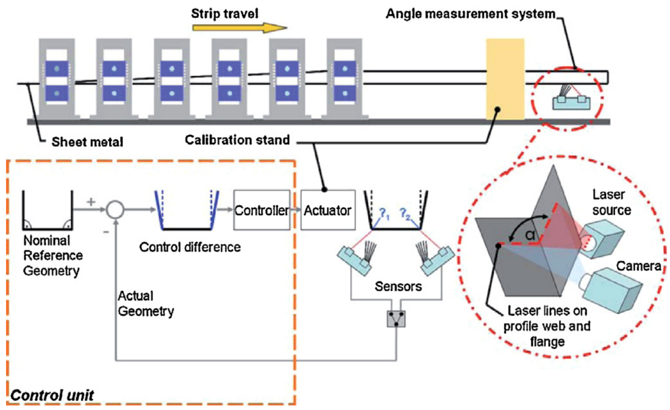

Fig. 24. Closed-loop calibration system integrated in a conventional roll forming line for U-profiles [66].

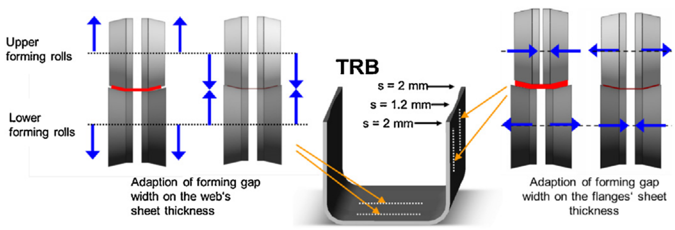

Fig. 25. Motion required for roll forming of Tailor Rolled Blanks [170].

specially designed calibration stand [75] to improve the geometric accuracy of the profile.

7.3. Control of geometry in section and tube bending

Section and tube bending also faces uncertainties of incoming material geometry and properties, but must operate within additional constraints to avoid wrinkling (on the inside of the bend) or cracking (on the outside). The development of actuation for this application is linked to the design of new processes aiming to avoid these constraints. However, the sensors and control algorithms of the previous two sections can be applied similarly to achieve the target distribution of bend angle.

A conceptual process window for section/tube bending is shown in Fig. 26, demonstrating that both failure modes become stronger as the bending radii reduce, with conventional three roll bending constrained to radii above around 1.5 times the tube diameter. Below this radius, at '[*C*]' in the diagram, a different process design, such as 'shear bending' is required [59]. The more strongly the tool constrains the flow of material, the more likely the occurrence of a crack. If the tools constrain material flow more weakly, wrinkling or buckling is more likely.

The industrial benefit of developing processes with tight constraints close to point '[*A*]' in the process window is clear, and this has stimulated a raft of process innovations. A novel approach is to extrude the tube through a die, which itself is moved relative to the axis of incoming material to create bending [126]. The complete containment of the tube as it is bent allows the creation of tight radius bends without wrinkling or cracking. Other processes with tight constraints on the tool include rotary draw bending [190], the Revolute, Prismatic, Spherical and Revolute joints parallel mechanism [173], a 2D die-less U-bend method with off-line control software [99], and the 3D hot bending and direct quench technology [158]. In this approach the tube is supported by a robot and the bent portion is rapidly heated by an induction coil, followed by quenching in water, to attain a high tensile strength.

An alternative to these processes requiring close encapsulation of the bend is the Torque Superposed Spatial bending process [76] in which the workpiece is brought to yield by an axial torque, allowing greatly reduced bending forces and hence much less

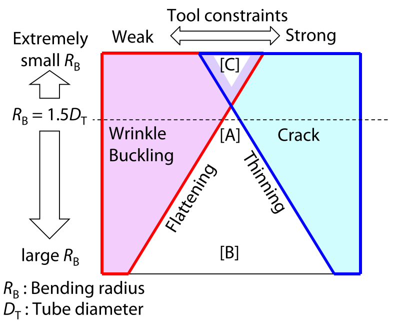

Fig. 26. Process window for shape/tube bending.

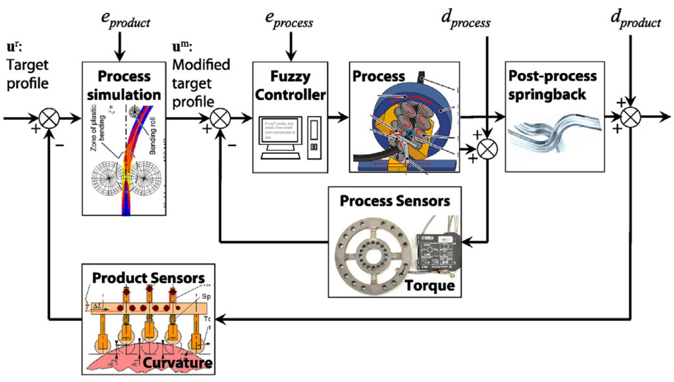

Fig. 27. TSS bending process: (a) Composition and (b) outline of closed-loop control [30].

springback than other methods. Fig. 27 illustrates the application of closed-loop control to this process to achieve a specified profile despite uncertainty about product properties.

The figure shows how on-line (or direct) closed-loop control is augmented by the use of process simulation (or indirect control) which calculates a modified target for the part based on current estimates of material properties. Various sensors have been developed including an array of displacement sensors for measuring product curvature, load cells on individual rolls and a wheel-shaped sensor with strain gauges to measure torque and bending moments applied to the workpiece.

7.4. Control of microstructure and flatness in strip rolling

Three product properties in rolled-strip metal have been the focus of closed-loop control system development: the centre-line thickness (or gauge) of the strip in both hot and cold rolling; the distribution of residual stress and thickness (flatness and profile) across the width of cold-rolled strip; the microstructure of hot rolled strip. Each is considered in turn.

The first control system for gauge in a tandem mill used a non-interactive approach to decouple the effects of roll force, gauge, rolling speeds and interstand tensions between the stands of the tandem mill [27]. This assumes that the process operates sufficiently close to a known operating point that it can be described as linear, in which case a non-interactive network can be solved to allow independent single-input single-output control of the gauge and speed of the strip at exit from each stand. A review of developments in more than three decades following this work [35] includes the development of different control algorithms (such as H∞ methods, optimal and model predictive control schemes) and various plant representations (such as adaptive models, auto-regressive (ARMAX) tuning algorithms, neuro-fuzzy control and the use of model based observers.) The relatively high frequency of response of mill screws, combined with the lower frequency disturbances to rolling, has allowed effective control of strip gauge, so that today's systems are more than able to meet customer requirements. An earlier review describes developments in gauge control in hot rolling, with a particular focus on those developed in Japan [172]. For a problem closely related to gauge control, the effect of interstand tension on the forming behaviour of rolling flat wire from round wire was examined experimentally [159] leading to development of an appropriate control system [100,131].

The flatness defects introduced in Section 2.3 arise from non-uniform reductions across the width of the strip due to the deflection of the rolls and mill stand under the high forces of rolling. A review of early work on strip flatness was motivated by the invention of controllable work and backup roll bending actuation [155]. This includes several attempts to develop on-line sensors for flatness defects and a subsequent survey, distinguishes contacting and non-contacting sensors [58]. For hot rolling, flatness defects are generally visible, so non-contacting optical sensing is typically used, such as on-line cameras that monitor projected-fringes [43]. For cold rolling, flatness defects lead to invisible residual stresses. A range of approaches has been tested to detect these residual stresses on-line, but in practice the use of deflecting narrow rotors (as described in Section 5.2) has become dominant [168]. The actuators used to control flatness defects are illustrated in Fig. 10 including bending jacks [155], Continuously Variable Camber intermediate roll shifting [89,92,128,150] and water sprays for roll profile control [18,12]. Some further actuation has been developed in research, but not been transferred widely into practice. For example, one-end tapered work roll shifting was used on a 12-high cluster mill for rolling hard materials [176]. One of the first models capable of predicting flatness defects [47] was based on a combination of a segmented plane strain model of rolling and an elastic model of mill deflection using influence functions [160]. This was further developed [4,118] with the elastic deformation of the strip outside the roll bite also incorporated [180] and many other developments [45]. The first control system for flatness, assumed that the frequency of response of the actuators is so much faster than the frequency of uncertainty in the flatness along the strip that the control system can operate without any time dynamics [168]. This was extended to allow for simple dynamics in flatness control in a 20-roll Sendzimir mill [61], with eight actuator settings to control the bending of the 20 rolls (in groups) related to the components of the measured flatness defects as characterised by eight polynomial basis functions. A more generalised analysis of the flatness control problem, uses a basis function expansion of Chebyshev polynomials up to the order of polynomial that can be detected by any particular shapemeter [46]. Flatness defects have been characterised with three polynomial basis functions using a genetic algorithm and neural network for control [109], a single basis function of parabolic variation of profile (or 'crown') controlled with strip gauge using a two-term MIMO controller [108], or by use of a learning algorithm to predict the sensitivity of flatness to actuator setpoints [189]. Current performance of flatness control systems in hot rolling is limited largely by the difficulty of applying finely resolved sensing in the hostile environment of the hot rolling mill. In cold rolling, performance is constrained by the limited bandwidth of actuation. Thermal spray control [12,18] allows control of higher spatial 'frequencies' (polynomial terms) and is applied in industrial practice, but has a relatively slow response and limited power.

Most microstructure control systems developed to date for hot strip rolling aim to influence the temperature history of the hot rolled strip in Fig. 8 as it passes through the run-out table. Initial work [138] aimed to control the temperature at cooling, but recent effort considered the temperature history from exit of the hot tandem mill to coiling. Modelling of recrystallisation, grain growth and phase change during hot rolling dates back to 1979 [154] which allowed the first prediction of the effect of rolling parameters on microstructure. This approach was greatly extended [19] leading to the rich body of today's knowledge [177]. Optical pyrometers are widely used to measure temperature at the mill exit and prior to coiling, and in some cases are also used in the middle of the run-out table, although this is constrained by the spray and water sitting on strip surface. A typical system aims to achieve on-line control of temperature at coiling, using a fuzzy logic algorithm to predict the transfer function from water spray intensity to strip cooling [195]. However, even if the coiling temperature is perfectly controlled, product microstructure may be disturbed if the temperature history of the strip has varied from that planned, as illustrated in Fig. 9. More recent developments in closed-loop control of temperature in hot strip rolling have therefore aimed at microstructure not just coiling temperature. Production of high-carbon (0.85 wt%) steel requires rapid cooling on the run-out table from mill exit temperature to between 500 and 600 °C, holding at this temperature for at least 4 s to allow transformation from austenite to pearlite, then quenching and coiling [140]. The required temperature profile can be maintained more accurately, through use of variable heat flux actuation on the run-out table [138]. The proprietary system illustrated in Fig. 28 controls not just the water sprays but also the speed of rolling in the finishing mill [192]. This allows a more consistent temperature at the entry to the run out table, and hence simplifies the requirements for the control of water sprays. Coupling this on-line system to an off-line prediction of microstructure evolution (grain size, recrystallisation and phase transformation) allows appropriate set points to be chosen across a range of steel grades. Within the context of this paper, the control system in Fig. 28 is an important demonstration of how future closed-loop control systems in metal forming can aim to compensate for disturbances that influence both product geometry and microstructural properties.

