CIRP Journal of Manufacturing Science and Technology 1 (2008) 2–17

Contents lists available at ScienceDirect

CIRP Journal of Manufacturing Science and Technology

journal homepage: www.elsevier.com/locate/cirpj

Review

Metal forming progress since 2000

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ARTICLE INFO

Keyword:
Metal forming

ABSTRACT

Considerable changes have occurred in metal forming in the last decade. A record of these changes can be found in keynote papers presented by the members of the Scientific Technical Committee—Forming, at the CIRP Annual General Meeting each year. The keynote papers are excellent references on important developments in metal forming and are used as a reference, globally. Not only is this paper a compendium of most of the keynotes presented, but from 2001 onward, it has updates on new information on five keynote subject areas. The authors of each keynote have written an update with new information that has developed since the writing of the keynote. The authors of each section are shown in order of presentation.

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1755-5817/$ – see front matter © 2008 CIRP.
doi:10.1016/j.cirpj.2008.06.005

1. Introduction

Metal Forming has played a central role as societies have developed. Groche et al [1] show bulk metal forming has played a significant role in manufacturing development. With the advent of the industrial revolution many changes occurred [2]:

- the “vital revolution”, which was the product of advances in European agriculture, enabled larger populations to be fed;
- there was a dramatic population increase due to the ability to feed larger populations;
- industrialization became widespread, causing urbanization.

Until the industrial revolution, manufacturing was done at a job-shop level, but with advent of new power sources, came the ability to manufacture on a larger scale. Innovation and automation steadily increased with a concomitant increase in the complexity of products. This trend can be observed in Fig. 1, which shows increasing complexity of products since the industrial revolution [3].

The rate at which production increased, including metal forming, can be extracted from Fig. 1.

A specific example of the rate of production increase is illustrated by the following example of gunsmithing, which was a craft-bound cottage industry before the industrial revolution [4]. In 1848, the inventor of the breech-loading Needle-gun rifle, Johann Nickolas von Dreyse was only able to produce 10,000 rifles per year, although demand was much higher. When the rifle was finally used in 1866, it had required 26 years to make 300,000 [5]. As O’Connell [4] states, “clearly something had to be done to speed production”.

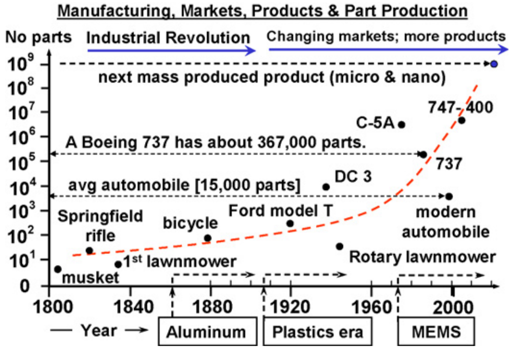

Fig. 1. The increase in complexity of parts from the industrial revolution onward [3].

From 1820 to 1850, metal forming, machining and standardization were improved to such an extent that Samuel Colt could demonstrate the interchangeability of his revolvers in 1851 [6,7] and by 1870 the ability to manufacture at high production rates had increased by orders of magnitude.

The foregoing was the result of changes in manufacturing and metal forming.

1.1. *CIRP metal forming keynotes*

Many significant advances have been made in metal forming and these advances are often subjects of keynotes in the Annals of CIRP. The STC F keynote papers are excellent references on important developments in metal forming and are used as a reference, globally. This paper is a collection of selected keynotes presented at the Scientific Technical Committee—Forming, from 2001 onward, with updates on new information in each keynote subject area. For each keynote selected, one of the authors has written an update with new information that has developed since the writing of the keynote.

The 2001 keynote on Microforming by Geiger et al [8] is an appropriate place to start. Microforming can be placed, approximately, at the year 2000 with respect to complexity and number of parts in Fig. 1, and as predicted [3] the ability to microform on a massive scale will likely lead to an increase in part complexity in the future.

2. Microforming

2.1. *Introduction*

Since the CIRP 2001 keynote paper “Microforming” [8], the trend towards further miniaturisation has been unabated as is the demand for high volume production of small metal parts needed for miniaturized products. Following this keynote several review articles focusing on microforming have been published [9–14]. As a concluding remark of the 2001 keynote paper, innovative tool manufacturing and new concepts for machine tools in general were identified by the authors to be the key factors for industrialization of microforming technology. The relevance of this conclusion is underlined by the initiation of many activities. These have been at a national level (e.g. Priority Programme "Process Scaling" 2002–2008 [15,16] and establishment of a collaborative research centre SFB 747 "Micro Cold Forming" 2007 [17], both funded by the German research foundation), on a European level (e.g. Network of Excellence 4M [18], Integrated Project MASMICRO [19], and EUREKA FACTORY Micrometal [20]), and at the international level (e.g. US-WTEC-Study [21]), all having a direct or a collateral relation to microforming.

In this chapter the most relevant developments in the field of microforming since the keynote paper are discussed in comparison to the state of the art in 2001.

2.2. Problems in the microworld

For a better understanding of the effects that occur with miniaturisation, four main groups in microforming systems were considered individually [8]: material, processes, tools and machine tools, and equipment. This systematic approach was and is the basis for investigating and identifying the so-called size effects, which in some way directly or indirectly are present in all the four groups, and which are commonly accepted as the reason why the knowledge of conventional (macro) forming technology cannot be simply transferred to micro-application. The sources of the size effects that occur have been subdivided by [16] into physical (e.g. ratio of surface to volume) and structural (e.g. surface structure scalability) sources. Both these approaches, including the use of scaled experiments, mostly use the theory of similarity, yet still represent the frame of all the ongoing research targeting to an improved understanding of the specific "microworld"-phenomena, and how to get them under control for a reliable process design and realization of effective microforming processes.

2.3. Basic research—effects of miniaturisation

2.3.1. Material

Regarding the material, substantial progress has been made, in particular, in the field of simulation based description of size dependent forming behaviour. In 2001, the decrease in flow stress with miniaturisation could be explained by the surface layer model. Based on that surface layer model, a mesoscopic model has been developed and refined in several steps [12,22–24] assigning individual properties to the grains within the specimen. By applying the mesoscopic model to FE-simulation, essential phenomena of microforming can be predicted, i.e. process scatter and the influence of material structure on the process results. Quite another approach, starting from a crystal plasticity-based analysis, is given in Ref. [25].

The paradox of increasing bending forces with decreasing specimen size (according to the surface layer the contrary is expected), once the ratio of sheet thickness to grain size reaches the range of 1 or smaller, described in 2001, led to several investigations that aimed to explain this finding. An explanation for this phenomenon is given by the theory of strain gradient plasticity [26]. In fundamental considerations a direct relation between the strain gradient and the density of dislocations, and thus the material strength, has been pointed out [27,28]. However, the influence of strain gradients on the forming behaviour has been verified only by few experiments, e.g. torsion and hardness measurements, but also by the analysis of spring-back in dependence of foil thickness in case of thin metal sheets [29]. A method for the experimental determination of the quantitative contribution of the strain gradient on the material strengthening is proposed by Ref. [30].

Huge progress also has been made in the field of mechanical material characterisation for microforming processes in particular for micro-sheet metal forming. Due to the small elongation to fracture, the mechanical characterisation by tensile testing is limited in case of thin metal sheets. Getting to larger strains, hydraulic [31] and aero [32] bulge test have been successfully applied for the determination of the size dependent material flow curve and for derived quantities like the strain hardening exponent of thin metal foils with minimum thicknesses of 25 and 10 μm, respectively.

Further investigations in the field of bulk metal forming addressed strain rate and size dependent material behaviour at high strain rates [33] and for W/Cu at different temperatures [34].

2.3.2. Friction

Since a significant size effect regarding friction has been identified in fundamental research, the tribological conditions have been addressed by several investigations in the last few years. A detailed discussion of tribology in microforming is given in Ref. [35]. The model of open and closed lubricant pockets (mechanical rheological model) as already cited in Ref. [8] is still the fundamental model used for the description of the tribological condition and its impact on microforming processes. Since the real contact area is predominant for tribology in microforming, the evolution of the submicron topography during forming is of paramount interest and subject of current research [36].

