

# Chapter 1

## Introduction to Collaborative Research Center Micro Cold Forming (SFB 747)



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### 1.1 Motivation

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Micro systems technology is one of the key enabling technologies of the 21st century [Hes03], with increasing relevance due to a general trend towards miniaturisation in many industries. The main boosters for this trend are currently the consumer and communication electronics market and—to a lesser extent—medical technology (especially microfluidic devices, which had a market volume of approx. \$2.5B in 2017 [Cle17]). As an example, for the companies organized in the industry association

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IVAM Microtechnology Network, medical technology is by far the most important market [NNI14]. Nevertheless, in the context of electromobility, autonomous driving, and industry 4.0, there should also be a significant increase in the demand for existing MEMS (micro electromechanical systems) including connectors, as well as a need for further improvement, miniaturization and functional integration.

A typical example of the benefits and challenges of miniaturization is the ABS (anti-blocking system) in modern cars. Whilst the weight could be decreased to approx. 10% of the weight of the first system, the part complexity has significantly increased. This is indicated by the decrease in the number of parts by approx. 90% in current systems, compared to the first versions [Nos14], even though additional functions are integrated. The trend towards an increase in miniaturization can also be illustrated using the example of HF (high frequency) connectors, where nowadays the minimum pin diameters commercially available off the shelf are in the range of 0.7 mm, with allowable tolerances for functional features of several  $\mu\text{m}$ .

As in most of the applications discussed above, significant quantities of parts ranging from several thousands to literally billions (e.g. for resistor end caps) have to be produced, micro cold forming is among the dominant production processes. Examples of components (containing) micro parts produced by cold forming are (listed by their application areas):

Medical technology/chemical technology: Hearing aid devices, cardiac pacemakers, micro pumps and micro pump couplings, microfluidic reactor devices;

Automotive technology: ABS and other advanced assistance systems based on MEMS, contacts and connectors, fuel pumps, injection nozzles;

Electronics: Battery caps, displays, diodes, electrodes, connectors, resistors, nozzles, contactors;

General industry: sensors (e.g. for pressure), hydraulic and pneumatic connectors, micro pumps, micro valves;

Consumer electronics: smartphone speakers, electric blades, compact cameras, microphones.

As a first conclusion, we find three main trends: an increase in miniaturization, an increase in functional integration, and an increase in total batch sizes. Moreover, common to many of these applications is the need for zero-defect quality. This is often due not only to cost considerations, but also to the safety criticality of many of the components (ABS, medical devices).

Consequently, and as most micro forming parts are produced under extreme cost pressure, the complete process chain has to be optimized to enable further cost-efficient miniaturization. This means that not only aspects relating to the micro cold forming process as such (e.g. non-systematic scatter in material properties), but also preceding and succeeding process steps (e.g. heat treatment) as well as materials handling have to be considered and optimized along the process chain. Moreover, in order to increase process stability and part quality, novel tool materials and tool production processes have to be investigated to minimize tolerances and improve wear behavior. Finally, and this is among the most urgent industrial needs in view of zero-defect requirements, methods and systems for 100% inline measurement and inspection at production rates of from 60 to 300/min and more are

required (depending, of course, on the part complexity). This is especially true for systems allowing the optical inspection and measurement of complex features, which are often inside longer cavities.

Research on micro metal forming in Germany was developed by Engel and Geiger, starting in the 1990s in Erlangen. Discussion of the scientific advances, achieved also in other countries like Japan and the USA, was held (not limited to but also) in The International Academy for Production Engineering (CIRP), documenting the milestones in numerous papers and 2 keynote papers. These keynote papers ‘Microforming’, [Gei01] and ‘Size effects in manufacturing of metallic components’ [Vol09] are key documents about the development of micro metal forming. The relevance of size effects is due to the fact that these effects are the reason why knowledge from (macro) metal forming cannot be transferred easily to the micro range. These effects have been the topic of a Priority Program (SPP 1138) funded by the Deutsche Forschungsgemeinschaft (DFG) in the period from 2002 to 2008.