7.5. Control of geometry and microstructure in hot ring rolling

Hot radial–axial ring rolling, operates with uncertainty over workpiece temperature due to cooling in air and heating during deformation, and must avoid two key process constraints: mechanical instability leading to non-circularity; unconstrained material flow leading to geometrical defects (fishtailing, waviness, conicity, cavity and dishing) [7,8,34,105]. Unlike hot strip rolling, ring rolling equipment does not have thermal actuation (for heating or cooling) but the rate of deformation can be adjusted through actuator motion. Ring geometry (and sometimes temperature) is monitored through non-contact sensors. Process models for ring rolling must deal with transient conditions throughout processing, so solve slowly, and as a result closed-loop control is largely limited to tracking a planned schedule of actuator motion [94] as illustrated in Fig. 29: feedback from tool position sensors is used to achieve the planned reduction schedule, and guide roll forces are adjusted to control the ring centre.

Current sensors of ring geometry are typically scalar, so new approaches based on on-line cameras are being developed. On-line cameras and image-processing software can be used to detect the full two-dimensional geometry of the ring during processing [10,123], and continuous laser measurements of the outer surface of the ring during processing can detect form errors [95]. Thermal imaging can also be used to monitor ring surface temperature with accuracy of ±2% of actual temperature if surface oxide formation is avoided [80].

Finite element models can predict the evolution of strain, strain-rate and temperature (the drivers of microstructural change) throughout the volume of the ring [145] and have been extended to predict void accumulation using Oyane's criterion [191]. These models show that the effects of the controlling parameters in Fig. 29 are strongly interdependent but have different distributional effects through the ring. Simplified linearised models are therefore unlikely to be valuable.

As yet no implementation of on-line closed-loop control of microstructural properties in ring rolling has been reported, although new forms of ring geometry control are emerging [37]. However, the components of the required system are all under development, and existing control algorithms can be applied to finite element simulations of the process, to reveal how geometry control also influences ring temperature distributions [87,205]. The addition of thermal actuation in future could allow the form of compensation used in hot strip rolling to achieve a target microstructure even in the presence of thermal disturbances.

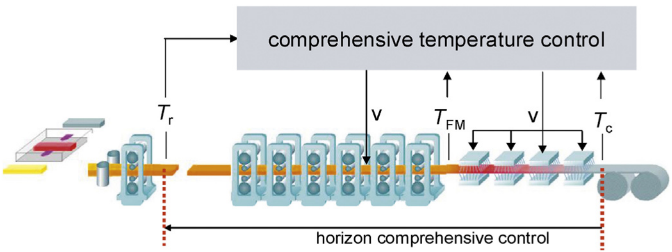

Fig. 28. Comprehensive temperature control including control of rolling speed to adjust mill exit temperature.
Adapted from [192].

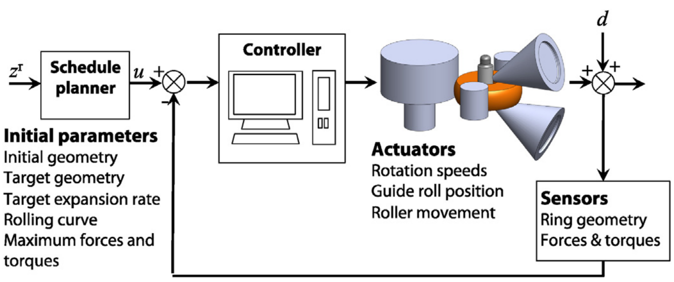

Fig. 29. On-line closed-loop control of equipment in ring rolling.

7.6. Control to avoid tearing and wrinkling in deep drawing

Deep drawing processes must operate with uncertainty in incoming material and variations in friction between workpiece and tools, and must avoid the two product failure constraints of wrinkling and tearing. To address this, the number of actuators used to control the distribution of blankholder pressure around the workpiece is steadily increasing, and new sensors are being developed to monitor material flow and stress during the punch stroke. Emerging closed-loop control strategies are being developed to adjust the distribution of blankholder pressure to achieve a specified distribution of perimeter flow, although due to process complexity these aim to track schedules developed through off-line models.

Two approaches have been taken to adding actuation to control material flow in the blank-holder: segmenting the blank-holder or actuating the draw bead. Distributed control of the binder pressure around the perimeter of the part may be achieved by use of many independent hydraulic [161,196] gas spring [68,163] or piezoelectric actuators [116] as illustrated in Fig. 30.

A consequence of applying actuation around a segmented blank-holder is the need for new designs of the binder [74]. There are many options for this and it can also provide improved localisation of the segmented forces [194]. Alternatively, an active draw-bead control system can be used to control the perimeter force restraining the workpiece [24,28]. This approach has been demonstrated for an industrial part, using hydraulic actuation of segmented draw-beads [22].

The main developments of sensors to allow control of deep-drawing have focused on monitoring the flow of material through the blank-holder during the stroke of the punch. This can be achieved with linear displacement transducers [162], laser triangulation [25], a roller ball, a non-contacting optical sensor [44], by non-contacting induction coils [115], Eddy-current sensors [130] or with an array of piezo-electric sensors mounted under a protective layer near the surface of the tool [3]. Table 3 provides a summary of the various sensors in current development for measuring material flow, although several have yet to be tested for industrial robustness.

In addition to material flow, several other variables can also be monitored in deep drawing operation as illustrated in Fig. 31. Opposed displacement transducers can be used in the upper and lower binders to monitor the height and wavelength of wrinkles, or the binders can be mounted on piezo-electric load cells, to monitor frictional forces [28]. Infrared thermography can be used to contrast the temperature distribution in each component with its predecessor, as a means to predict changes in process operating conditions [178]. A mini bulge test [125] allows on-line monitoring of material hardness during deep drawing. A novel sensor can be embedded in the perimeter of a deep-drawing punch to estimate wall stress in the part during the deep drawing stroke [23], or a 'borescope' (a small CCD camera which can be placed inside a small space between the tool cavities) can be used to monitor the three-dimensional deformation of the sheet during the punch stroke, for example to monitor wrinkles developing inside the blank-holder [70].

The existence of these new actuators and sensors enables two forms of control action during each punch stroke: the average blank-holder force can be varied as the punch descends and the distribution of blank-holder force around the perimeter of the part can be adjusted. A typical control scheme to achieve this is shown in Fig. 32, with an inner loop controlling the blank-holder forces to match a schedule created by an outer loop which controls the flange draw-in.

Early work on blank-holder control largely assumed a single blank-holder force applying uniformly around the binder, and aimed to establish safe trajectories between the limits of wrinkling and tearing [132]. For example, there is an advantage to having the blank-holder force decrease through the punch stroke [181]. Higher perimeter forces are required early in the stroke, and these should be reduced as the part is formed [24,67,161]. The

Table 3
Evaluation of sensor systems used in deep drawing [186].

Sensor	Advantages	Disadvantages
Displacement transducer	Reliable	Loading capacity Geometrical limits
Roller ball	Capsuled integration into tool; Detects flow direction	Risk of dirt Weakens tool
Piezoelectric thin film	High resolution and measuring sensitivity Sensing over an area	Extensive signal processing Complex assembly
Optical sensor	Capsuled integration into tool Detects flow direction	Risk of dirt Weakens tool Workpiece material dependency
Laser triangulation	Contact free Simple assembly	Risk of dirt Geometrical limits
Inductive coil/ Eddy current	Integration into tool High resolution	Signal processing Calibration required Weakens tool

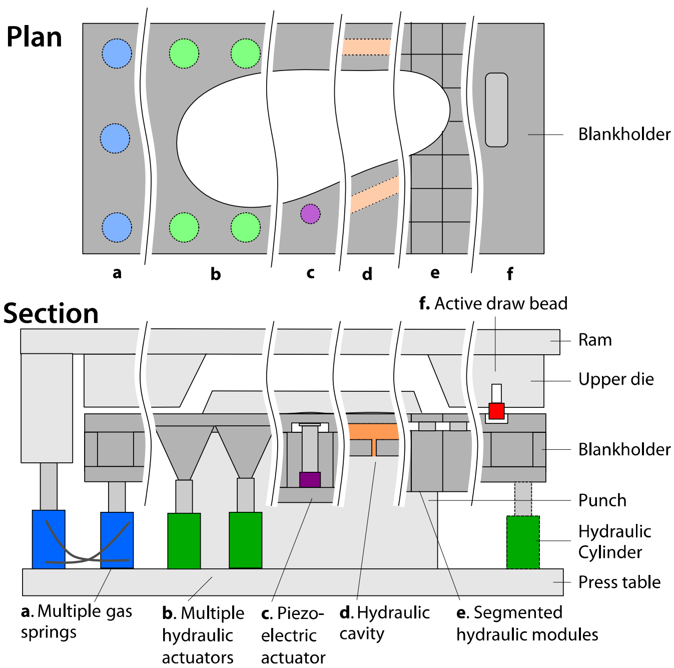

Fig. 30. Actuators for control of material flow in deep drawing.

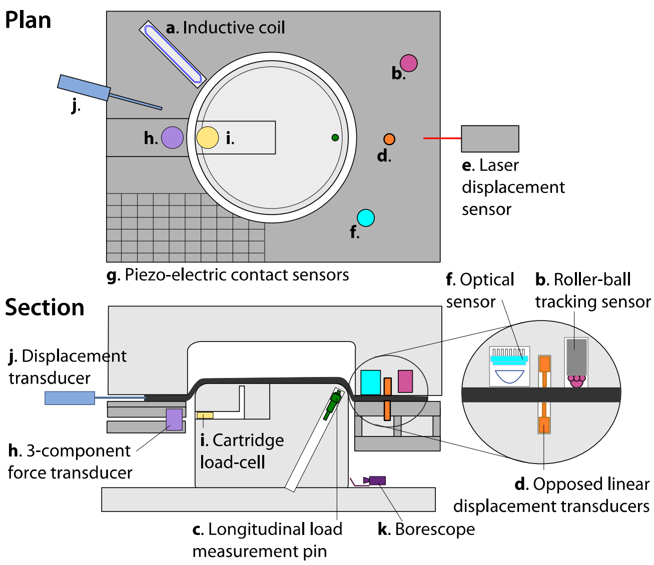

Fig. 31. Sensors to monitor material flow in deep drawing.

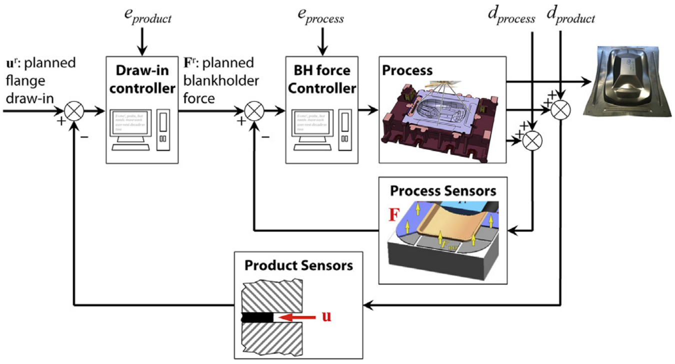

Fig. 32. Typical scheme for closed-loop control of material flow in deep drawing.

tendency to wrinkle is reduced when there is less unformed material left in the binders, but the risk of tearing increases. Nevertheless, higher perimeter forces help to reduce springback. Artificial neural networks [119] and fuzzy control algorithms [120] have been used to examine the deep-drawing of a cup with variable punch speed and blank-holder force. This leads to improved production speed and higher drawing ratios when both punch speed and blank-holder force are varied optimally, compared to a reference case with constant values. A system for control of segmented blank-holders, with the force adjusted to control material flow along twelve radial lines towards the centre of a representative non-symmetric part has been developed [97]. An ARMA model of process behaviour has demonstrated (in a process simulation) how the forces in a segmented blank-holder can be controlled to achieve a constant (small) height of wrinkling within the binder [98] and this has also been shown in practice [204]. Related approaches have used a genetic algorithm [203] or a control scheme based on modelling rather than estimation [51,52]. Flange-draw was monitored in these trials during drawing of a square cup, and the blank-holder pressure adjusted (through adjusting fluid pressure in a series of cavities within the binder) to match the draw-in to a target determined from finite element simulations. The multi-input multi-output control scheme is based on process gains calculated by finite element analysis of the process, which can be re-calculated for any different workpiece properties or tooling. A detailed finite element model has been used to predict the sensitivity of the thickness distribution in a representative part to variations in the blank-holder force trajectories in each of ten independently controlled segments around the part [106]. This is arduous, but because of the richness of the resulting sensitivity matrix, is likely to give better performance than the statistical methods above.