Further work focussed on the investigation of process specific friction conditions. While in Refs. [37,38], the size effect on friction conditions in micro-extrusion processes was studied, [39] developed a strip drawing method allowing the determination of friction parameters for micro-deep drawing. The objective is to develop a size-dependent friction function for the integration into FEM-simulation [40]. The size effects on friction of micro-strip rolling was investigated by Ref. [41] using a rolling and plane strain compression testing. In Ref. [42] it is shown, that WC-C coatings are capable of preventing aluminium transfer to carbide forming tools.

2.4. Applied research on microforming processes

2.4.1. Cold forging

Following the identification of various size effects influencing micro-extrusion processes, as described in Ref. [8], there has been considerable effort to achieve reliable forming results in microforming processes.

Examples of industrial micro-components manufactured by microforming technology can be found in Ref. [43], where a micropart consisting of seven different diameters (minimum diameter 0.6 mm), and a non-symmetrical geometry at the top is produced. Using Zr-based metallic glass micro-dies, a micro-gear with 1 μm in diameter was manufactured [44]. Also, in an innovative forming concept, a floating die which reduced process forces and increased die filling for forming of micro-gears was introduced [45]. Other approaches aim for minimization of size effects by shifting the temperatures close to warm forging conditions [46,47]. It has been found, that forming at elevated temperatures leads to a distinct decrease of scatter in forming forces, shape evolution and geometrical accuracy. Investigations into the influence of temperature on the forming behaviour of titanium at the micro-scale [48], revealed no significant impact on the process scatter, however a positive one on the increase of formability, which is poor at room temperature, was observed. In Ref. [49], an industrial demonstration for dental purposes is manufactured by microforming at an elevated temperature.

2.4.2. Embossing/coining

Coining processes also play an important role for the microscopic structuring of macroscopic products. Recent developments can be found in the fields of micro-fluidics, micro-optics, micro-electronics and micro-reactors. These were identified in the 2001 keynote paper [8] as the most promising areas. In micro-fluidic technology, however, the structured materials mostly are polymers which are embossed by metal tools. Regarding the field of optical technologies, the hot embossing process is applied in the production of micro-lens arrays using bulk metallic glasses in Ref. [50]. In Ref. [44], the large potential of metallic glasses for nanoimprinting is demonstrated by coining 500 nm logo characters in Pt-based metallic glass.

The optimization of general conditions for micro-coining processes in metal was done by Ref. [51] by applying a new coining tool design for the production of micro-channel and rib structures and reducing, e.g. inhomogeneous rib formation. The influence of grain size on the rib formation in micro-coining processes was investigated in Ref. [52] by coining ribs with 40 μm in width in pure aluminium, with different mean grain sizes.

2.4.3. Extrusion

In micro-extrusion, the trend towards the application of innovative material continues. In 2001, first experiments with amorphous alloys were reported. Recent investigations are focussed on ultra fine-grained material with its outstanding mechanical properties. In Ref. [53], the influence on grain size on shape evolution in micro-extrusion processes was evaluated. A comparison of backward extrusion of coarse grained and ultra fine-grained material was done in Ref. [54] by preliminary trials of micro-extrusion of a cylindrical cup. The production of high strength magnesium micro-gears by micro-extrusion was accomplished by Ref. [55] using ECAP processed magnesium. In Ref. [56] an innovative method of sheet extrusion is presented for the fabrication of micro-billets.

2.4.4. Blanking and punching

Blanking and punching are well-established sheet metal forming industrial processes. As presented in Ref. [8], the limits of blanking processes are reached, when lead frame production is considered. Due to ongoing miniaturisation the required dimensions (e.g. pitch) decrease and, correspondingly, the accuracy demanded is increasing leading to the development of innovative blanking processes such as dam-bar cutting. Continued research on the cutting of thin bars has been done extensively by [57], including the evaluation of the cross-section of a bar with widths between 60 and 80 μm for different materials. In Ref. [58], the influence of the ratio between punch width and sheet thickness on the strain distribution in the forming area and the material flow next to the cutting edge is discussed. A tool for the simulation of blanking operations of thin sheets and the prediction of geometrical and mechanical characteristics is proposed in Ref. [59].

2.4.5. Bending

An important factor for the accuracy of bending processes is the spring back that is significantly influenced by size effects [8]. Thus recent research has been done with the aim of enhancing the understanding of relevant size effects and to improve process accuracy.

The spring back behaviour of thin brass sheets with a minimum thickness of 290 μm was investigated in Ref. [60] by three point bending experiments. In Ref. [29], the contrary influence of the strain gradient and the surface grains on the spring back behaviour of thin metal foils with thicknesses ranging from 25 to 500 μm is discussed. In the field of laser bending the influence of size effects on laser induced deformation is experimentally, numerically and analytically investigated in Ref. [61].

As a further important factor for bending accuracy the strain distribution in the forming area was determined using an optical measurement system by Ref. [57].

2.4.6. Deep drawing

In 2001, only few investigations on micro-deep drawing had been published, this process has since been studied intensively using fundamental scaled experiments by several investigators [9,62,63]. An approach for thermo-mechanically coupled FE-simulation of micro-deep drawing processes is presented in Ref. [64].

To overcome difficulties in the deep drawing of very thin metal foils, new concepts for deep drawing processes were investigated. An improvement in formability as well as shape and dimensional accuracy has been achieved [65] by using an auxiliary metal punch together with a polyurethane ring and in Ref. [66] by using auxiliary sheets and a resin die. Another approach, using hot isostatic pressing to form micro-channels from ultra thin foils, is described in [67]. In Ref. [68] mechanical micro-deep drawing is compared with a new laser deep drawing technology by generating shock waves.

2.5. Machine tool, tools and handling

As discussed in the 2001 keynote paper, there are two strategies for designing tool and machine systems for microforming processes that are still pursued: scaling down from conventional length scale or by development of new concepts for tools and machines. An example for the former strategy is the BSTA-press series of Bruderer with a counter balance system [69]. In the field of new machine tool and tooling concepts, several new approaches have been made. Whereas the piezo-electric drive, e.g. applied in Ref. [45], due to its limited stroke of less than 1mm will be restricted to only specific fields of application, the electromagnetic direct drive, first investigated by [70], seems to be promising in a more general way. Technical/laboratory solutions are described in Refs. [71,72]. With respect to tool design, Ref. [73] presents a flexible tool system for cold forging of micro-parts, and strategies regarding the design and manufacturing of tools for bulk metal microforming are discussed in Ref. [74] using an example micro-component. Considerable progress has been made regarding tool manufacturing by electrical discharge machining. The current potential of EDM-technology is discussed in Ref. [75]. An alternative is cutting technology; its state of the art and compared to micro-EDM and other energy-assisted processes are reviewed in Refs. [76,77], respectively. A recent review of existing systems for handling of micro-parts can be found in Ref. [78].

2.6. Summary

A brief survey of recent developments in microforming has been given in comparison to the state of the art in 2001. Although brief, this section in microforming shows that since 2000 many activities and innovative ideas have been initiated encouraging the microforming community to continue. Progress has been made towards the industrial application of microforming technology, however the final breakthrough must still be made. There are many laboratory and prototype examples and a few industrial microforming process chains have been realized, indicating the potential for cost effective, large quantity microforming production technology systems.