Three categories of size effects are specified, taking their names from the feature that is kept constant: density, shape and structure. Fundamental knowledge concerning size effects is documented in the book “Micro Metal Forming” [Vol13].

Specific features are:

1. The size or at least one of the dimensions of the produced parts is comparable with the grain size of the material used, resulting in hard to control material behavior.
2. The very small volume of the parts changes the failure behavior due to different probabilities of the occurrence of a defect in a particular workpiece, if homogeneous defects with low density exist in the raw material.
3. The very low weight (typically between 100  $\mu\text{g}$  and 10 mg) of the (raw) parts makes handling difficult due to, for example, adhesion effects. Therefore parts should integrate multiple functions to reduce the number of components in an assembly and to minimize the number of handling and joining operations. On the other hand, the small weight might allow the use of more expensive materials or enable new processes.
4. Quality assurance becomes more difficult compared to macro parts, as many methods usually employed cannot be used for the measurement of micro part dimensions. Also the (scaled down) tolerances interfere greatly with the precision of the metrology, making the use of methods like statistical process control (SPC) impossible.

Research in Collaborative Research Centers (CRC) started in 1998 by several CRC, each addressing a special aspect of micro technology. The aim of SFB 440 was the Assembly of Hybrid Microsystems, SFB 499 focused on the development, production and quality assurance of molded micro components of metallic and ceramic materials and SFB 516 addressed the design and production of active microsystems. From 2010–16 a research group “Small Machine Tools for Small Workpieces” made new approaches for machine tools. In the period 2007–2018 the Collaborative Research Center “Micro Cold Forming” (SFB 747) with about 60 scientists worked on topics relevant for the further development of mass micro metal forming.

## 1.2 Aim of the SFB 747

### Frank Vollertsen\* and Sybille Friedrich

The central concern of the Collaborative Research Center (CRC) “Micro Cold Forming” is the provision of processes and methods for the production of metal micro parts by forming, whereby all essential aspects for the forming process, from material development through component testing to process design, are included. With the resulting knowledge of the mechanisms and correlations, a purposeful process design is made possible for the process-reliable production of metallic components with a size of less than 1 mm and the necessary tools. Batch sizes over 1 million parts are in focus. As a basis for this, the CRC serves industrial requirements with a manufacturing frequency of typically 300 parts/minute. By definition [Gei01], micro forming deals with parts having dimensions less than 1 mm in at least two directions. For further limitation of the research program, sheet thicknesses of 10–200  $\mu\text{m}$  and wire diameters of 200–1,000  $\mu\text{m}$  are specified.

The Collaborative Research Center focuses on micro components that are produced in unit quantities or batch sizes over 1 million parts. The increase in the number of variants results in the need for the reconfigurability of the production lines with the aim of making the production of micro parts more flexible. There is demand for individual processes that are easy to handle and flexible in use and thus support a modular production. Here, the planning of the processes, the definition of the interfaces and the monitoring strategies are of particular importance in order to be able to quickly realize economically the start-up of the production of different micro parts. The materials used in the central process chains are steel (1.4301), aluminum (99.5) and copper (E-Cu58), as well as their alloys. The microstructure in terms of homogeneity, grain size and isotropy plays an important role in the formability. These factors are of particular importance for the alloys of the metals listed above, since the production-related variables determine them. In addition, other materials and combinations of materials are used, which can exploit the opportunities offered with regard to component and workpiece design. The goal is the production of the already mentioned micro technical components. Microsystem technology (MST) and micro electromechanical systems (MEMS) are explicitly not the subject of the CRC research.