Development of closed-loop control of deep drawing to date has largely been at laboratory scale, to demonstrate feasibility. All of the published reports discussed above involve monitoring material flow (as shown in Fig. 32) or the part wall stress and using the distributed actuation to adjust these variables to match previously determined master curves. However, while this reduces the complexity of the control problem, it is not clear that such master curves accurately reflect customer requirements for product properties. If in future faster process models are developed, it may be possible to design control systems with the same actuation and sensing which instead control directly for customer requirements, such as thickness or residual stress distributions.

Further equipment developments will allow an expansion in the capability of closed-loop control in deep drawing. One option that has emerged with the recent advances in servo-presses, is to allow for complete control of the punch stroke. Early work on this possibility [134], has focused on the benefits from lubrication spreading during a partial withdrawal of the punch interrupting a conventional stroke. Future developments may allow more sophisticated combinations of punch motion and blank-holder force control.

7.7. Control of geometry in hydroforming

As with deep drawing, the uncertainties in both sheet and tube hydroforming arise from variations in material thickness, properties and lubrication. However, in addition to the actuation available for deep drawing, hydroforming processes can also exploit actuation of fluid pressure or volume flow. Sensing is more constrained in hydroforming, as the fluid must be fully contained and this has led to increased interest in off-line closed-loop control as illustrated in Fig. 6.

Many researchers in hydroforming, such as [139], have worked on the development of closed-loop control of the equipment, as illustrated in Fig. 4, typically to ensure that these actuators track some specified target schedule. For example, the back-up pressure can be controlled with respect to the punch stroke to maintain the uniform wall thickness [198] or the fluid volume can be controlled which may improve stability [64]. However, this form of equipment control is insensitive to product properties. Attempts to control properties have emerged only recently with the incorporation of appropriate sensors.

One approach to adding product sensing to hydroforming is the use of a CCD camera to monitor the leakage of fluids between the workpiece and die [62]. This allows active control of the clamping force at the minimum level required to contain the fluid, hence increasing the forming limits of the process. Direct measurement is possible in the hydraulic bulge test illustrated in Fig. 33, where no tool is required to constrain the bulging sheet. Thermocouples, a pair of CCD cameras and a pressure sensor in the fluid were used to monitor and control the temperature, strain, strain rate and stress state of the sheet during the bulge test to allow improved material characterisation [114].

In tube hydroforming of the 'T'-shaped part in Fig. 34, a displacement sensor measures form-filling deviations at the base of the 'T' and a distributed sensor monitors the contact area between counter punch and the projected branch of the T. In a two stage control process, firstly the gap e and then the contact length C_l are

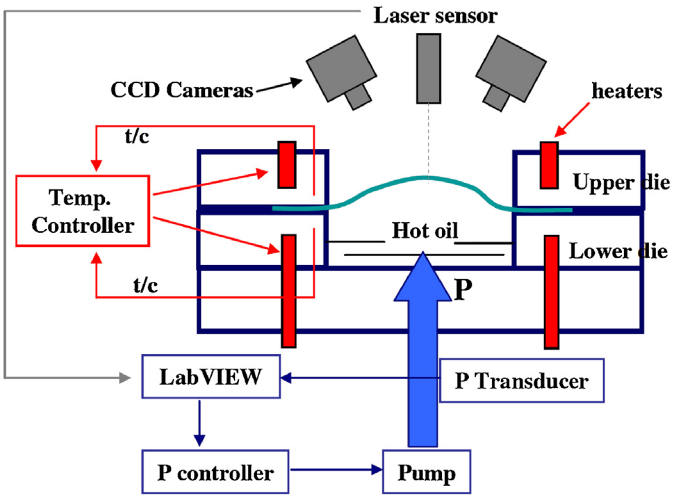

Fig. 33. Hydraulic bulge test with on-line sensing of strain, strain-rate, temperature and fluid pressure [114].

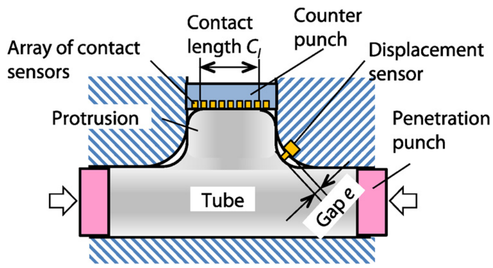

Fig. 34. Novel in-tool sensors in tube hydroforming [121].

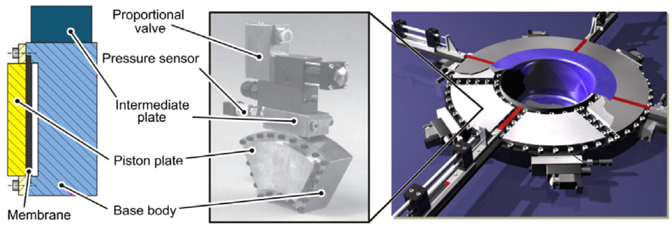

Fig. 35. Multi-point blank holder system.

controlled by fuzzy closed-loop control to match reference values which are predicted to minimise buckling and rupture [121].

Two attempts at distributed blank-holder control in sheet hydroforming have been reported. The influence of variations in the blank holder force on the final product geometry was monitored [40] and a closed-loop control system built to control hydraulically supported segmented binders for changing friction conditions during the process. The multi-point blank holder system illustrated in Fig. 35 was used to control the material flow in the flange area. The draw-in of the sheet was measured locally by a tactile sensor system and controlled [182].

The difficulty of sensing the product in hydroforming has stimulated interest in off-line closed-loop control. For example, sheet hydroforming was simulated to assess the distribution of thinning, wrinkling and die conformance achieved by a given schedule of blank-holder force, punch speed and hydraulic pressure. A fuzzy algorithm was then used to update the schedule [36]. Similar approaches for tube hydroforming have controlled the schedule using a fuzzy logic controller linked to a finite element simulation [146], or by stating the control problem as an optimisation with the form of Eq. (2) with two objective functions; one for die filling and the other for thickness uniformity [82]. Several other groups worked on this approach in the period 2001–7 [86,103] and continue this work with the fuzzy-logic approach illustrated in Fig. 36. The approach of Fig. 36, has also been attempted with genetic algorithms to transform circular tubes to square sections [1] and a closed-loop servo control system was applied to control internal and external pressures and axial feeding in a double-sided tube hydroforming process to minimise wrinkle formation, based on sensing of axial feed [202].

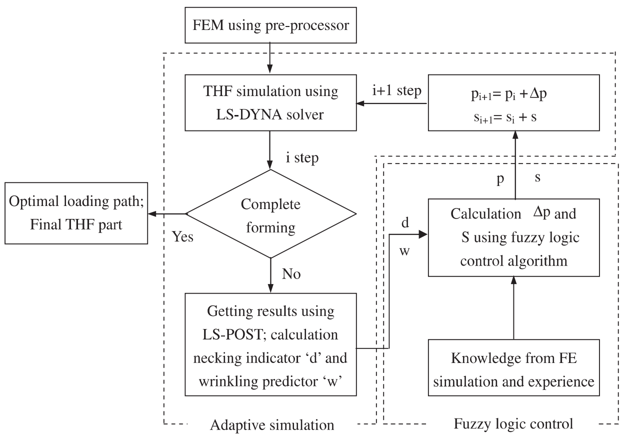

Fig. 36. Off-line fuzzy logic control of tube hydroforming.

7.8. Control of geometry in flexible sheet forming processes

Many flexible or incremental sheet forming processes have been developed, with either increased actuation or mobile tools, aiming to create many part geometries without dedicated tooling. The primary source of uncertainty in these processes is model error. Although the actuation can apparently provide great flexibility and camera systems can sense complete part geometry in real time, the success of any controller depends on prediction of the actuator response. In most flexible processes these responses are strongly dependent on process history, and process models are orders of magnitude slower than the actual process.

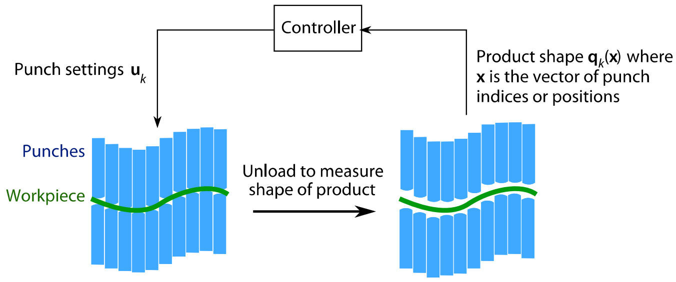

Fig. 37. Stamping with matrix of punches. From [144].

The most successful implementation of closed-loop control in a flexible forming process is the earliest. A die was constructed as a matrix of pins, with which part geometry can be stamped with high accuracy [72]. The pins are set to some geometry, the part is stamped and measured, and then based on the difference between measured and intended geometry, the pins are adjusted. This approach, repeated by many others [102] and illustrated in Fig. 37, converges well. Unfortunately, the use of dies made from pins although widely explored, has had little industrial interest due to the poor surface quality created by the pins.

The same approach used by [72] was applied to laser bending of sheet metal [48,33]. A first tool path is applied, the sheet geometry compared to the target, and a corrective second path is designed. The results demonstrate incremental improvement in geometric accuracy, subject to the constraint that laser bending is one-sided so, unlike the process in Fig. 37, cannot correct for over-bending. The process has largely been explored within research laboratories due to the very limited Gaussian curvature that can be achieved by bending.

Twenty-five years of academic research into incremental sheet forming has led to few industrial applications due to poor geometric accuracy, high residual stresses and constrained forming limits. A significant body of research has aimed to develop strategies for tool-path design, for example through rigid body transformation theory [117], feature based non-*z*-level slicing algorithms [112] or the morph mapping strategy [16]. However, these strategies have no feedback, so do not adapt when the outcome of the strategy fails to achieve its intended target. Unlike the uncertainties in deep drawing and sheet hydroforming which relate to the workpiece, the uncertainties of incremental sheet forming relate to the unpredictability of the process mechanics: the response of the workpiece to the next movement of the forming tool depends so strongly on the previous history of deformation and the current location of the tool, that it is difficult to simplify the process model in Eq. (1).

An off-line closed-loop control strategy was developed with iterative correction of tool-paths [77], following the same idea as [72] and in parallel with [48]. This was subsequently applied to a double-sided incremental forming process, using the scheme illustrated in Fig. 38 [122]. However, unlike the off-line approaches that work successfully in tube hydroforming, the effect of these

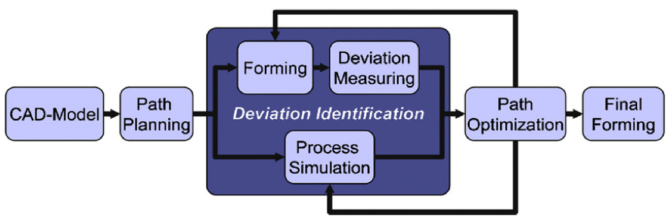

Fig. 38. Schematic of process-control in DSIF [122].

approaches in incremental sheet forming may be disappointing. For example in forming a flat-sided pyramid shape, after the first tool-path completes, the faces of the pyramid will not be flat, suggesting that in the next iteration the tool should press further into the face, but this will not cause the face to flatten. Instead, the face will be further stretched, and may be further from flat after the intended corrective step.