3. Manuacturing of lightweight components by metal forming

In modern transportation engineering, the application of lightweight components is a central challenge. Due to economics,

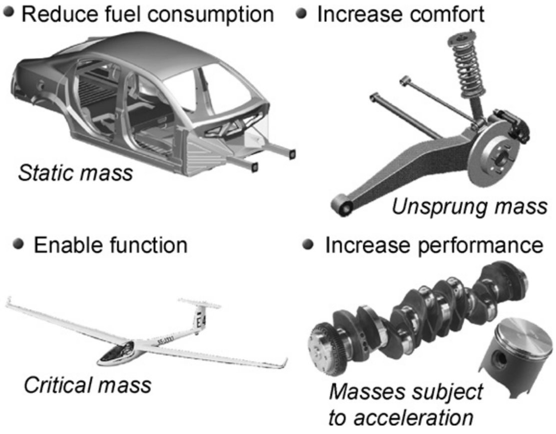

Fig. 2. Purpose of lightweight components.

ecological reasons and improving product properties, mass reduction is necessary. This involves approaches from different engineering disciplines. Therefore, lightweight construction can be defined as an integrative construction technique using all available means from the field of design, material science, and manufacturing, combined to reduce the mass of a whole structure and its single elements while at the same time the increasing the functionality.

Lightweight construction is crucial where mass is critical to enable the product function, such as aeronautical applications. Where masses are subject to acceleration, lightweight components can increase the product performance, e.g. allow higher revolutions with lighter crankshafts. Driving comfort and safety can be increased when unsprung masses are reduced as in a car chassis. Reducing masses also improves the fuel consumption.

Much effort is being put into the development of lightweight components and structures in automotive applications (Fig. 2). In these fields, lightweight construction deals first, with the use of light materials and secondly, with different design strategies. Concerning the body structure of trains or cars, frame and shell structures can be differentiated. Both design strategies are commonly linked to a specific material: aluminium in the case of frame structures [79], steel in the case of shell structures [80]. Therefore, different manufacturing demands arise using different design strategies [81,82].

Design, choice of material, and manufacturing technology are closely related. In the case of large-scale production, especially for automotive applications, metal forming provides possibilities for the cost effective manufacture of lightweight components and structures. Advantages like work hardening and load adjusted material orientation offer additional potential for lightweight constructions.

3.1. Forming lightweight materials

In a material based approach to the manufacture of lightweight components, the use of light metals – keeping the same workpiece geometry – reduces the component's weight. Although the density of aluminium is a third that of steel, aluminium has only a third of the strength and tensile modulus. As the use of light metals must not decrease product properties such as strength, specific material properties must be taken into account.

The tensile modulus is metal dependent and cannot be changed by alloys or grades. An increase in specific stiffness (tensile modulus/density), as needed, e.g. for structural automotive applications, can therefore only be achieved with larger hollow cross-sections. The strength to weight ratio of some high strength steels (HSS), in particular stainless steel, make them excellent lightweight construction materials compared to some aluminium alloys. Depending on the actual alloy and grade, steel and aluminium are likewise 'light metals' as well as magnesium and titanium. In addition, compound materials like metal matrix composites (MMC) provide means for ultra lightweight components.

Unfortunately, progress in alloy development in terms of higher strength always results in lower nominal strain at fracture thus limiting their formability [83]. As a consequence, high strength alloys necessitate higher forces in forming operations as well as more rigid presses and more wear resistant tools. The latter can be achieved by ceramic inserts for forging [84] or deep drawing operations [85], for example.

At the same time, low ductility restrains design possibilities. In order to obtain lightweight components, the material distribution is crucial. The material used should be distributed ideally according to the load applied to the component. Recent developments employ more and more topological optimization using bionic methods [86]. In an iterative design process, material is added to a component where required due to the load, and material is removed where it is obsolete. This process can be compared to the growth of bone or a tree.

It is well known that in contrast to casting, which offers alternatives when manufacturing complex components, forming processes enable a dense material structure orientated parallel to the load path (Fig. 3). Furthermore, the already higher yield stresses of wrought alloys designated for forming processes are increased by the work hardening effect. Unfortunately, forming processes do not allow as complex shapes as casting or cutting processes. To overcome this restraint, one possibility is to use semi-finished products that already provide a suitable material distribution.

With tailored sheet metal products, where different dimensions, materials, alloys, or grades are combined within a single workpiece, a more sophisticated product or process design and more complex shapes can be achieved. On the other hand, forming processes of such semi-finished products require increased process knowledge, the observation of different material behaviours, and the development of designated adaptive forming processes and tools [87–89].

In addition, high strength but low ductile materials used for lightweight components have limited material distribution options. In order to avoid this, some solutions include:

- forming at elevated temperatures,
- incremental forming,
- superplastic forming, and
- thixoforming.

An example of successful forming of high strength steels is the manufacturing of a fuel tank made of stainless steel with a very complex geometry by means of conventional and hydro mechanical deep drawing. For many years, fuel tanks for passenger cars have been made of plastic by the blow moulding process, accounting for about 70% of all tanks produced. It allows the

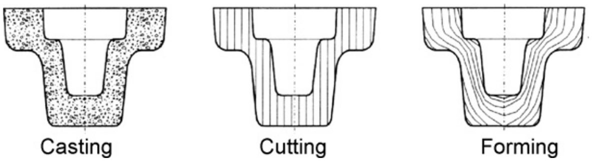

Fig. 3. Schematic material orientation in different manufacturing processes [87].

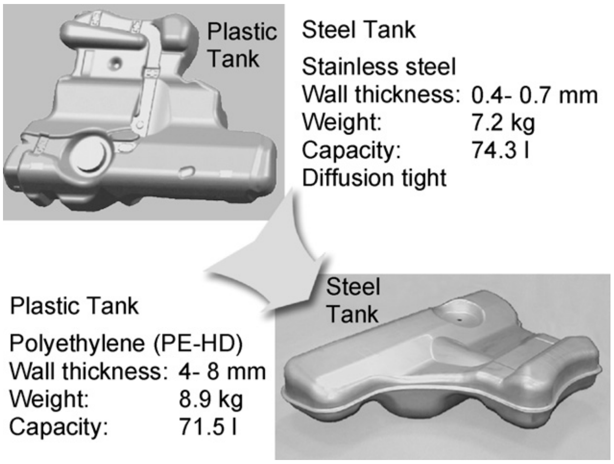

Fig. 4. Comparison between plastic and steel tank [91].

manufacture of complex shapes required due to complex package limitations. But legislation requires zero emission of hydrocarbon from tanks which plastics do not meet at present. Besides diffusion tightness, stainless steel provides high corrosion resistance, outstanding formability, and high strength compared to mild steel. Still, the manufacture of such a complex shape could only be achieved by the intense use of finite element simulation. As a result, the stainless steel tank is 20% lighter while providing 4% more capacity than the conventional plastic tank due to smaller wall thickness (Fig. 4) [90].

3.2. *Forming technology for lightweight structures*

Lightweight constructions are optimal if material is used only in component areas where stresses appear and if the material used is charged near yield stress. Therefore, such a structure is primarily designed for strength, i.e. the structure does not fail. This design principle is followed in aerospace applications where materials with highest specific strength are used, for example 680 MPa aluminium alloy EN-AW7449 in the wing up side of the Airbus A380.

In automotive applications, structures are designed for stiffness, i.e. the structure does not elastically bend too much. This additional requirement naturally increases the structural weight. Only crash relevant structures are solely designated for absorbing crash energy by deformation and therefore are designed for strength.

Depending on the purpose of a lightweight structure, two main construction principles are employed, overlapping each other to a certain degree. As long as a structure only has to carry a given load, frameworks are used, e.g. in cranes, scaffolds, bridges, or monuments like the Eiffel tower. A shell structure on the other hand is used if the structure has to seal against, e.g. pressurized water, fuel, or air.

While frameworks mainly involve the use of beams like tubes or profiles, shell structures deal with sheet metal blanks [92].

3.2.1. *Frame structures*

In contrast to automotive shell structures, only simple geometries are used in frame structures. In many applications, most of the members are tubes with round or rectangular cross-sections. Welded round tubes are very common in axle tubes, bicycle frames, garden chairs, or ski sticks. Extruded tubes are used in simple space frames like the BMW C1 (Fig. 5). Seamless tubes offer best mechanical properties, but due to high cost, they only account for a small market segment like in helicopter landing vats, drive shafts, or hydraulic pipes [93].