### 1.3 Structure and Partners

#### Frank Vollertsen\* and Sybille Friedrich

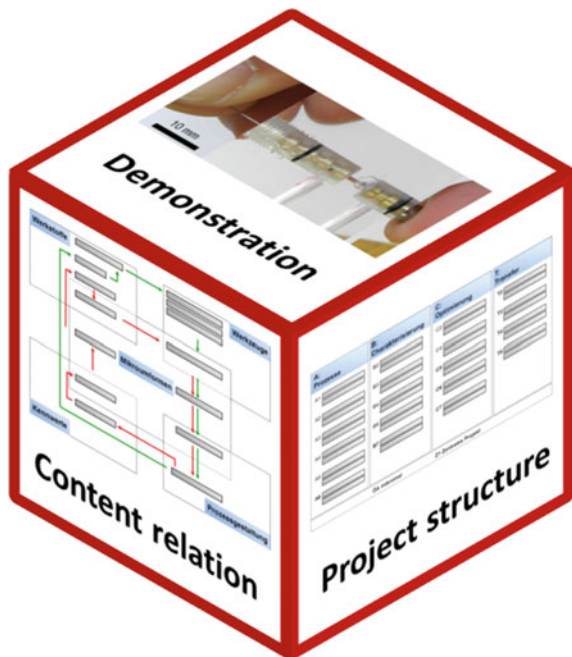
The research program gives the Collaborative Research Center a broad basis, from the development of materials through the processes and their optimization to the planning aspects of micro forming technology production. In order to visualize the internal collaboration, three perspectives on the structure of the CRC were defined, by means of which the CRC is presented as a whole (see Fig. 1.1). As a superordinate element, a demonstrator was realized, on which all subprojects describe their research progress in terms of the hardware, concept or virtual contribution. Research work was coordinated using two further structural elements—the project structure and the content relation.

The CRC offers a comprehensive overview of all aspects of micro forming technology for sheet metal and massive forming with regard to the safe production of micro components. Based on this objective, the structure of the Collaborative Research Center with the project areas processes, characterization and optimization results. Table 1.1 shows the project structure of the Collaborative Research Center.

#### A—Processes

Project area A of the CRC “Micro Cold Forming” deals with fundamental questions of the single processes. The forming processes themselves are examined, as well as

**Fig. 1.1** Perspectives of the structure of the CRC allowing optimal internal interaction and collaboration



**Table 1.1** Project Structure of the Collaborative Research Center (SFB 747). Line 1: DFG Short number and title, Line 2: Running Head(s) of the project, Line 3: Duration of the project (start and end), Line 4: Link for further details

A: Processes	B: Characterization	C: Optimization	T: Transfer
A1 PVD-sheets Zoch, Mehner 2007–2018 Section 6.3	B1 Deformation behavior Vollertsen 2007–2010 [Hu10]	C1 Tool Materials Partes 2007–2013 [Feu13]	T2 Refining Kuhfuß 2015–2016 Section 2.4
A2 Heat treatment Zoch 2007–2018 Section 6.4	B2 Distribution based simulation Brannath, Schmidt, Hunkel 2007–2014 [Lüt14]	C2 Surface optimization Riemer, Maaß 2007–2018 Section 4.5	T3 Micro cavity Bergmann, Lütjen 2015–2016 Section 5.3
A3 Material accumulation Vollertsen, Schmidt 2007–2018 Section 2.2	B3 Tool duration Vollertsen, Bergmann 2007–2018 Section 4.2	C4 Simultaneous Engineering Lütjen 2007–2018 Section 3.3	T4 Micro milled dental products Riemer, Maaß 2015–2017/1. Hj. Section 4.6
A4 Material displacement Kuhfuß 2007–2018 Section 2.3	B4 Material strength Zoch, Clausen 2007–2018 Section 5.5	C5 Linked parts Tracht, Kuhfuß 2011–2018 Section 3.2	T5 TEC-Pro Vollertsen 2015–2016 Section 4.4
A5 Laser contour Goch, Vollertsen 2007–2018 Section 4.3	B5 Safe processes Bergmann, Goch, Lütjen 2007–2018 Section 5.2	C6 Spray-graded tool steels Schulz 2011–2017 Section 6.2	
A6 Friction polishing Brinksmeier 2007–2017 Section 4.6	B7 Process stability Vollertsen 2011–2018 Section 2.5		

further process steps before and after the forming step. At the beginning of the interacting processes is the production of semi-finished products for the micro forming production.