The scheme in Fig. 38 is a form of off-line closed-loop control, with measurement and tool-path design occurring after a complete part has been formed. In contrast, the on-line closed-loop system shown in Fig. 39, was developed with a stereo-vision camera monitoring sheet geometry during the process [9]. Circular cones were formed and the response of the workpiece to small deviations from each planned circular tool path were parameterised linear spatial impulse functions. The geometry of the part after each circular path was compared to the geometry predicted by the spatial impulse functions, allowing adjustment of the schedule for the next path. This approach was extended to allow linearisation around a general tool path [71] thus representing the process in the form of Eq. (4) and allowing a rapid solution of the optimisation statement in Eq. (10). This led to a reduction in geometric errors from ± 3 mm to ± 0.2 mm for a particular test part but this approach to linearisation allows only small deviations from the planned path.

The approach of [71] was applied to metal spinning, using a finite element model of the spinning process to determine the sensitivity of the workpiece geometry to the direction of each next short increment of tool measurement, thus building up a tool path step by step [142]. However, the model solution time was prohibitively long, so this work is now continuing by an exploration of tool-path parameterisation [143].

A surprising outcome of these attempts to control flexible sheet forming processes is that despite great flexibility in actuation, and easy access for the application of sensing, it is the unpredictability of the mechanics of the flexible processes that inhibits the implementation of control systems.

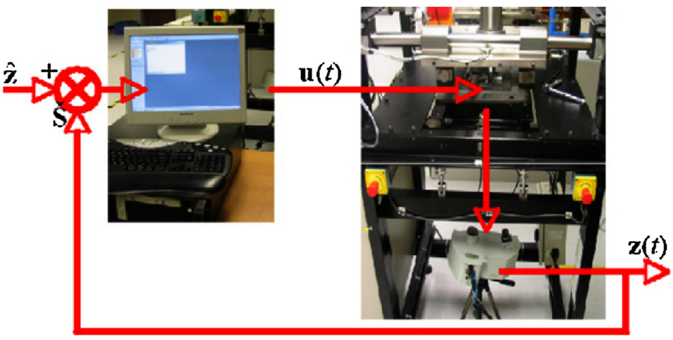

Fig. 39. Closed-loop control in incremental sheet forming [9].

7.9. Control of geometry and grain size in open die forging

Open-die forging faces uncertainties in incoming material geometry and microstructure (as well as segregations, voids and porosity) and in workpiece temperature during the process. The goal of the pass schedule is to place individual strokes so that the strain distribution is relatively homogeneous and the strain is large enough to close porosity and initiate recrystallization while also achieving the target geometry. Actuators allow selection of the location and depth of each stroke. Surface geometry and temperatures can be sensed, to some extent, but the quality of the product is largely determined by the microstructure at its core. Control is currently achieved by skilled operators, but operator-assistant systems are being developed to provide predictive information on core microstructure.

Long solution times and model inaccuracy preclude automatic closed-loop control at present, but Fig. 40 proposes a 'man in the loop' control system. Sensing and an observer are used to anticipate the internal microstructure of the part, and the automatic assistant then suggests the next action to the operator.

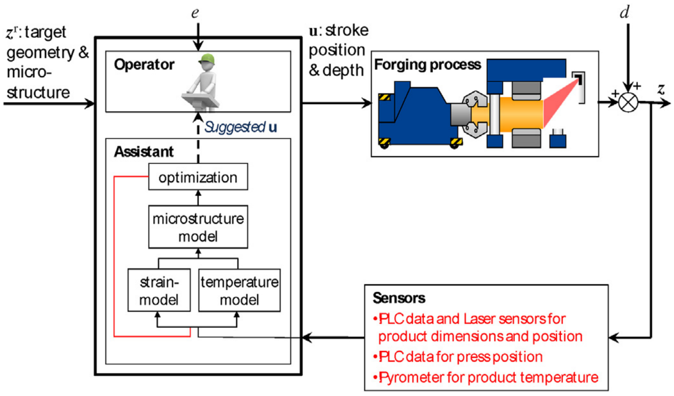

Fig. 40. Vision of an on-line assistant system for open die forging [149].

Fast models are a prerequisite for such a system. The equivalent strain for single strokes can be determined from the bite ratio and height reduction [73]. The strain in the core fibre allowing for height reduction and bite ratio was calculated to find a minimum strain required to close pores in the core fibre [93]. These findings were combined to develop an empirical squared sine function for the true strain [164] allowing a uniform equivalent strain in the core fibre [21].

The equivalent strain can be modelled as a cosine function based on FEM results to improve the strain distribution by controlling the bite length [113], and the results from [73] fit with an equivalent strain equation [151]. Measurement data is analysed semi-automatically and compared to ultrasonic inspection results from forged ingots. The equivalent strain in the core can be predicted based on a Gaussian function for cogging and upsetting [31,32]. This was later extended with a temperature model allowing comparison of different pass schedules by using fast models of pore closure ratio, energy consumption, etc. [54].

A commercially available measurement system LACAM FORGE was applied to monitor the equivalent strain in the core fibre on-line during forging and to present it to the press operator [147]. The strain models were enhanced by finite element results and additionally a temperature model and grain size calculation were applied [148,149]. The results correlated well with measured grain size after cooling. However the information displayed as well as the interrelationship between the stroke sequence and the resulting microstructure were too complex for use by operators in practice, so numerical optimisation procedures and cost functions are under development [149].

7.10. Control of hot extrusion

In hot metal extrusion the exit temperature of the extrudate is uncertain due to variability in the pre-heating of equipment and billet, and due to heat generated during forming [2]. However, the exit temperature can be measured and controlled by adjusting the ram speed, subject to constraints of maximum ram force and the need to avoid hot cracking [41].

The approach in Fig. 41 combining closed-loop control of the ram speed during a batch run of the extrusion process with on-line identification of the response of the exit temperature to ram speed, draws on a decade's developments [20,84,136]. The results, based on simulation, demonstrate that by the second product in a batch a constant exit temperature can be maintained for all but the first ~20% of the billet length.

Temperature measurement at the die exit is essential for controlling extrusion, and contactless measurement is challenging for materials such as aluminium with low emissivity. Existing options, particularly pyrometers that measure infrared radiation in multiple spectral regions, have been reviewed [137]. Pressure and

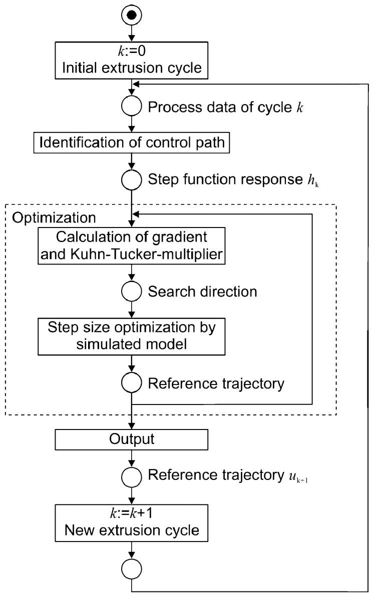

Fig. 41. Closed-loop control of ram speed in extrusion [135].

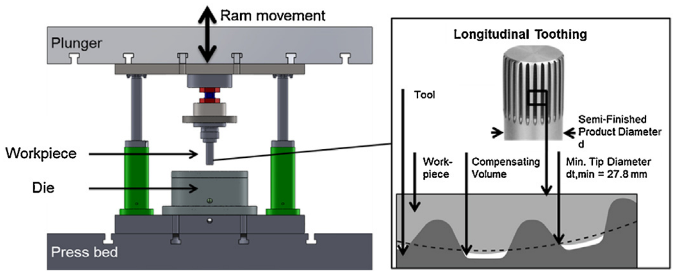

Fig. 43. Oscillating press system (left) and formed gear (right) [63].

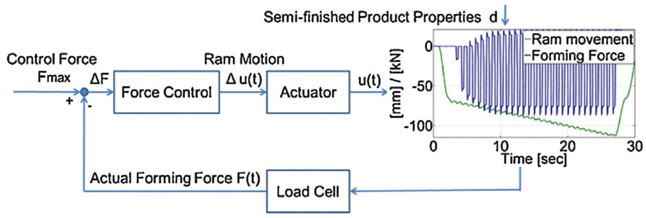

Fig. 44. Control strategy for accuracy-optimised cold forged parts [63].

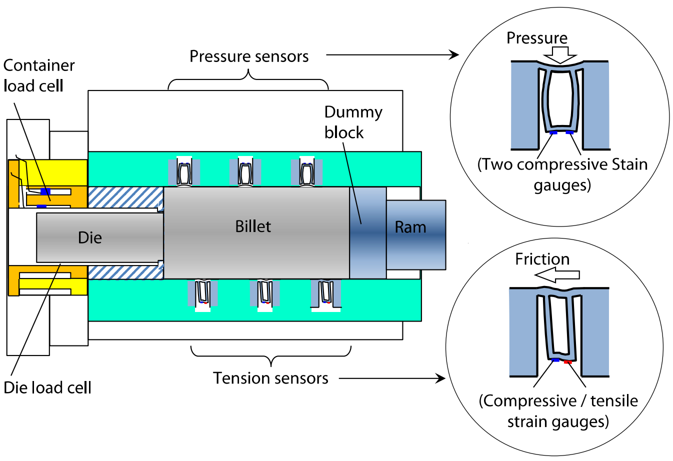

Fig. 42. Sensors for hot extrusion: (a) sensors for pressure and friction and (b) implementation to extrusion.

friction sensors, inserted behind the tool wall as shown in Fig. 42, may also support improved control of extrusion in future [201]. A structure of π shape is engraved into the tool wall and deforms in response to the pressure or friction on the tool surface. Novel actuation aiming to improve temperature control further includes active cooling of the container or active cooling of the dies. The option to make extrusion dies with conformal cooling channels by additive manufacturing methods offers new potential for increasing productivity in hot aluminium extrusion [78].

7.11. Control of cold forging

The process of backward cup extrusion is subject to uncertainties in material properties, geometry and variations due to both heat and surface treatment of the feedstock. These uncertainties affect the elastic deformation of the tools and thus the thickness of the bottom of the cup. An additional counterpunch can be added to the conventional process [107] to track schedules of force, position or velocity, which are all monitored during forming. The distance between punch and counterpunch is monitored and two trigger points are set. If the first trigger point is detected, the control switches from position to velocity control, so that the difference between punch and counterpunch velocity is reduced. If the second trigger is detected, the process stops. Experimental investigations showed that with this approach the punch load is reduced by around 20% compared to the conventional backward cup extrusion process and cups with wall thickness below 1 mm can be made [152].

In the cold forging process of Fig. 43, friction and therefore the forming force is reduced by an oscillating ram motion that allows a redistribution of lubrication [63]. Friction impedes axial material flow and leads to an increased tip diameter, but this can be controlled by the closed-loop system of Fig. 44.

The forming force is measured by a load cell, and the force controller generates a forwards ram motion until the maximum forming force is reached and then a back stroke. Numerical simulations showed that a closed-loop force controller can deal with uncertainties due to varying diameters in the incoming feedstock without loss of accuracy in the final part geometry.