Fig. 5. Tubular frame structure of the BMW C1.

In automotive applications, single hollow extrusions prevail. Especially in low volume productions like prototypes or niche cars, more and more space frame body-in-whites are made from aluminium extrusions [79]. This is mainly due to the fact that extrusions offer cross-section design possibilities that include additional functions together with the structural property of a high moment of area inertia [94]. Due to low tool costs, straight profiles are more economical in low batch sizes, compared to conventionally deep drawn double half-shell workpieces, such as roof rails or cross members that require more expensive tools [79]. On the other hand, deep drawn parts offer a better material distribution because complex three-dimensional (3D) parts can be manufactured, whereas extruded profiles are symmetric on the longitudinal axis. This symmetry restricts design options. Furthermore, deep drawn parts can be directly manufactured in a curved shape while extruded profiles usually require a subsequent bending operation to obtain a curvature. Here, expensive tools raise the minimum economical batch size.

Magnesium is a useful material in lightweight frame structures. It offers a considerably higher specific strength compared to steel and regular aluminium alloys [95]. In contrast to aluminium and magnesium, steel cannot be extruded into hollow profiles with walls thin enough to meet car body requirements. Therefore, space frames made of laser welded steel tubes are considered [96].

The conventional process chain for the production of curved semi-finished products involves extrusion, stretching, and bending of the profiles in succession. However, such semi-finished products feature disadvantages typical for bending which complicate the process design and can negatively influence the manufacture. Some relevant problems, especially in bending and concerning a further processing by hydroforming, are the inaccuracy of the

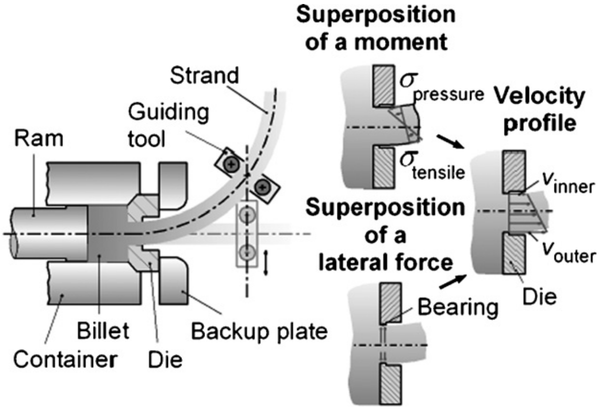

Fig. 6. Process principle rounding during extrusion.

profile contour due to springback, cross-section deformation, residual stresses inside the component, and the reduction of formability. For these reasons, the conventional process chain often fails to accomplish the required component properties.

In the extrusion process variant, curved profile extrusion (CPE), the exiting strand is deflected by a guiding tool and, as a result, the profile exits the die directly in a curved shape (Fig. 6, left). The curved extrusion is a result of a specific velocity profile of the material flow, caused by tensile and pressure stresses as well as a lateral force. Here, the contour radius of the curved profile is solely determined by the position of the guiding tool in relation to the die [84].

During CPE, plasticity results from the extrusion process itself, not from the lateral force. Therefore, the properties of curved profiles manufactured by CPE are better than those of bent profiles. These are, among others, a high accuracy of shape (no springback), a minimal cross-section deformation, reduced residual stresses, and an unreduced formability [97,98].

3.2.2. *Shell structures*

In contrast to frame structures used for small and medium lot production, shell structures for automotive car body applications are used for large-lot production. In contrast to casting processes, only forming technology is able to provide large thin walled hollow components with a surface quality suitable for outer skin panels.

Because the material price accounts for about 50% of the total vehicle cost at large-lot production [99], steel is commonly used. With the need for weight reduction, particularly in the front of the car, more expensive materials like aluminium and even magnesium are considered for sheet metal applications. Although providing the same specific strength and stiffness, their lower density results in a higher sheet thickness at the same weight per area thus considerably increasing specific dent resistance and shell stiffness.

Different studies have been carried out to investigate the feasibility of ultra lightweight car bodies. While the ULSAB consortium propagates the mono-use of steel [100], Ford developed the P2000 as an all-aluminium car body in a shell structure design [78].

With the demand to decrease costs in lightweight structures, sheet metal parts have become larger. Therefore workpieces and their forming processes are more complex and difficult not only due to the size but also because of the use of tailored blanks. Whereas previously, parts of different thicknesses were joined in the assembly, now single parts consisting of different wall thicknesses are used as semi-finished products (Fig. 7) [100].

Depending upon the material used, specific forming problems arise in deep drawing and related processes. In aluminium concepts, close attention has to be paid to the specific forming behaviour of aluminium. Aspects like adapted drawing depth, larger radii, and a homogenous feed need to be taken into consideration [101].

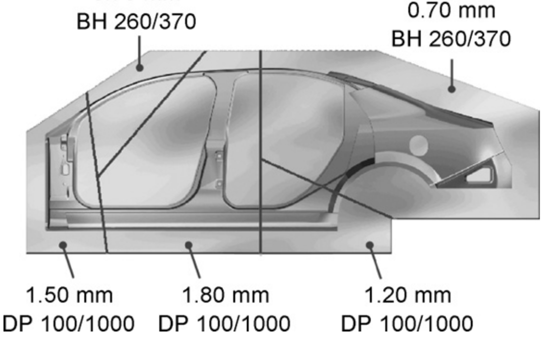

Fig. 7. Use of tailored blanks for side panel [100].

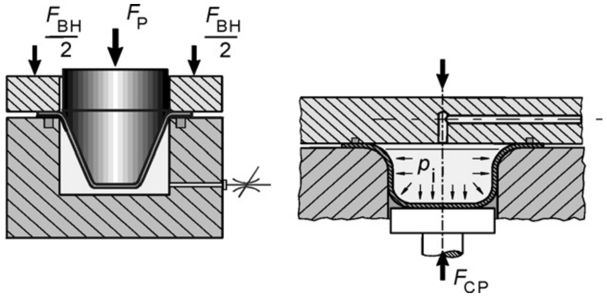

Fig. 8. Process principle of HMD (left) and HBU (right).

In the processing of steel sheets, the use of high strength grades leads to significant challenges such as higher tool stresses. In order to prevent wrinkling, the binder has to apply higher forces causing increased tool wear and making premium tool material, tool coatings, or even the use of ceramic inserts necessary. The high strength of the material is also responsible for an increase in springback that has to be compensated by FEM-simulations [102].

Forming by using flexible working media allows the manufacturing of complex sheet metal components and, thus, supports lightweight construction [103,104]. In pneumo-mechanical deep drawing, pneumatic preforming can be used to cause additional work hardening in the sheet metal or to pre-distribute material for subsequent deep drawing operations [105]. In hydro mechanical deep drawing (HMD, Fig. 8, left), the die is replaced by a fluid [106]. In high-pressure sheet metal hydro forming (HBU, Fig. 8 right), it is the punch that is replaced [107]. HBU allows for an increased work hardening in sheet metal by a distinctive stretching operation. An advantage of HMD is a higher limiting drawing ratio that can be achieved, because of the higher surface pressure in a larger contact area between punch and workpiece, which enables higher drawing forces to be transferred. On the other hand, HBU allows for an arbitrary distribution of stretching and deep drawing portions over the draw depth. Furthermore, a better shape accuracy is attained compared the conventional deep drawing [108].

3.3. *Joining by forming*

Depending on the geometry of the lightweight structure and the material used, different joining processes can be applied. Joining by forming is an alternative to established resistance or arc welding techniques especially in case of limited fusion weldability. Mechanical welding processes like stir and inertia friction welding have advantages as a solid state process, clinching and riveting are also applicable to hybrid structures [109], and electro-magnetic forming in addition provides a high velocity and contact free forming principle [110].

3.4. *Summary*

From the foregoing publications cited, it can be seen that manufacturing lightweight components from metals has continued apace, especially with the need to manufacture lightweight automotive components for more environmentally friendly vehicles. Indeed environmental concerns and the need to decrease automotive weight has been a major driver.