## B—Characterization

With regard to new materials, tools and processes for micro forming, an exact knowledge concerning the material behavior of both the workpieces and the tools and their interaction is essential. This is subject of the project area B characterization of this Collaborative Research Center.

## C—Optimization

In order to meet the precision and speed requirements of a reliable and cost-effective production process, this project area uses the results of process development and the characterization of basic material properties and product parameters to optimize the key production steps.

## T—Transfer

Research enhancing the basic research results of the CRC is examined in transfer projects, each realized in cooperation with an industry partner.

The results of the complete funding period of all projects running in 2016 or later are described in Sects. 2.1–6.4. In addition, a special approach for in situ geometry measurement in fluids, using confocal fluorescence microscopy, is presented in Sect. 5.4.

## Internal Cooperation

### Collaborating Institutes

Eight institutes, located on the campus of the University of Bremen, collaborate with their special knowledge to achieve the collective aim. They are listed in alphabetical order together with the most important research areas covered within the CRC. The names of the actual responsible heads of the projects are given in brackets:

**BIAS**—Bremer Institut für angewandte Strahltechnik: Laser material processing, sheet and bulk metal micro forming (Prof. Dr.-Ing. Frank Vollertsen); optical metrology (Prof. Dr. rer. nat. Ralf Bergmann).

**BIBA**—Bremer Institut für Produktion und Logistik: Logistics and simultaneous engineering (Dr.-Ing. Michael Lütjen).

**BIMAQ**—Bremer Institut für Messtechnik, Automatisierung und Qualitätswissenschaft: Process control including metrology, quality assurance (Prof. Dr.-Ing. Andreas Fischer, Prof. Dr.-Ing. Gert Goch).

**bime**—Bremer Institut für Strukturmechanik und Produktionsanlagen: Bulk metal forming including machine development (Prof. Dr.-Ing. Bernd Kuhfuß); process chain layout and automatization (Prof. Dr.-Ing. Kirsten Tracht).

**IFS**—Institut für Statistik: Monte-Carlo simulation and statistics (Prof. Dr. Mag. rer. nat. Werner Brannath).

**Leibniz**—IWT Leibniz-Institut für Werkstofforientierte Technologien: Physical vapor deposition, heat treatment and mechanical testing (Prof. Dr.-Ing. Hans-Werner Zoch, Prof. Dr.-Ing. Brigitte Clausen, Dr.-Ing. Andreas Mehner, Dr.-Ing. Alwin Schulz, Dr.-Ing. Martin Hunkel).

**Leibniz**—IWT (LFM) Leibniz-Institut für Werkstofforientierte Technologien, Laboratory for Precision Machining: Cutting, machining and polishing (Prof. Dr.-Ing. Prof. h.c. Dr.-Ing. E.h. Ekkard Brinksmeier, Dr.-Ing. Oltmann Riemer).

**ZeTeM**—Zentrum für Technomathematik: Industrial mathematics (Prof. Dr. Dr. h.c. Peter Maaß), simulation systems (Prof. Dr. Alfred Schmidt).

