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Closed-loop control of product properties in metal forming

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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.

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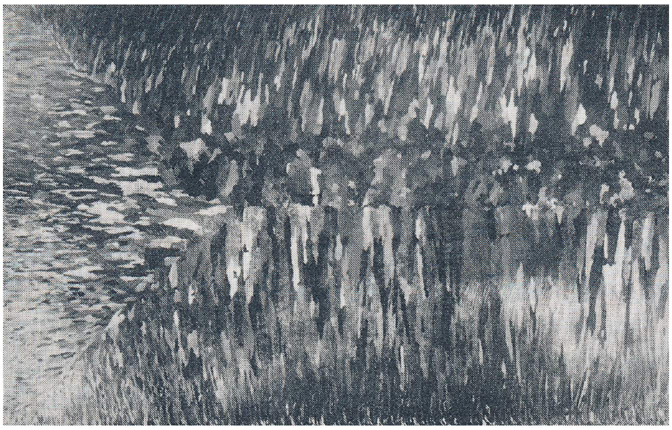

Fig. 1. Uncertainties related to the material: grain size distributions in cast steel. From [153], p120.

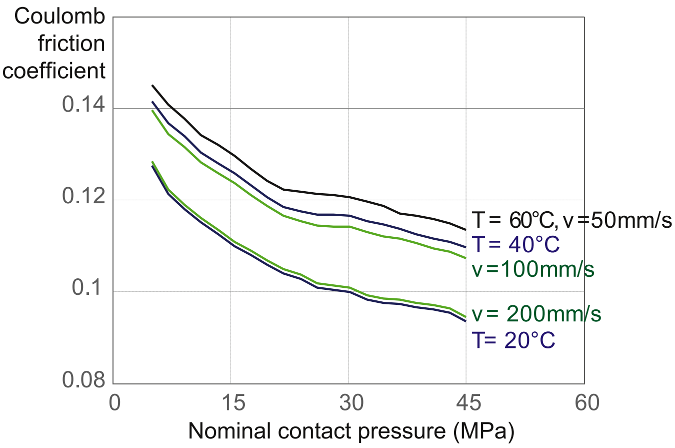

Fig. 2. Variation of friction coefficient with temperature and speed during a strip drawing test [183].

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.

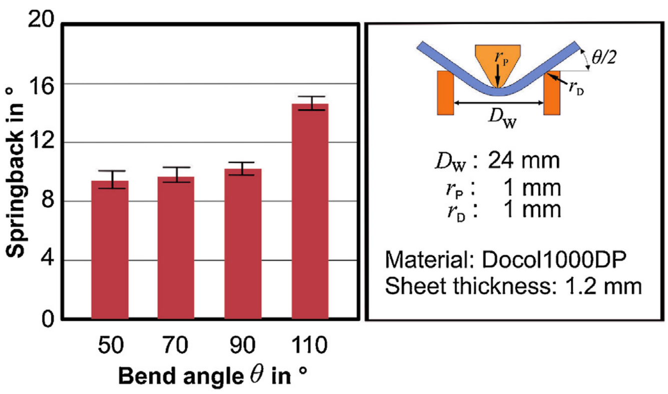

Fig. 3. Variation in springback during the air bending of sheets of the high-strength steel Docol100DP to different bend angles [49].

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, **u**. Any errors in the model, Δ, will influence the schedule and degrade the product state, **z**. However, even were the process model perfect, un-modelled disturbances, **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