Among the changes that have occurred is the introduction of new processes which can be used to shape sheet metal into complicated shapes. This is the subject of a subsequent section.

4. Single-point incremental forming of sheet metal

Asymmetric single-point incremental forming (AISF) of sheet metal was first envisaged by Lezak who patented it in 1967 [111]. However, the process was not viable at the time because computer numerical control systems and associated software were still in their infancy. In the 2005 keynote paper on asymmetric single-point incremental forming [112], the progressive development of the process was traced to 2005. In the paper future opportunities were listed as [113]:

- automotive body panels (prototype, low-volume, e.g. motorsport, and after-sales);
- other automotive sheet metal parts—structural, or non-aesthetic;
- architectural—custom made formwork, panels;
- customized white goods;
- reflectors and casings for lighting;
- dental—custom made dental crowns;
- housings and fairings for aerospace;
- ship hull plates.

Incremental forming of sheet metal has matured to the point that it now is a major topic at International conferences. For instance, in Sheet Metal 2007, a CIRP sponsored International Conference [114] there were nineteen papers about Incremental Sheet Forming.

4.1. Single-point incremental forming description

Single-point incremental forming is commonly referred to as SPIF. The process works as illustrated in Fig. 13.

Single-point incremental forming only uses a blank holder and a forming tool with (semi-) spherical head. A so-called faceplate or backing plate can be added to improve the accuracy (Fig. 9). The angular velocity of the tool, ω, and the tool speed, v, are two important parameters which contribute to the ability to form at higher rates of production.

Sheet metal thicknesses are typically in the 1 mm range. In contrast with the 'Backward Bulge Forming' or two point incremental forming variant [115] where a dedicated support structure typically still needs to be configured and manufactured, SPIF does not require any tailored tooling.

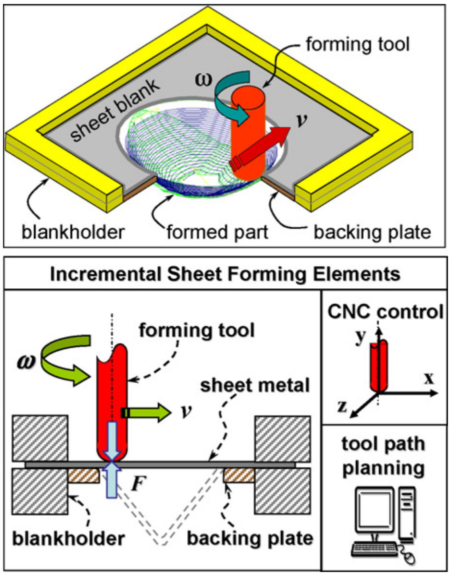

Fig. 9. Single-point incremental sheet forming.

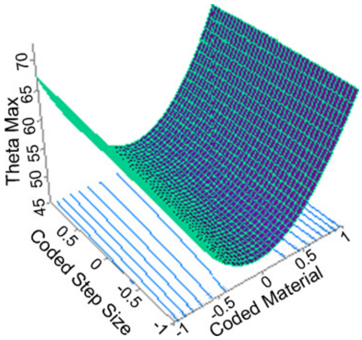

Fig. 10. RS $\phi_{\max}$—material type and step size [116].

4.2. Recent developments

Known limitations driving ongoing research dedicated to Incremental Sheet Forming are:

1. the forming of steep angles cannot be performed in a single step procedure;
2. springback occurs;
3. due to high localised stress concentrations, uncontrolled plastic deformations can occur in already processed zones.

4.2.1. Forming at steep angles

Related to the first problem, the factors influencing the formability limits for different materials were extensively investigated by Ham and Jeswiet [116]. Martins et al. [117] contributed to a better understanding of the underlying material behaviour by means of a model based on membrane analysis, thus providing a theoretical background for SPIF and a better understanding of the high strainability characterising SPIF. Fig. 10 is an example of this which shows material type and step size for a maximum forming angle, $\phi_{\max}$, for a response surface (RS).

The challenge of shifting the process limits has been addressed by several research teams using multi-step forming strategies, effectively achieving vertical wall angles [118,119]. For some materials the limits of this strategy were investigated by Skjoedt et al. [120]. Recent in-process observations help to understand the strain distributions underlying the effectiveness of the multi-step procedures [121]. Results for a multi-step process may be observed in Fig. 11.

A single-step approach, in which a dynamic heating system with active cooling significantly improves the formability of hard to form materials, has been developed by Duflou et al. [121] (Fig. 12). Where friction heating was already known to contribute to an increased formability in the tool workpiece contact zone, the laser based heating system allows contact-free temperature control without the detoriating surface roughness effect of increased tool friction.

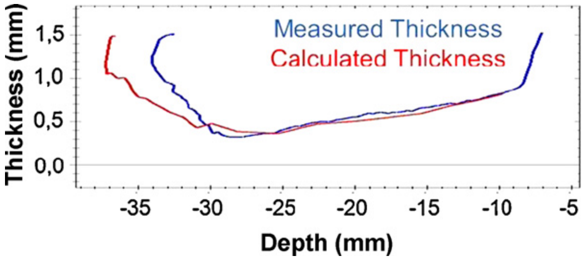

Fig. 11. Measured and calculated thickness profiles for multi-step SPIF [125].

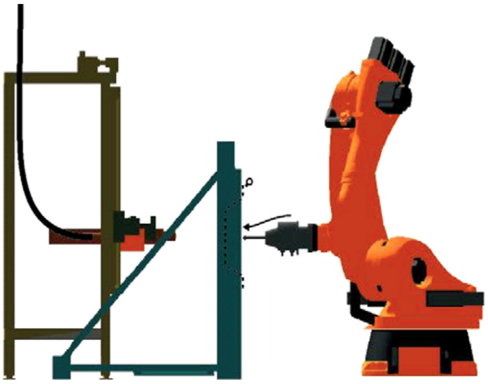

Fig. 12. Single-point incremental forming machine structure with dynamic, laser-supported heating [122].

New tools are also being developed to increase formability. For instance, Alwood et al. [123] have designed paddle shaped tools to achieve higher formabilities.

4.2.2. Springback in SPIF

The dimensional accuracy problems linked to springback effects have been addressed by several authors. For instance in the model developed by Lasunon and Knight [124], who compared single-point incremental forming and double-point incremental forming, they found their FE model was in good agreement with experimental data [112]. Fig. 13 shows an example of a result for their model, and Fig. 14 shows a comparison of plots for their model and experiments.

The compensation schemes described in the CIRP keynote paper [125–127] have been enhanced in a feature based toolpath optimisation approach proposed by Verbert et al. [128]. The use of the dynamic heating system described above [122] was also found to reduce springback effects, thus contributing to improved process accuracy.

While the toolpath optimisation strategies referred to above allow to compensate for elastic springback, they do not help to overcome unwanted plastic deformation in already processed workpiece areas. For generic workpiece geometries, the simplicity of the basic SPIF setup indeed provides insufficient degrees of freedom to allow full control over the forming process [128] In consequence poor accuracy continues to form a major shortcoming of the process. A structured search for applications of the incremental sheet forming process by product segmentation [129] revealed that lack of accuracy formed the main obstacle for industrial adaptation of the process.

Several systems with flexible programmable back support structures have been proposed to overcome this accuracy problem [130,131]. The complexity of the process control when working with multiple, synchronised tools however remains a challenging problem for future research. The localised heating system described in Refs. [122,132] allows incremental forming of a wide range of materials with significantly reduced process forces. This does not only allow to process thicker sheets, but the resulting, more localised, plastic deformation also contributes to a better workpiece accuracy. As the application screening in Ref. [123] indicated, further shifting the achievable process accuracy to ±0.2 mm tolerances would open a wide range of industrial opportunities. This will require further research, targeting improved hardware, toolpath generation and control strategy development.