## Fields of Competence

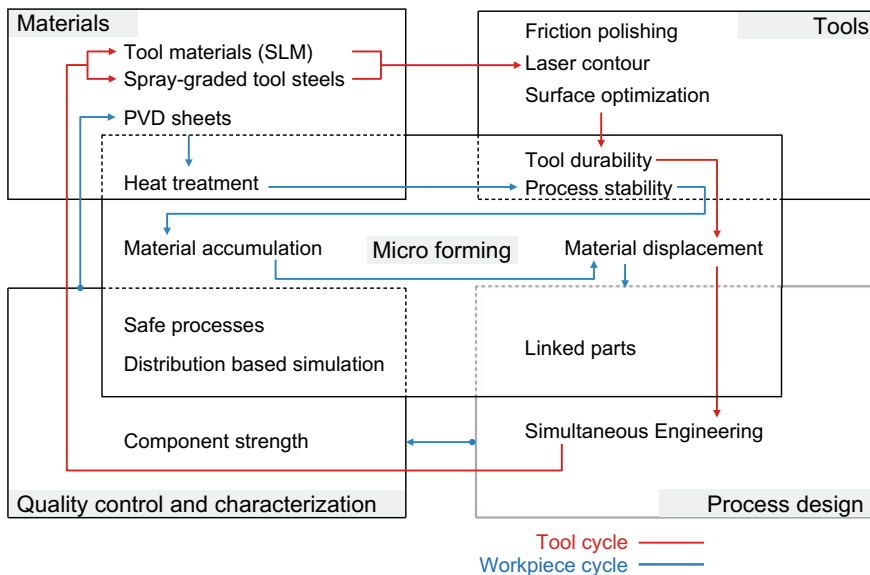
The global approach, which spans a bridge from the base materials to the finished component in terms of micro forming technology, is a specialty of this Collaborative Research Center. Two exemplary cycles are shown in Fig. 1.2. Within the fields of competence, working meetings focused on material aspects, on process design including the demonstrator and on the aspects of component characterization as well as on tool-specific issues.

In Chaps. 2–6, more can be learned about the knowledge gained in the fields of competence micro forming, tooling, quality control and characterization, as well as concerning new materials for thin sheets and adapted tools, which were especially developed to fulfill the needs of micro forming aspects.

## Communication with the International Scientific Community

An essential device is the discussion of research results at relevant conferences and congresses, as well as publications in international journals and books. In addition, there are contacts with renowned scientific networks, such as acatech, AGU, AHMT, AWT, CIRP, euspen, ICFG, IDDRG, I<sup>2</sup>FG, GCFG, GQW, MHI, SME, WAW, WGP und WLT by the principal investigators and participating institute directors.

The book “Micro Metal Forming”, written by the scientists of SFB 747 and edited by F. Vollertsen, was published by Springer in the book series “Lecture Notes in Production Engineering” in 2013 [Vol13].



**Fig. 1.2** Exemplary display of one workpiece and one tool cycle within the fields of competence of CRC (for space reasons without transfer projects)



Further, the research of the CRC has been sustainably supported by numerous impulses gained by close collaboration with international partners in relevant research fields, such as:

Micro forming (Prof. Ming Yang, Tokyo Metropolitan University, Japan)

Laser material processing and micro milling (Prof. Frank E. Pfefferkorn, University of Wisconsin-Madison, USA)

Microstructuring of polycrystalline diamond (Dr. Yiqing Chen and Prof. Liagchi Zhang of the University of New South Wales in Australia)

Wear (Prof. Hans Norgaard Hansen and Dr. Guido Tosello of the Technical University of Denmark (DTU))

Mathematical methods (Prof. Pham Quy Muoi, The University of Danang, Vietnam; Dr. Jonathan Montalvo-Urquizo, CIMAT Centro de Investigación en Matemáticas, Guanajuato, Mexico; Prof. Eberhard Bänsch, University Erlangen).

The CRC (co)organized the following scientific conferences:

The national Colloquium Micro Production has taken place biannually since 2003. The joint organization of the collaborative research groups of micro technology and their follow-up projects have the overall objective of micro technical questions. The conference was hosted in Bremen in 2009 and 2017. The event was also used intensively by the industrial partners for the exchange of information. Since 2014 the CRC has established a session “micro forming technologies” at the International Conference on Nanomanufacturing (nanoMan), which is biannually organized by the International Society for Nanomanufacturing. The International Conference on New Forming Technology (ICNFT) is an inspiring forum for researchers and professional practitioners to discuss aspects of leading-edge novel forming technologies. The steering committee of the conference comprises members from BIAS, Germany, Harbin Institute of Technology, China, the University of Birmingham, UK and the University of Strathclyde, UK. The CIRP and DFG sponsored 5th ICNFT 2018 took place in Bremen, Germany. In 2018, special sessions focusing on micro cold forming were included. Within this scope, the CRC held its final Colloquium in exchange with international specialists.