8. Discussion and outlook

The paper was motivated by the fact that all metal forming processes must cope with uncertainties. The introduction also noted that developments in the science of property prediction creates opportunities to develop new advanced products. Furthermore, the motivation to reduce the cost of small batch production has stimulated development of new flexible process designs, and these designs with increased actuation invite new approaches to control. The evidence of the survey in Section 7 demonstrates that there is a rapidly growing activity around the development of closed-loop control systems motivated by all three of these drivers. By drawing together current experience and presenting an overarching framework for the analysis of future control systems, the authors hope this will stimulate further growth in the area.

All of the applications reviewed in this paper have faced the non-linearity of the processes they consider. Many have dealt with this by linearising about a single operating point for the current product, with the parameters for the operating point either found by on-line identification, or by some form of analytical or statistical model. There has been widespread use of statistical models, such as fuzzy-controllers or genetic algorithms, to capture the non-linear variation in operating points. However, some authors have also used more detailed off-line process models in order to generate sensitivities for on-line use.

The majority of applications to date have aimed to control either product geometry or avoid failure. The control of temperature is less common, but the example of microstructure control in hot rolling in Section 7.4 demonstrates a pathway for future development. Emerging models of microstructure evolution depend primarily on the history of strain, strain-rate and temperature in the workpiece, and there are now sufficient sensors to allow monitoring of these variables across the surfaces of most workpieces. The development of operator-assisting software for open-die forging [149] is an excellent demonstration of how, in future, observers could be used to provide new feedback about currently unobservable properties.

The framework of analysis set out in Section 3 created a basis for analysing both temporal and spatial dynamics in metal forming control systems. This approach has been used widely in rolling, particularly for flatness control, but the survey has revealed opportunities for extending this spatial approach to other applications. The development of segmented blank-holders for deep drawing has so far been applied only to the control of material flow in the flange. However, the growing array of sensors available to this process suggests that a more sophisticated spatial characterisation of the workpiece is possible, and this creates a richer opportunity for control system development. For other processes specifically designed for flexibility, the opportunity to move actuators across the space of the workpiece creates a high spatial bandwidth, which to date has been difficult to exploit due to complex process mechanics. However future machine designs may be able to maintain mobile tools and actuator flexibility while creating more predictable process responses (spatial impulse functions) which would also enable a richer approach to spatial control.

This paper has aimed to complement its predecessor [177] to demonstrate the breadth of opportunity for research and development in the prediction and control of product properties in metal forming. The scientific understanding of property prediction is growing rapidly, reducing uncertainty about process outcomes. Where this prediction can be made sufficiently rapidly, existing processes may now be controlled to achieve higher product specifications. New metal forming processes can also be designed to enable the efficient application of the approach to closed-loop of properties set out in this paper.

Acknowledgements

The work of Professors Allwood and Duncan on this paper was funded by the UK's Engineering and Physical Sciences Research Council (EPSRC) under grant EP/K018108/1. We are grateful to Christopher Cleaver who created Figs. 30 and 31, and for significant input from Dr. S. Chatti from Dortmund.

References

[1] Abedrabbo N, Worswick M, Mayer R, van Riemsdijk I (2009) Optimization Methods for the Tube Hydroforming Process Applied to Advanced High-Strength Steels With Experimental Verification. *Journal of Materials Processing Technology* 209(1):110–123.
[2] Akeret R (1971) Die Produktivität beim Strangpressen von Aluminium-Werkstoffen – Einfluss von Werkstoff und Verfahren. *Zeitschrift für Metallkunde* 62(6):451–456.
[3] Albert A, Biehl S (2009) ORUM – Optimierte Regelung von Umformprozessen. Erfolgversprechende Gegensätze: Prozesskontrolle gewaltiger Umformanlagen mit hauchdünnen Sensorschichten. *Wt Werkstattstechnik Online* 99(10):779–784.
[4] Allwood JM, Bryant GF (1997) Fast Modelling of Roll Stack Behaviour for Control Applications. *Proceedings of the Institution of Mechanical Engineers Part C: Journal of Mechanical Engineering Science* 211(5):373–386.
[5] Allwood JM, Cullen JM (2012) *Sustainable Materials: With Both Eyes Open*, UIT Cambridge Ltd., Cambridge, England.
[6] Allwood JM, Utsunomiya H (2006) A Survey of Flexible Forming Processes in Japan. *International Journal of Machine Tools and Manufacture* 46(15):1939–1960.
[7] Allwood JM, Tekkaya AE, Stanistreet TF (2005) The Development of Ring Rolling Technology. *Steel Research International* 76(2–3):111–120.
[8] Allwood JM, Tekkaya AE, Stanistreet TF (2005) The Development of Ring Rolling Technology. Part 2. *Steel Research International* 76(7):491–507.
[9] Allwood JM, Music O, Raithathna A, Duncan SR (2009) Closed-Loop Feedback Control of Product Properties in Flexible Metal Forming Processes with Mobile Tools. *CIRP Annals – Manufacturing Technology* 58:287–290.
[10] Arthington MR, Cleaver CJ, Allwood JM, Duncan SR (2014) Real-Time Measurement of Ring-Rolling Geometry Using Low-Cost Hardware. *International Conference on Control UKACC 2014*, 603–608.
[11] Astrom KJ, Wittenmark B (1995) *Adaptive Control*, 2nd ed. Addison-Wesley, Reading, MA.
[12] Atack P, Robinson IS (1994) An Investigation into the Control of Thermal Camber by Spray Cooling. *Journal of Materials Processing Technology* 45(1–4):125–130.
[13] Avrami M (1939) Kinetics of Phase Change. I. General Theory. *Journal of Chemical Physics* 7:1103–1112.
[14] Baseri H, Bakhshi-Jooybari M, Rahmani B (2011) Modeling of Spring-Back in V-Die Bending Process by Using Fuzzy Learning Back-Propagation Algorithm. *Expert Systems with Applications* 38:8894–8900.
[15] Becker C, Tekkaya AE, Kleiner M (2014) Fundamentals of the Incremental Tube Forming Process. *CIRP Annals – Manufacturing Technology* 63(1):253–256.
[16] Behera AK, Lauwers B, Duflou JR (2013) Tool Path Generation for Single Point Incremental Forming Using Intelligent Sequencing and Multi-Step Mesh Morphing Techniques. *Key Engineering Materials* 554–557:1408–1418.
[17] Beiter P, Groche P (2011) On the Development of Novel Light Weight Profiles for Automotive Industries by Roll Forming of Tailor Rolled Blanks. *Key Engineering Materials* 473:45–52.
[18] Bennon WD (1985) Evaluation of Selective Coolant Application for the Control of Work Roll Thermal Expansion. *ASME Journal of Engineering for Industry* 107(2):146–152.
[19] Beynon JH, Sellars CM (1992) Modelling Microstructure and its Effects During Multipass Hot Rolling. *ISIJ International* 32/3:359–367.
[20] Biswas AK, Repgen B, Steinmetz A (1992) Computer Simulation of Extrusion Press Operation Experience with CADEX, A New Computer Aided Process Optimizing System. *Proceedings of the Fifth International Aluminum Extrusion Technology Seminar*, Chicago, 149–155.
[21] Blaes N, Bokelmann D, Poppenhäger J, Wagner H (1997) Optimization of the Forging Process of Heavy Forgings for Power Generation Machinery. *13th International Forgemasters Meeting*, Pusan, Korea.
[22] Blaich C, Liewald M (2008) Closed-Loop Control Strategy for Deep Drawing Processes on Utilizing Part Wall Stress. *Proceedings of the IDDRG 2008*, 545–556.
[23] Blaich C, Liewald M (2010, May) Detection and Closed-Loop Control of Local Part Wall Stresses for Optimization of Deep Drawing Processes. in Liewald M, (Ed.) *New Developments in Sheet Metal Forming*, MAT-INFO Werkstoff-Informationsgesellschaft, Fellbach. Frankfurt/M..
[24] Bohn ML, Xu SG, Weinmann KJ, Chen CC, Chandra A (2001) Improving Formability in Sheet Metal Stamping with Active Draw-Bead Technology. *Journal of Engineering Materials and Technology* 123(4):504–510.
[25] Braunlich H, Neugebauer R (2001) Closed Loop Control of Deep Drawing Processes. *SheMet 2001*, Mechanical Engineering Department, Katholieke University Leuven, 529–538.
[26] Bruni C, Forcellese A, Gabrielli F, Simoncini M (2006) Air Bending of AZ31 Magnesium Alloy in Warm and Hot Forming Conditions. *Journal of Materials Processing Technology* 177:373–376.
[27] Bryant GF, Higham JD (1973) A Method for Realizable Non-Interactive Control Design for a Five Stand Cold Rolling Mill. *Automatica* 9:453–466.
[28] Cao J, Boyce MC (1993) Draw Bead Penetration as a Control Element of Material Flow. *Journal of Materials and Manufacturing* 102(5):694–702.
[29] Cao J, Kinsey B, Solla S (2000) Consistent and Minimal Springback Using a Stepped Binder Force Trajectory and Neural Network Control. *ASME Journal of Engineering Materials and Technology* 122:113–118.
[30] Chatti S, Dirksen U, Kleiner M (2004) Optimization of the Design and Manufacturing Process of Bent Profiles. *Journal of the Mechanical Behaviour of Materials* 15(6):437–444.
[31] Chen K, Yang Y-T, Shao G-J, Liu K-J (2011) Simulation of Large Forging Flat-Anvil stretching process and Its Optimization. *Journal of Shanghai Jiaotong University* 16(2):199–202.
[32] Chen K, Liu K, Chen H, Yang Y (2013) Function Representation for the Strain Field during the Steel Forging and Its Application on the Deformation of Void Defects. *Steel Research International* 84(10):948–955.
[33] Cheng J, Yao YL (2004) Process Design of Laser Forming for Three-Dimensional Thin Plates. *ASME Journal of Manufacturing Science and Engineering* 126:217–225.
[34] Choi HD, Cho HS (1989) An Adaptive Control Approach to the Ring Geometry Control for Radial–Axial Rolling Processes. *Journal of Mechanical Engineering Science* 203:243–254.
[35] Choi IS, Rossiter JA, Fleming PJ (2007) Looper and Tension Control in Hot Rolling Mills: A Survey. *Journal of Process Control* 17:509–521.
[36] Choi H, Koç M, Ni J (2007) Determination of Optimal Loading Profiles in Warm Hydroforming of Lightweight Materials. *Journal of Materials Processing Technology* 190(1):230–242.
[37] Cleaver CJ, Arthington MR, Mortazavi S, Allwood JM (2016) Ring rolling with variable wall thickness. *Annals of CIRP* 65:281–284.
[38] Cullen JM, Allwood JM (2013) Mapping the Global Flow of Aluminium: From Liquid Aluminium to End-Use Goods. *Environmental Science and Technology* 47:3057–3064.
[39] Cullen JM, Allwood JM, Bambach MD (2012) Mapping the Global Flow of Steel: From Steelmaking to End-Use Goods. *Environmental Science and Technology* 46:13048–13055.
[40] Damborg FF, Jensen MR (1998) Hydromechanical Deep Drawing. Part I. Control of the Blank Holder Force. *Proceedings of the Baltic Sea Metal Forming and Cutting Seminar*, 2–3 June, 104–111.
[41] Das AK (1988) Special Features of Process Defects in Aluminium Alloy Extrusions. *Proceedings of the Fourth International Extrusion Technology Seminar, Vol. 2*, April 11–14, Chicago, 227–233.
[42] De Vin LJ (2000) Curvature Prediction in Air Bending of Metal Sheet. *Journal of Materials Processing Technology* 100:257–261.
[43] Degner M, Müller U, Thiemann G, Winter D (1998) Topometric On-Line Flatness Measuring System for Improved Flatness Control of Hot Strip Mill.