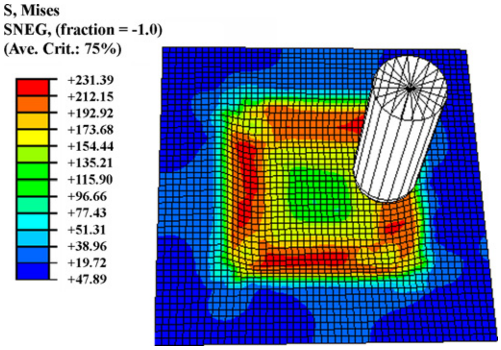

Fig. 13. Contour plot of the von Mises stress for a 45° pyramid formed by SPIF [124].

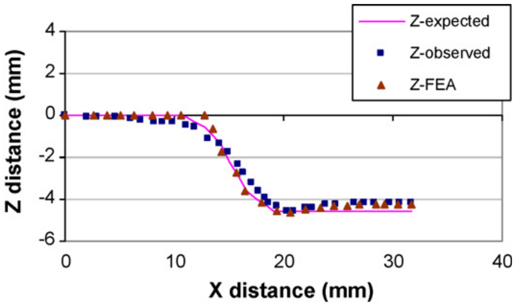

Fig. 14. Profile plots of a 45° pyramid [124].

4.3. Summary

The SPIF process is continually being refined in order to improve productivity. The major parameters in SPIF have been identified and process capabilities are being expanded.

SPIF has not found widespread application, however the development of SPIF for niche metal formed products is well underway. Controlling springback remains a major problem.

5. Sheet forming at elevated temperatures

Against the background of the challenge of drastically reducing CO_2 emissions, one of the most significant tasks facing motor vehicle manufacturers is how to achieve a definite reduction in fuel consumption. Based on the relationship between vehicle weight and fuel consumption, one solution would appear to lie primarily in reducing the weight of the components. In so doing, the consistent use of lightweight construction takes on a highly significant role [133,134].

In addition to a requirements-based approach to lightweight construction along with methodology which takes into account form and/or structure, lightweight construction based on materials is one of the most promising strategies. Examples of materials which demonstrate potential as far as lightweight construction is concerned include aluminium, magnesium, high strength and increased strength steel materials, but also titanium alloys.

However, it is worth pointing out that these materials are often associated with limited formability, so that producing complex sheet parts is either not possible at all or only with increased expenditure. The processing of high strength materials is, furthermore, associated with high processing forces and/or pressures, as well as with definite springback behaviour.

The specific use of temperature as a process parameter opens up the possibility of improving the formability of these materials and of achieving a significant reduction in the forces and/or pressures required for forming. The keynote paper, Sheet metal forming at elevated temperatures [135], incorporated an overview of research activities as well as primary industrial applications where

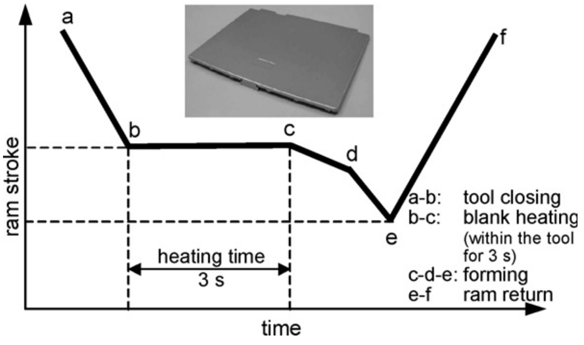

Fig. 15. Use of servomotor-driven press for magnesium forming [136].

temperature is used specifically as a process parameter for sheet metal forming. At the same time, mechanical, action media-based as well as laser-based forming operations were taken into account.

5.1. Mechanical forming operations

Taking selected studies as an example, the potential of temperature application when it comes to relocating the forming limits of magnesium and aluminium alloys is illustrated. In the case of magnesium in particular, the use of temperature represents a significant pre-condition for the production of components using forming technology. In addition to the research activities, the temperature-assisted manufacture of magnesium laptop housings was also presented by way of a primary industrial application where the forming process takes place with the help of servomotor-driven presses [139]. In this way an optimum adjustment of the ram stroke to suit the requirements of the forming process can be achieved (e.g. for blank heating); see Fig. 15.

In the case of high- and ultra-strength steels, the achievement of a positive effect on forming and springback behaviour and reductions in the required forming forces are possible by means of a specifically targeted application of temperature.

The foregoing were analysed as part of basic investigations into different types of load in relation to forming technology, in which the limits for temperature application were also established. During the bending process, it proved possible to minimize spring-back in a corresponding temperature window and to achieve a significant reduction in the forming forces required during thermoforming. As regards extension of the forming limits, it was evident that marginal conditions (e.g. tribology) would need to be taken into account in order to be able to make full use of temperature application potential [137].

Another strategy that can to be found in industrial applications is the hot forming of boron alloyed manganese steels. This technology is described as ‘‘press hardening’’ and is used in the fabrication of complex, crash-relevant components. It is a combination of processes based on hot sheet metal forming and hardening of the component fabricated, something which gives maximum component strengths in excess of $R_m > 1500$ N/mm^2. At the same time, two basic process variants can be identified—direct and indirect press hardening.

The number of industrial applications for press hardening has risen consistently over the last few years. More and more OEMs and supplier companies are using this technology for manufacturing structural components featuring high levels of strength. In order to guarantee a high level of process reliability, reproducibility and quality on the one hand whilst maintaining a high degree of commercial viability on the other, the users are faced with a range of challenges. Research is focused on the qualification of FE simulations, the development of new sheet metal coatings, the introduction of efficient post-processes or the implementation of new tool concepts (including materials, coatings and cooling) [138–140]. As far as the need to increase resource efficiency in component manufacturing is concerned, new process chain concepts will continue to play an outstanding role as regards effective temperature usage.

5.2. Action media-based forming

The use of temperature as a process parameter is also appropriate for flexible media-based forming. At the same time, the use of liquid action media, where the medium can be used both for heating the semi-finished item and for tempering the tool, represents a suitable approach.

Within the framework of various studies concerned with shifting forming limits and/or increasing the degree of forming achievable, it has been possible to obtain proof of the potential offered by temperature application both for hydromechanical deep drawing and for sheet hydroforming processes. In addition to aluminium, particular use was made of magnesium alloys in the studies, with tests being carried out using both simple cup geometries and model geometries relevant to practical application (e.g. bonnet, licence faceplate and nodal element) [142,143]; see Fig. 16a.

Both magnesium and aluminium materials were included. In a comparison with fluid-based forming operations, gas offers the chance to provide higher temperatures. A distinction is made in the following between superplastic forming, which is characterized by long cycle times ranging from several minutes to hours, and fast gas forming, with forming times of a few seconds [140].

Superplastic forming (SPF) is a process by which lightweight components with extremely complex shapes are produced. Superplasticity is the ability of materials to undergo extreme elongation, and occurs within a narrow range of temperatures and deformation rates. Several titanium alloys are superplastic, as are many specially formulated aluminium, stainless steel and inconel alloys. During SPF, in a single operation, highly complex, detailed structures that would normally be realised by assembling numerous components can be produced.

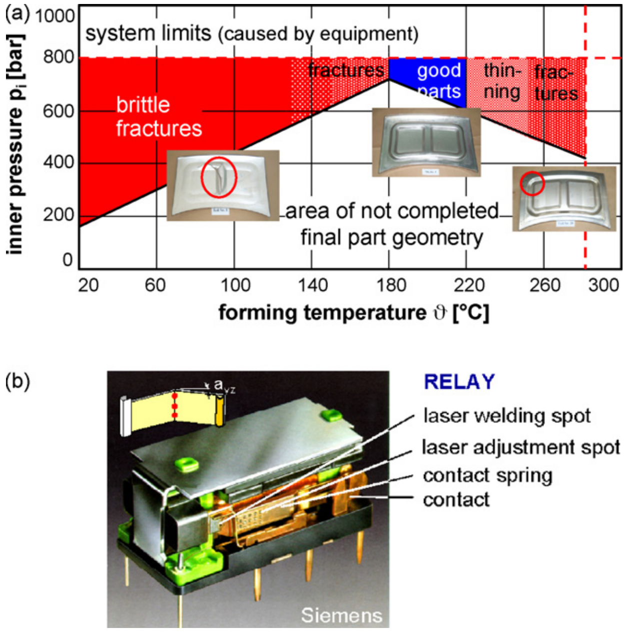

Fig. 16. (a) Process window identified (AZ31B; s_0 = 1.3 mm) [141] and (b) examples of application of laser beam forming.

In the aerospace industry, superplastic forming is already in established use for TiAl6V4 sheets [144]. In addition to pure superplastic forming, innovative process developments can be observed. The integration of additional process steps represents a promising way to meet these requirements. In this context, challenging integral structural parts are being produced by combining superplastic forming with diffusion bonding (SPF/DB). This combination of processes has potential for the realization of complex, integral reinforcing structures, with simultaneous savings both in terms of the number of forming steps and the tools required.

However, the SPF method is not economically competitive because of its long cycle time. Therefore, in recent years, various means of shortening the cycle time have been investigated with encouraging results. Hot metal gas forming (HMGF) is an alternative and combines heating of a flat sheet workpiece with expansion (forming) of the workpiece in a die cavity using gas pressure, followed by in-line quenching [145]. It allows many of the disadvantages of current hydroforming techniques to be overcome, and permits a reduction in product piece processing costs. This is primarily the result of lower capital investment and tooling costs. These advantages were achieved by exploiting the extremely high elongations and low forming loads offered by superplastic forming. In addition to single sheet metal forming, HMGF has also been identified as being capable of meeting the needs of double-blank forming.

5.3. Laser-assisted forming operations

Another focus of the keynote paper [135] was laser-assisted forming processes, where a distinction was made between whether the laser is used directly for forming or only for heating the sheet to be formed.

In laser-assisted spinning, the forming zone is heated and the pressing rollers are used to form the sheet [146]. The focal spot of the laser is positioned directly in front of the pressing rollers. This approach offers the following advantages by comparison to conventional pressing processes:

- improvement of formability, in particular for materials that are difficult to form;
- reduction in the forming forces required;
- reduction of tool wear;
- increase in geometric flexibility.

In order to provide evidence for the industrial relevance of laser-assisted pressing, one-piece catalyst tunnels were produced made from titanium alloys (Ti2 grade 2, TiAl6V4 grade 5).

Laser bending is one example of the direct use of a laser to realize a forming operation. It is based on the generation of thermal stresses in the component for forming. In addition to the principles of the procedure and the relevant influencing variables possible, examples from industrial usage were also discussed and the advantages illustrated. A typical laser forming application is the adjustment of electronic systems (Fig. 16b), which have to be adjusted with extremely small tolerances, coupled with high reproducibility. In order to increase accuracy, the direct contact with the system during calibration has to be eliminated. Laser forming would therefore seem to be suitable, and the non-contact laser beam adjustment was investigated [147].

5.4. Summary

The foregoing examples show that the use of the temperature as a process parameter in forming operations continues to be expanded further and that it can have a significant effect on the forming behaviour of lightweight materials.

In order to make full use of the potential for expanding forming limits, improving form and dimensional accuracy but also for achieving reductions in the forming forces and pressures required, appropriate conditions must be created in relation to process technology and tool technology. Important aspects which will need to be considered include, for example, the design of the tool, the layout of the heating device for the provision of suitable temperatures and/or temperature distribution or the guarantee of suitable tribological conditions.

6. Testing and modelling of material response to deformation in bulk metal forming

6.1. Background

Nowadays more reliable and versatile simulation software is available for bulk metal forming processes, thereby becoming a real prospect for industries. To accurately and efficiently predict the events that products and processes are subjected to, the use of models capable to evaluate the different aspects of the material response to plastic deformation is one of the most critical prerequisites.

Various models are utilised to investigate and describe those phenomena, characterising material response in bulk forming. They can be classified according to:

- the length scale of the described phenomena;
- the origin and nature of their formulation;
- the aspects of the material behaviour they focus on.

As regards the length scale, models can cover from the atomic to the continuum scale, as indicated in the previous section on microforming. While atomic-scale models are still on a fundamental scale basis, as indicated earlier, mesoscale models, when dealing with polycrystalline models (usually $1–10^3$ μm), are the subject of extensive industrial and scientific research efforts, and their application in the design of the whole process chain of manufacturing processes is becoming more and more widespread. However, continuum models, describing the material response at a macroscopic scale, are still the most utilised, especially in industrial environments, thanks to their simple formulations, well suited for FEM implementation. On the other hand, as they remain at a macroscopic level and are not coupled with a lower-scale phenomena, they cannot take into account microstructural-related effects on material response.

Depending on the origin of their formulation, models can be either physical-based models, which utilise scientific theory to predict material behaviour, or empirical models, which rely on experimental laboratory observations.

A further classification can be made according to the aspects of the material behaviour the model focuses on. From Fig. 17, models can be:

- material-oriented models, that usually address the intrinsic features of the material rather than its interaction with the process,
- process-oriented models, where the description of the material response is strictly connected to the deformation and post-deformation conditions of the actual manufacturing process, and
- product-oriented models, that focus on the material properties to be measured on finished components and are consequences of prior plastic deformation operations in the manufacturing cycle.

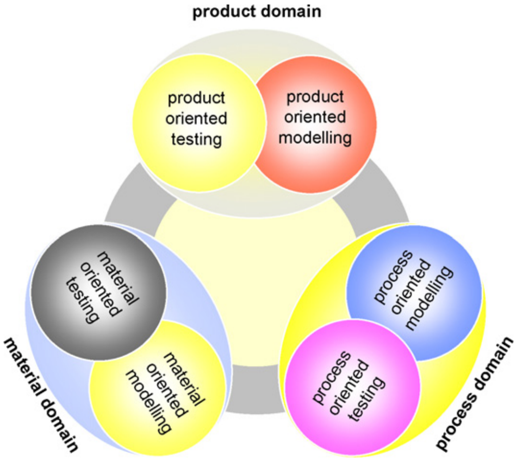

Fig. 17. Material-, process- and product-oriented modelling and testing [148].

Each model has its own unique and precise requirements in terms of experimental data need to develop and validate the model. As is in the case of modelling, the tests can be classified depending on the aspects of the material behaviour they address:

- material-oriented testing, or simply, material testing,
- process-oriented testing, also known as physical simulation testing, carried out on real material samples, and
- product-oriented testing.

In material testing, material response to deformation is measured under specific physical conditions, which are not usually representative of the actual process. On the other hand, a physical simulation experiment is characterised by a real-material sample processing under thermo-mechanical conditions very close to those of the process being studied. In product-oriented testing, the properties of the finished workpiece are analysed, thus limiting the interest of process designers on this kind of testing. In recent years, one of the main changes in testing has been represented by the gradual move from material testing towards physical simulation. In fact, one of the major advantages of physical simulation is the capability to simulate different operations and events, such as heat treatments before and after deformation, and coupled and/or uncoupled events that are typical of the heating, deformation and cooling phases. The actual trend is to reproduce on the sample the history of events that cover a significant portion of the whole manufacturing cycle or even the whole cycle. In this way, physical simulation testing can provide the proper calibration to process-oriented models. The evolution of testing technology guides and influences the evolution of models predicting material response, as outlined in Fig. 18.

6.2. Selected present research

In Ref. [148] academic and industrial on-going research activities were addressed, including underlying limits and perspectives of both testing and modelling with particular focus on operating conditions and phenomena to be reproduced and modelled. Most of those fields are still a subject of research. In the following, two distinguishing topics will be presented briefly, the first one related to the most advanced features in modelling process chains, and the second related to the coupling between material response and damage characteristics.