Proceedings of the Seventh International Conference on Steel Rolling, Chiba, Japan, 42–47.
[44] Doege E, Seidel H-J, Griesbach B, Yun J-W (2002) Contactless On-Line Measurement of Material Flow for Closed Loop Control of Deep Drawing. *Journal of Materials Processing Technology* 130–131:95–99.
[45] Domanti SA, McElwain DLS (1998) Cold Rolling of Flat Metal Products: Contribution of Mathematical Modelling. *Proceedings of the Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture* 212(1):73–86.
[46] Duncan SR, Allwood JM, Garimella SS (1998) The Analysis and Design of Spatial Control Systems in Strip Metal Rolling. *IEEE Transactions on Control Systems Technology* 6:220–232.
[47] Edwards WJ, Spooner PD (1973) Analysis of Strip Shape. *Automation of Tandem Mills A Collection of Monographs Metals Society London* 1973:176–212.
[48] Edwardson SP, Moore AJ, Abed E, McBride R, French P, Hand DP, Dearden G, Jones JDC, Watkins KG (2004) Iterative 3D Laser Forming of Continuous Surfaces. *Proceedings of ICALEO 2004* 36–45.
[49] El Budamusi M, Becker C, Clausmeyer T, Chen L, Gebhard J, Tekkaya AE (2015) *Erweiterung der Formänderungsgrenzen von höherfesten Stahlwerkstoffen bei Biegeumformprozessen durch innovative Prozessführung und Werkzeuge*, Final report (P930) FOSTA, Verlag und Vertriebsgesellschaft mbH, Düsseldorf.
[50] Elkins KL, Sturges RH (1999) Springback Analysis and Control in Small Radius Air Bending. *ASME Journal of Manufacturing Science and Engineering* 121:679–688.
[51] Endelt B, Nielsen KB, Danckert J (2006) New Framework for On-Line Feedback Control of a Deep-Drawing Operation. *Journal of Materials Processing Technology* 177(1):426–429.
[52] Endelt B, Tommerup S, Danckert J (2013) A Novel Feedback Control System – Controlling the Material Flow in Deep Drawing Using Distributed Blank-Holder Force. *Journal of Materials Processing Technology* 213:36–50.
[53] Fan Z, Ng M, Gao R, Cao J, Smith E (2012) Real-Time Monitoring of Pressure Distribution in Microrolling Through Embedded Capacitive Sensing. *CIRP Annals – Manufacturing Technology* 61(1):367–370.
[54] Feng G, Cui Z, Chen W (2015) Optimisation of pass schedules for flat-tool forging based on analytical method. *International Journal of Materials and Product Technology* 51(4):385–400.
[55] Forcellese A, Gabrielli F, Ruffini R (1998) Effect of the Training Set Size on Springback Control by Neural Network in an Air Bending Process. *Journal of Materials Processing Technology* 80–81:493–500.
[56] Fu Z, Mo J (2011) Springback Prediction of High-Strength Sheet Metal Under Air Bending Forming and Tool Design Based on GA–BPNN. *International Journal of Advanced Manufacturing Technology* 53:473–483.
[57] Garcia-Romeu ML, Ciurana J, Ferrer I (2007) Springback Determination of Sheet Metals in an Air Bending Process Based on an Experimental Work. *Journal of Materials Processing Technology* 191:174–177.
[58] Ginzburg VR (1989) *Steel-Rolling Technology: Theory and Practice*, CRC Press.
[59] Goodarzi M, Kuboki T, Murata M (2005) Deformation Analysis for the Shear Bending Process of Circular Tubes. *Journal of Materials Processing Technology* 162–163:467–492.
[60] Gossard DC, West J, Stelson KA, Blair A, Webb RD, Hardt D (1983) Press Brake Having Spring-Back Compensating Adaptive Control. US Patent 4408471 A.
[61] Grimble MJ, Fotakis J (1982) The Design of Strip Shape Control Systems for Sendzimir Mills. *IEEE Transactions on Automatic Control* 27(3):656–666.
[62] Groche P, Ertuğrul M (2008) Process Control at the Sealing Line During Sheet Metal Hydroforming. *Production Engineering* 2(1):3–8.
[63] Groche P, Heß B (2014) Friction Control for Accurate Cold Forged Parts. *CIRP Annals – Manufacturing Technology* 63:285–288.
[64] Groche P, Steinheimer R, Schmoeckel D (2003) Process Stability in the Tube Hydroforming Process. *CIRP Annals – Manufacturing Technology* 52(1):229–232;
Liang SY, Hecker RL, Landers RG (2004) Machining Process Monitoring and Control: State of the Art. *ASME Journal of Manufacturing Science and Engineering* 126:297–310.
[65] Groche P, Fritsche D, Tekkaya AE, Allwood JM, Hirt G, Neugebauer R (2007) Incremental Bulk Forming. *Annals of CIRP* 56(2):635–656.
[66] Groche P, Beiter P, Henkelmann M (2008) Prediction and Inline Compensation of Springback in Roll Forming of High and Ultra-High Strength Steels. *Production Engineering* 2:401–407.
[67] Gunnarsson L, Schedin E (2001) Improving the Properties of Exterior Body Panels in Automobiles Using Variable Blank Holder Force. *Journal of Materials Processing Technology* 114(2):168–173.
[68] Gunnarsson L, Asnafi N, Schedin E (1998) In-Process Control of Blank Holder Force in Axi-Symmetric Deep Drawing with Degressive Gas Springs. *Journal of Materials Processing Technology* 73(1):89–96.
[69] Halmos GT (2006) *Roll Forming Handbook*, Taylor and Francis, Boca Raton.
[70] Hamedona Z, Mori K, Abe Y (2014) In-Situ Measurement of Three-Dimensional Deformation Behaviour of Sheet and Tools During Stamping Using Borescope. *Journal of Materials Processing Technology* 214:945–950.
[71] Hao W, Duncan SR (2011) Optimization of Tool Trajectory for Incremental Sheet Forming Using Closed Loop Control. *IEEE International Conference on Automation Science and Engineering*, 779–784.
[72] Hardt D, Webb R (1982) Sheet Metal Die Forming Using Closed-Loop Shape Control. *CIRP Annals – Manufacturing Technology* 31(1):165–169.
[73] Heil H-P, Schütza A (1975) Einfluß von Sattelformen und -abmessungen auf die mechan. Eigenschaften von Freiformschmiedestücken. *Archiv Eisenhüttenwesen* 46(3):201–208.
[74] Hengelhaupt J, Häussermann M (2002, June) New Deep Drawing Tooling Concept. in Siegert K, (Ed.) *New Developments in Sheet Metal Forming 2002*, MAT-INFO Werkstoff-Informationsgesellschaft, Fellbach. Frankfurt/M..
[75] Henkelmann M (2009) *Entwicklung einer innovativen Kalibrierstrecke zur Erhöhung der Profilgenauigkeit bei der Verarbeitung von höher- und höchstfesten Stählen*, (Dissertation) PtU TU Darmstadt.
[76] Hermes M, Chatti S, Weinrich A, Tekkaya AE (2008) Three-Dimensional Bending of Profiles With Stress Superposition. *International Journal of Material Forming* 1:133–136.
[77] Hirt G, Ames J, Bambach M, Kopp R (2004) Forming Strategies and Process Modelling for CNC Incremental Sheet Forming. *Annals of the CIRP* 53(1):203–206.
[78] Hölker R, Jäger A, Ben Khalifa N, Tekkaya AE (2013) Controlling Heat Balance in Hot Aluminum Extrusion by Additive Manufactured Extrusion Dies with Conformal Cooling Channels. *International Journal of Precision Engineering and Manufacturing* 14(8):1487–1493.
[79] Huber JE, Fleck NA, Ashby MF (1997) The Selection of Mechanical Actuators Based on Performance Indices. *Proceedings of the Royal Society of London: Series A* 453:2185–2205.
[80] Husmann T, Magnus CS (2016) Thermography in Incremental Forming Processes at Elevated Temperatures. *Measurement* 77:16–28.
[81] Imai K, Koyama J, Jin Y (2008) High-Accuracy V-Bending System by Real Time Identifying Material Property. *Journal of Materials Processing Technology* 201–3:193–197.
[82] Imaninejad M, Subhash G, Loukus A (2005) Loading Path Optimization of Tube Hydroforming Process. *International Journal of Machine Tools and Manufacture* 45(12):1504–1514.
[83] Inamdar M, Date PP, Narasimhan K, Maiti SK, Singh UP (2000) Development of an Artificial Neural Network to Predict Springback in Air Vee Bending. *International Journal of Advanced Manufacturing Technology* 16:376–381.
[84] Ingvorsen J (2000) Closed-Loop Isothermal Extrusion. *Proceedings of the 7th International Aluminum Extrusion Technology Seminar*, Chicago, 549–557.
[85] Isermann R (2007) *Mechatronische Systeme, Issue 2*, Springer-Verlag, Darmstadt.
[86] Jansson M, Nilsson L, Simonsson K (2007) On Process Parameter Estimation for the Tube Hydroforming Process. *Journal of Materials Processing Technology* 190(1):1–11.
[87] Jenkouk V, Hirt G, Franzke M, Zhang T (2012) Finite Element Analysis of the Ring Rolling Process with Integrated Closed-Loop Control. *CIRP Annals – Manufacturing Technology* 61:267–270.
[88] Jeswiet J, Micari F, Hirt G, Bramley A, Duflou J, Allwood JM (2005) Asymmetric Single Point Incremental Forming of Sheet Metals. *Annals of CIRP* 54(2):623–650.
[89] Jiang Z, Wang G, Zhang Q, Ma D, Tang C, Wu G (1993) Shifting-Roll Profile and Control Characteristics. *Journal of Materials Processing Technology* 37(1–4):53–60.
[90] Jones EE (1989) Apparatus and method of compensating for springback in a workpiece. US Patent 4802357 A.
[91] Kim HS, Koc M (2008) Numerical Investigations on Springback Characteristics of Aluminum Sheet Metal Alloys in Warm Forming Conditions. *Journal of Materials Processing Technology* 204:370–383.
[92] Klaus K (1985) CVC Technology in Cold Rolling Mills. *Metallurgical Plant and Technology* 8(3):60–62.
[93] Kopp R, Stenzhorn F (1983) Zum Problem des Schließens von Hohlräumen beim Freiformschmieden – Ergebnisse aus Labor – und Betriebsversuchen. *Stahl und Eisen* 103(8):377–382.
[94] Kopp R, Koppers U, Wiegels H (1984) New Control System for Ring Rolling. *Advanced Technology of Plasticity* 2:803–807.
[95] Koppers U (2012) RMS – Ring Monitoring System. *1st International Conference on Ingot Casting, Rolling and Forging ICRF 2012*, 1–7.
[96] Koren Y (1997) Control of Machine Tools. *ASME Journal of Manufacturing Science and Engineering* 119:749–755.
[97] Koyama H, Wagoner R, Manabe K (2004) Blank Holding Force Control in Panel Stamping Process Using a Database and FEM-Assisted Intelligent Press Control System. *Journal of Materials Processing Technology* 152:190–196.
[98] Krishnan N, Cao J (2003) Estimation of Optimal Blank Holder Force Trajectories in Segmented Binders Using an ARMA Model. *Journal of Manufacturing Science and Engineering* 125(4):763–770.
[99] Kuboki T, Furugen M, Osaka S, Ono T (1998) Development of Die-Less Bending Process for Precision U-Bent Tube. *The 7th International Conference on Steel Rolling*, Chiba, 981–987.
[100] Kuboki T, Furuta H, Murakami S, Kuroda K (2000) Theoretical Analysis of Tandem Stand Rolling Using Three-Dimensional Finite Element Method. *Journal of the Japan Society for Technology of Plasticity* 41–476:701–705. (in Japanese).
[101] Leu DK, Hsieh CM (2008) The Influence of Coining Force on Springback Reduction in V-Die Bending Process. *Journal of Materials Processing Technology* 196:230–235.
[102] Li M-Z, Cai Z-Y, Liu C (2007) Flexible Manufacturing of Sheet Metal Parts Based on Digitized-Die. *Robotics and Computer-Integrated Manufacturing* 23:107–115.
[103] Li SH, Yang B, Zhang WG, Lin ZQ (2008) Loading Path Prediction for Tube Hydroforming Process Using a Fuzzy Control Strategy. *Materials and Design* 29(6):1110–1116.
[104] Liang SY, Hecker RL, Landers RG (2004) Machining Process Monitoring and Control: The State-of-the-Art. *Journal of Manufacturing Science and Engineering* 126:297–310.
[105] Lieb A (1992) *Minimierung von Formfehlern beim Ringwalzen*, RWTH Aachen, Stahl and Eisen Verlag, Düsseldorf.
[106] Liewald M, Blaich C (2009) Approaches for Closed-Loop Control and Optimization of Deep Drawing Processes. *Proceedings of the Ansys Conference and 27th CADFEM User's Meeting*, 18–22, Leipzig.
[107] Liewald M, Schiemann T, Mletzko C (2014) Automatically Controlled (Cold-) Forging Processes. *Procedia CIRP* 18:39–44.
[108] Linghu K-Z, He A-R, Yang Q, Zhao L, Guo XB (2008) Dynamic Decoupling for Combined Shape and Gauge Control System in Wide Strip Rolling Process. *Journal of Iron and Steel Research International* 15(2):28–31.