6.2.1. Modelling the process chain

When referring to manufacturing processes, it is more and more usual to refer to the whole process chain, including not only the actual forging phase, but also pre- and post-thermal cycles, additional plastic deformation steps, and, eventually, machining operations. The major restriction in modelling the process chain is the insufficient predictive capability of the numerical simulation tools in calculating properties or features of the component at different stages of the process chain. In the process chains based on hot deformation operations, the physical and mechanical properties of the final part depend on the final microstructure which is the result of phenomena occurring in each step of the process chain. Since most of the microstructural phenomena are affected by the thermal and mechanical history generated in the previous steps, the analyses of the microstructure evolution and of the material response in the different steps must be closely interconnected. Fig. 19 illustrates the connectivity at a “macro” level between the thermo-mechanical–metallurgical FE analyses of the hot-deformation phase and the post-deformation cooling phase in a process chain [149]. Fig. 19 refers to commercial FE codes with standard predictive capabilities of the models for microstructural analysis. Thanks to the transfer of microstructural evolution data between the steps, technological characteristics, such as workability and machinability, can be properly modelled.

Models capable of taking into account the coupling between thermal, mechanical and metallurgical events, usually implemented in FEM codes for bulk metal forming, are generally physically

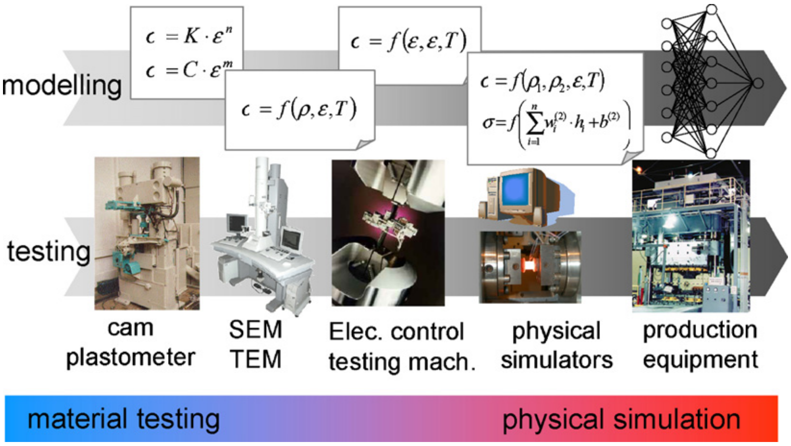

Fig. 18. Evolution of testing technology and material response modelling [148].

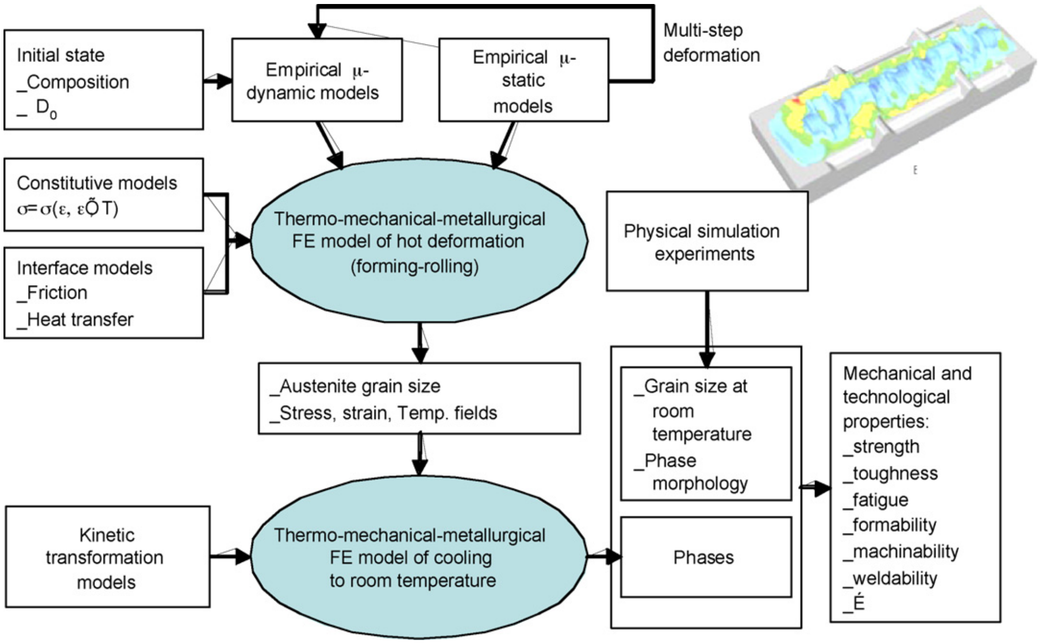

Fig. 19. Connectivity at a "macro" level between the thermo-mechanical–metallurgical FE analysis of the deformation and cooling phases [149].

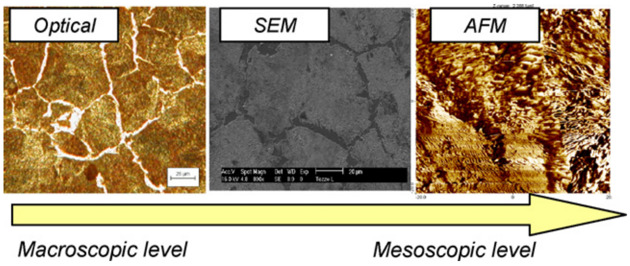

Fig. 20. Increasing level of complexity in microstructure analysis.

based, but they still remain at a macroscopic level. However, to get a deeper insight into several phenomena, such as the material's reaction to machining, more fundamental microstructural features need to be addressed. The related modelling then moves towards a mesoscopic approach. To propose an example, microstructural parameters, such as pearlite lamellar shape and inter-lamellar distance, play a fundamental role in assuring high levels of machinability. In order to properly machine steel wheel hubs after hot forging, the cooling stage after hot forging should assure a proper pearlite morphology. Microstructural models must then include the evolution of pearlite morphology during thermo-mechanical treatment. On the other hand, the testing related to this kind of modelling has to involve physical simulation experiments replicating process parameters evolution, together with advanced SEM and/or AFM microstructural analysis to quantify pearlite features for each processing condition (Fig. 20).

6.2.2. Connection between material response and damage evolution

The continuous search for high quality components requires more accurate modelling of damage evolution along the whole process chain. Either cracks have to be avoided (as in the case of cross and wedge rolling) or it is strongly recommended, for process efficiency (as in the Mannesmann process), that damage evolution models are closely linked to material response models. Based on continuum damage mechanics, the well-known Le Maitre model [150] considers the effective stress of the damaged material as function of a damage variable and of the undamaged material flow stress.

The effectiveness of such models requires accurate calibration of the damage variable (both in testing and modelling) and the proper modelling of the material flow stress. Uniaxial tensile tests are often used to determine the damage-related parameters, this being the tensile state of stress responsible of the crack appearance and growth. However, the actual state of stress in the above mentioned processes is usually more complex, making the need to move towards physical simulation testing greater. Moreover, especially in hot conditions, where the material response is strongly influenced by microstructural evolution, a further coupling with microstructural features is fundamental.

Research work is on-going on how to modify the damage variable law in order to take into account the dependence on microstructural features and on the definition, conduction and analysis of the most suitable test to determine the damage parameters in hot conditions.

6.3. Summary

Many challenges still exist in testing and modelling material response to deformation in bulk metal forming. As indicated, many excellent models exist at the macro-scale but much remains to be done on in the area of microforming due to the change in size effect mentioned earlier.

7. Conclusion

The foregoing has reviewed selected metal forming processes that have been keynote subjects of CIRP STC F since 2000. Included in this review is new information, including updates, that have occurred since those keynotes were given. This paper can be viewed as a continuation of those keynotes. It may be seen that much remains to be done in all areas.

Sheet forming at elevated temperatures (warm forming) and manufacturing with light-weight materials now are actively used in production processes.

Finally, it can be predicted, especially in view of Fig. 1, that environmental effects will become a major consideration, especially increased energy consumption in producing smaller many parts for one product.

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