[109] Liu HM, Zhang XL, Wang YR (2005) Transfer Matrix Method of Flatness Control for Strip Mills. *Journal of Materials Processing Technology* 166(2):237–242.
[110] Ljung L (1999) *System Identification: Theory for the User*, 2nd ed. Prentice Hall, Upper Saddle River, NJ.
[111] Löbbe C, Hoppe C, Becker C, Tekkaya AE (2015) Closed loop springback control in progressive die bending by induction heating. *International Journal of Precision Engineering and Manufacturing* 16(12):2441–2449.
[112] Lu B, Chen J, Ou H, Cao J (2013) Feature-Based Tool Path Generation Approach for Incremental Sheet Forming Process. *Journal of Materials Processing Technology* 213:1221–1233.
[113] Lundbäck H, Sarnet J, Hagelberg G, Mauritzon T, Sondell J, Ödegård E (2004) Uniform Deformation in Open Die Forging by Optimized Pass Schedules and Bite-Shift. *ESAFORM2004*, Trondheim, Norge, 375–381.
[114] Mahabunphachai S, Koç M (2010) Investigations on Forming of Aluminum 5052 and 6061 Sheet Alloys at Warm Temperatures. *Materials and Design* 31(5):2422–2434.
[115] Mahayotsanun N, Sah S, Cao J, Peshkin M, Gao RX, Wang CT (2009) Tooling-Integrated Sensing Systems for Stamping Process Monitoring. *International Journal of Machine Tools and Manufacture* 49:634–644.
[116] Mainda P (2012) *Piezoelektrische Sensoren in Presswerkzeugen zur Beeinflussung desUmformprozesses*, (Dr. -Ing. thesis) Technische Universität Chemnitz. (in German).
[117] Malhotra R, Bhattacharya A, Kumar A, Reddy NV, Cao J (2011) A New Methodology for Multi-Pass Single Point Incremental Forming with Mixed Tool Paths. *Annals of CIRP* 60(1):323–326.
[118] Malik AS, Grandhi RV (2008) A Computational Method to Predict Strip Profile in Rolling Mills. *Journal of Materials Processing Technology* 206:263–274.
[119] Manabe K, Yang M, Yoshihara S (1998) Artificial Intelligence Identification of Process Parameters and Adaptive Control System for Deep-Drawing Process. *Journal of Materials Processing Technology* 80:421–426.
[120] Manabe K, Koyama H, Yoshihara S, Yagami T (2002) Development of a Combination Punch Speed and Blank-Holder Fuzzy Control System for the Deep-Drawing Process. *Journal of Materials Processing Technology* 125:440–445.
[121] Manabe K, Chen X, Kobayashi D, Tada K (2014) Development of In-Process Fuzzy Control System for T-Shape Tube Hydroforming. *Procedia Engineering* 81:2518–2523.
[122] Meier H, Buff B, Laurischkat R, Smukala V (2009) Increasing the Part Accuracy in Die-Less Robot-Based Incremental Sheet Metal Forming. *Annals of CIRP* 58(1):233–238.
[123] Meier H, Briselat J, Husmann T, Kreimeier D (2011) Online Measurement of Radial–Axial Rolled Rings with an Image Processing System. *Proceedings of the 18th International Forgemasters Meeting 2011*, 138–142.
[124] Moon YH, Kang SS, Cho JR, Kim TG (2003) Effect of Tool Temperature on the Reduction of the Springback of Aluminum Sheets. *Journal of Materials Processing Technology* 132:365–368.
[125] Müller R (2007) *Simulation und Verifizierung technologierelevanter Blechwerkstoffeigenschaften*, (Dr. -Ing. thesis) Technische Universität Dresden .. (in German).
[126] Murata M, Ohashi N, Suzuki H (1989) New Flexible Penetration Bending of a Tube: 1st Report, a Study of MOS Bending Method. *Transactions of the Japan Society of Mechanical Engineers Series C* 55–517:2488–2492. (in Japanese).
[127] Music O, Allwood JM (2012) The Use of Spatial Impulse Responses to Characterise Flexible Forming Processes With Mobile Tools. *Journal of Materials Processing Technology* 212:1139–1156.
[128] Nakajima K, Asamura T, Kikuma T, Matsumoto H, Awazuhara H, Kimura T, Shida S, Kajiwara T (1984) Hot Strip Crown Control by Six-high Mill. *Transactions of the Iron and Steel Institute of Japan* 24:284–291.
[129] Narayanasamy R, Padmanabhan P (2012) Comparison of Regression and Artificial Neural Network Model for the Prediction of Springback During Air Bending Process of Interstitial Free Steel Sheet. *Journal of Intelligent Manufacturing* 23:357–364.
[130] Neugebauer R, Drossel W-G, Mainda P, Roscher H-J, Wolf K, Kroschk M (2011) Sensitivity Analysis of Eddy Current Sensors Using Computational Simulation. *Proceedings of the Symposium Progress in Electromagnetics Research*, 450–454.
[131] Noguchi Y, Baba K, Ogai H, Oka T, Ishii H, Baba M (2001) Strip Width Control Using Strip Tension of Hot Strip Finishing Mill. *Journal of the Japan Society for Technology of Plasticity* 42–480:70–74. (in Japanese).
[132] Obermeyer EJ, Majlessi SA (1998) A Review of Recent Advances in the Application of Blank-Holder Force Towards Improving the Forming Limits of Sheet Metal Parts. *Journal of Materials Processing Technology* 75(1):222–234.
[133] Osakada K (2010) History of Plasticity and Metal Forming Analysis. *Journal of Materials Processing Technology* 210:1436–1454.
[134] Osakada K, Mori K, Altan T, Groche P (2011) Mechanical Servo Press Technology for Metal Forming. *CIRP Annals – Manufacturing Technology* 60(2):651–672.
[135] Pandit M, Buchheit K (1995) Isothermes Strangpressen von Aluminium, Teil II. *ALUMINIUM, 71. Jahrgang, 4*, 614–619.
[136] Pandit M, Buchheit KH (1999) Optimizing Iterative Learning Control of Cyclic Production Processes with Application to Extruders. *Control Systems Technology IEEE Transactions on* 7(3):382–390.
[137] Pandit M, Baqué S, Deis W, Müller K (2000) Implementation of Temperature Measurement and Control in Aluminum Extruders. *Proceedings of the 7th International Aluminum Extrusion Technology Seminar (ET2000)*, Chicago, USA, 387–395.
[138] Park CJ (2012) Dynamic Temperature Control with Variable Heat Flux for High Strength Steel. *International Journal of Control Automation and Systems* 10(3):659–665.
[139] Park HJ, Cho HS (1992) A Fuzzy Rule-Based Iterative Learning Control Method with Application to Hydroforming Processes. *Mechatronics* 2(6):577–593.
[140] Park CJ, Yoon KS, Lee CH (2010) Advanced Temperature Control of High Carbon Steel for Hot Strip Mills. *Journal of Mechanical Science and Technology* 24(5):1011–1017.
[141] Peng L-G, Liu X-G, Zhao X-M, Wu D (2014) Mathematic Modelling on Flexible Cooling System in Hot Strip Mill. *Journal of Central South University* 21:43–49.
[142] Polyblank JA (2015) *The Mechanics and Control of Flexible Asymmetric Spinning*, (PhD thesis) University of Cambridge .. Available for download at: www.repository.cam.ac.uk/handle/1810/247395.
[143] Polyblank JA, Allwood JM (2015) Parametric Toolpath Design in Metal Spinning. *CIRP Annals – Manufacturing Technology* 64:301–304.
[144] Polyblank JA, Allwood JM, Duncan SR (2014) Closed-Loop Control of Product Properties in Metal Forming: A Review and Prospectus. *Journal of Materials Processing Technology* 214:2333–2348.
[145] Qian DS, Peng YY (2015) Effects of Forming Parameters on Coupled Thermo-mechanical Behaviours in Combined Ring Rolling. *Ironmaking and Steelmaking* 42(6):471–480.
[146] Ray P, Mac Donald BJ (2004) Determination of the Optimal Load Path for Tube Hydroforming Processes Using a Fuzzy Load Control Algorithm and Finite Element Analysis. *Finite Elements in Analysis and Design* 41(2):173–192.
[147] Rech R, Müller N, Lamm R, Kirchhoff S (2007) Einsatz von Lasermesstechnik (LaCam Forge) an Freiformschmiedepressen. *22. ASK, Aachen*.
[148] Recker D, Franzke M, Hirt G (2011) Fast Models for On-Line-Optimization During Open Die Forging. *CIRP Annals – Manufacturing Technology* 60(1):295–298.
[149] Rosenstock D, Recker D, Franzke M, Hirt G, Sommler D, Steingießer K-J, Tewes A, Rech R, Gehrmann B, Kirchhoff S, Lamm R (2014) On-Line Visualization During Open Die Forging and Optimization of Pass Schedules. *Steel Research International* 1–7.
[150] Rosenthal D (1988) CVC Technology on Hot and Cold Strip Rolling Mills. *Revue de Metallurgie - Cahiers d'Information Techniques* 85(7):597–606.
[151] Sarnet J, Wedin E, Furuberg J (2008) Experience from the Capturing, Analyzing, and Presenting of the Heating and Forging Processes at Scana Steel Björneborg AB. *17th International Forgemasters Meeting*, Santander, Spain.
[152] Schiemann T, Liewald M, Beiermeister C, Till M (2014) Influence of Process Chain on Fold Formation during Flange Upsetting of Tubular Cold Forged Parts. *Procedia Engineering* 81:352–357.
[153] Schrewe H (1987) *Stranggießen von Stahl – Einführung und Grundlagen*, Verlag Stahleisen mbH, Düsseldorf. ISBN 3-514-00347-5.
[154] Sellars CM, Whiteman JA (1979) Recrystallization and Grain Growth in Hot Rolling. *Metal Science* 13:187–194.
[155] Sheppard T, Roberts JM (1973) Shape Control and Correction in Strip and Sheet. *International Metallurgical Reviews* 18(1):1–18.
[156] Shieh J, Huber JE, Fleck NA, Ashby MF (2001) The Selection of Sensors. *Progress in Materials Science* 46:461–504.
[157] Shim HB, Kim KH (2011) Springback Correction of Stamped, Curved U-Channel Part by Laser Bending. *Journal of Engineering Manufacture* 225(3):367–376.
[158] Shimada N, Tomizawa A, Kubota H, Mori H, Hara M, Kuwayama S (2014) Development of Three-Dimensional Hot Bending and Direct Quench Technology. *Procedia Engineering* 81:2267–2272.
[159] Shinkawa M, Utsunomiya H, Saito Y, Oka K, Shimaya F (2001) Elongation–Control Effects in Rolling of Flat Wire from Round Wire-Development of Elongation–Control Rolling II. *Japan Society for Technology of Plasticity* 42–481:134–138. (in Japanese).
[160] Shohet KN, Townsend NA (1968) Roll-Bending Methods of Crown Control in Four-High Plate Mills. *Journal of the Iron and Steel Institute* 206(11):1088–1098.
[161] Siegert K, Doege E (1993) CNC Hydraulic Multipoint Blankholder System for Sheet Metal Forming Presses. *CIRP Annals – Manufacturing Technology* 42(1):319–322.
[162] Siegert K, Ziegler M, Wagner S (1997) Closed Loop Control of the Friction Force. Deep Drawing Process. *Journal of Materials Processing Technology* 71(1):126–133.
[163] Siegert K, Häussermann M, Haller D, Wagner S, Ziegler M (2000) Tendencies in Presses and Dies for Sheet Metal Forming Processes. *Journal of Materials Processing Technology* 98(2):259–264.
[164] Siemer E (1987) *Qualitätsoptimierende Prozesssteuerung des Reckschmiedens Dissertation*, RWTH Aachen.
[165] Singh AP, Sharma M, Sing I (2013) A Review of Modeling and Control During Drilling of fiber Reinforced Plastic Composites. *Composites: Part B* 47:118–125.
[166] Snoeys R, Dauw DF, Kruth JP (1983) Survey of Adaptive Control in Electro-Discharge Machining. *Journal of Manufacturing Systems* 2(2):147–163.
[167] Soderstrom T, Stoica P (1989) *System Identification*, Prentice-Hall, London, UK.
[168] Spooner PD, Bryant GF (1976) Analysis of Shape and Discussion of Problems of Scheduling Set-Up and Shape Control. *The Metals Society Conference on Shape Control*, London, 19–29.
[169] Srinivasan K, Tsao TC (1997) Machine Tool Feed Drives and Their Control: A Survey of the State of the Art. *ASME Journal of Manufacturing Science and Engineering* 119:743–748.
[170] Storbeck M, Beiter P, Berner S, Brenneis M, Schmitt W, Groche P (2013) Lightweight Products by Load Optimized Profile Design. *Future Trends in Production Engineering*, Springer-Verlag: 161–179.
[171] Sunseri M, Cao J, Karafillis AP, Boyce M (1996) Accomodation of Springback Error in Channel Forming Using Active Binder Force Control: Numerical Simulation and Experiments. *ASME Journal of Engineering Materials and Technology* 118:426–435.
[172] Takahashi R (2001) Review. State of the Art in Hot Rolling Process Control. *Control Engineering Practice* 9(9):987–993.

[173] Takeda Y, Xiao X, Hirose K, Yoshida Y, Ichiryu K (2010) Kinematic Analysis and Design of 3-Rpsr Parallel Mechanism with Triple Revolute Joints on the Base. *Journal of Automation Technology* 4:346–354.
[174] Tan Z, Persson B, Magnusson C (1992) An Empiric Model for Controlling Springback in V-Die Bending of Sheet Metals. *Journal of Materials Processing Technology* 34:449–455.
[175] Tapia G, Elwany A (2014) A Review on Process Monitoring and Control in Metal-Based Additive Manufacturing. *ASME Journal of Manufacturing Science and Engineering* 136. 060801-1-10.
[176] Tateno J, Kohiro Y, Katsura S, Kitahama M, Hangai Y (2003) Flatness Control of Complex Buckling in 12-High Cluster Mill Using One-End Tapered Work Roll Shifting Method-Advanced Control of Strip Flatness in Hard Steel Rolling. *Journal of the Japan Society for Technology of Plasticity* 44–513:1044–1048. (in Japanese).
[177] Tekkaya AE, Allwood JM, Bariani PF, Bruschi S, Cao J, Gramlich S, Groche P, Hirt G, Ishikawa T, Löbbe C, Lueg-Althoff J, Merklein M, Misiolek WZ, Pietrzyk M, Shivpuri R, Yanagimoto J (2015) Metal Forming Beyond Shaping: Predicting and Setting Product Properties. *Annals of CIRP* 64(2):629–653.
[178] Thamm U (1998) *Bewertung von Tiefziehprozessen durch Infrarot-Thermografie*, (Dr. -Ing. thesis) Technische Universität Chemnitz.. (in German).
[179] Thipprakmas S, Phanitwong W (2011) Process Parameter Design of Spring-Back and Spring-Go in V-Bending Process Using Taguchi Technique. *Materials and Design* 32:4430–4436.
[180] Tozawa Y, Ishikawa T, Iwata N (1982) Improved Three-Dimensional Analysis for Strip Rolling – Analytical Study on Three Dimensional Deformation in Strip Rolling V. *International Journal of the Japan Society for Technology of Plasticity* 23:1181–1187.
[181] Traversin M, Kergen R (1995) Closed-Loop Control of the Blank-Holder Force in Deep-Drawing: Finite-Element Modelling of its Effects and Advantages. *Journal of Materials Processing Technology* 50(1):306–317.
[182] Trompeter M, Önder E, Homberg W, Tekkaya AE, Kleiner M (2005) Material Flow Control in High Pressure Sheet Metal Forming of Large Area Parts. *Steel Research International* 76(12):905–910.
[183] van den Boogaard T, Hol J, Meinders T (2015) *Advanced Local Friction Modelling for Forming Simulations, Simulation in Metal Forming 2015, Dortmund*.
[184] van den Boogaard T, Havinga J, van Tijum R (2015) Model-Based Control of Strip Bending in Mass Production. *Annals of CIRP* 64(1):297–300.
[185] Viswanathan V, Kinsey BL, Cao J (2003) Experimental Implementation of Neural Network Springback Control for Sheet Metal Forming. *ASME Journal of Engineering Materials and Technology* 125:141–147.
[186] Waltl H (2009) Werkzeugsysteme der Zukunft – Anforderungen und Lösungsansätze aus der Sicht der Marke Volkswagen. *Proceedings of the 3rd ICAFT and 16th SFU*, 9–16.
[187] Wang C, Kinzel G, Altan T (1993) Mathematical Modeling of Plane-Strain Bending of Sheet and Plate. *Journal of Materials Processing Technology* 39:279–304.
[188] Wang J, Verma S, Alexander R, Gau J-T (2008) Springback Control of Sheet Metal Air Bending Process. *Journal of Manufacturing Processes* 10:21–27.
[189] Wang PF, Peng Y, Liu HM, Zhang DH, Wang JS (2013) Actuator Efficiency Adaptive Flatness Control Model and its Application in 1250 mm Reversible Cold Strip Mill. *Journal of Iron and Steel Research International* 20(6):13–20.
[190] Wang G, Kuboki T, Watanabe M, Tsuchiya A (2015) Effect of mandrel position in draw bending of copper tube. *Tubehydro 2015*, Xi'an, China, 273–280.
[191] Wang C, Geijselaers HJM, Omerspahic E, Recina V, van den Boogaard AH (2016) Influence of Ring Growth Rate on Damage Development in Hot Ring Rolling. *Journal of Materials Processing Technology* 227:268–280.
[192] Weinzierl K, Löffler HU, Rößiger M (2011) Comprehensive Strip Temperature and Microstructure Control revolutionizes Hot Strip Mill Automation. *AISTech – Iron and Steel Technology Conference Proceedings 2011*, 1051–1059.
[193] Wellstead PE, Zarrop MB (1991) *Self-Tuning Systems: Control and Signal Processing*, Wiley, Chichester, UK.
[194] Wu-rong W, Guan-long C, Zhong-qin L (2010) The Effect of Binder Layouts on the Sheet Metal Formability in the Stamping with Variable Blank Holder Force. *Journal of Materials Processing Technology* 210(10):1378–1385.
[195] Xie HB, Jiang ZY, Liu XH, Wang GD, Tieu AK, Yang M, Manabe K (2007) Application of Fuzzy Control of Laminar Cooling for Hot Rolled Strip. *Journal of Materials Processing Technology* 187–188:715–719.
[196] Yagami T, Manabe K, Yang M, Koyama H (2004) Development of Intelligent Forming Simulator with Segment Blank Holder Modules. *Journal of Materials Processing Technology* 155–156:2099–2105.
[197] Yan Z, Xu D, Li Y, Tan M, Zhao Z (2007) A Survey of the Sensing and Control Techniques for Robotic arc Welding. *Measurement and Control* 40(5): 146–150.
[198] Yang DY, Noh TS (1990) An Analysis of Hydroforming of Longitudinally Curved Boxes with Regular Polygonal Cross-Section. *International Journal of Mechanical Sciences* 32(11):877–890.
[199] Yang M, Manabe K, Nishimura H (1996) Development of Real-Time Process Control System for Precision and Flexible V-Bending with an On-Line Database. *Journal of Materials Processing Technology* 760(1–4):249–254.
[200] Yang M, Manabe K, Nishimura H (1998) Development of an Intelligent Tool System for Flexible L-Bending Process of Metal Sheets. *Smart Materials and Structures* 7:530–536.
[201] Yoneyama T (1999) Development of a New Pressure Sensor and its Application to the Measurement of Contacting Stress in Extrusion. *Journal of Materials Processing Technology* 95(1–3):71–77.
[202] Yuan SJ, Cui X-L, Wang X-S (2015) Investigation into Wrinkling Behavior of Thin-Walled 5A02 Aluminum Alloy Tubes Under Internal and External Pressure. *International Journal of Mechanical Sciences* 92:245–258.
[203] Zhao J, Cao HQ, Ma LX, Wang FQ, Li SB (2004) Study on Intelligent Control Technology for the Deep Drawing of an Axi-Symmetric Shell Part. *Journal of Materials Processing Technology* 151(1):98–104.
[204] Zhong-qin L, Wu-rong W, Guan-long C (2007) A New Strategy to Optimize Variable Blank Holder Force Towards Improving the Forming Limits of Aluminum Sheet Metal Forming. *Journal of Materials Processing Technology* 183(2):339–346.
[205] Zhu S, Yang H, Guo L, Hu L, Chen X (2014) Research on the Effects of Coordinate Deformation on Radial–Axial Ring Rolling Process by FE Simulation Based on In-Process Control. *International Journal of Advanced Manufacturing Technology* 72:57–68.