Additionally, the CRC presented itself at fair trade stands, for example at the International Conference on Technology of Plasticity (ICTP) in 2011 and 2017. Around 700 international, mainly scientific, participants were informed about the collaborative focus and research results.

### **Cooperation with Industry**

In addition to the scientific national and international networks, an industrial working group was established in the first funding period, with the aim of transferring the research results to industry and orienting the scientific research to current needs. Members of the industrial workgroup are:

BEGO Medical GmbH, Robert Bosch GmbH, Uni Bremen Campus GmbH, Felss GmbH, Harting Applied Technologies GmbH & Co. KG, Hella Fahrzeugkomponenten GmbH, Huber und Suhner AG, IFUTECH GmbH, Keyence GmbH, Philips Consumer Lifestyle B.V., SITEC Industrietechnologie GmbH, SLM



**Fig. 1.3** A selection of national and international conferences and exhibition stands on trade fairs for research and industry, (co)organized by SFB 747

Solutions GmbH, Stüken GmbH & Co. KG, Tyco Electronics GmbH & Co. KG, Wafios Umformtechnik GmbH, Werth Tool MT GmbH, Weidmüller Interface GmbH & Co. KG.

The consortium has been regularly provided with information from the CRC and an annual industry colloquium was held to identify co-operation issues. From this consortium also the transfer themes emerged (Fig. 1.3).

### Definition of Demands on Mastering Mass Production of Micro Parts

Research with the aim of providing new processes and methods especially adapted to the production of micro parts in high numbers took place in three funding periods (see Fig. 1.4).

From 2007 to 2010, the researchers developed new processes and methods that are especially designed for micro forming. The findings were improved in the second period (2011–14) to be more stable and to be used for the production of more complex products, while the processes were kept as easy as possible. In the last period, the knowledge was increased by upscaling the number of parts and the transfer to multistage processes.

The challenges arising from the goal of mastering the mass production of micro parts, which are to be solved with different weighting in the individual subprojects (see Table 1.1), consisted in the shortening of the process times, the increase in the forming speed, the modification of the tribology and the heat balance, as the higher clock rates result in an effectively higher power dissipation in the process zones. This is followed by the demand for faster transport, faster measurement and control processes, mastery of the tribology, thermal balance of the processes, and the dispersion of material properties (see Fig. 1.5). The main results of the



Fig. 1.4 Funding periods and their main research focus

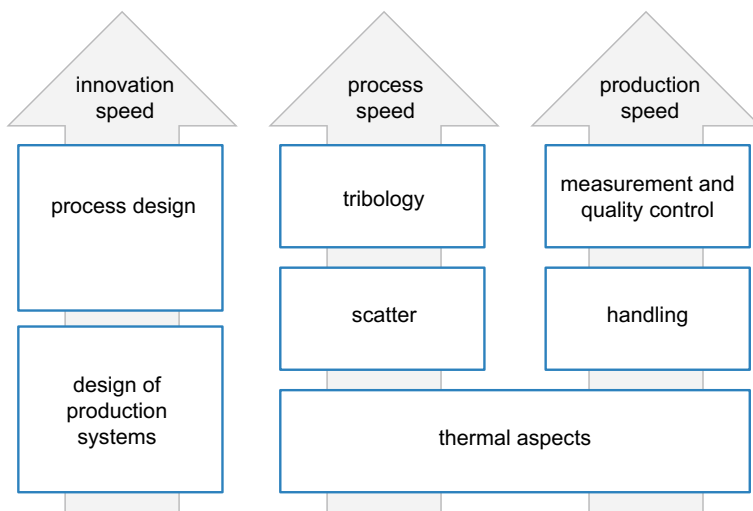


Fig. 1.5 Mastered aspects for a high quality and economic mass production of more than one million batches/micro parts

Collaboration Research Center “Micro Cold Forming” concerning mastering these aspects of innovation speed, process speed and production speed are summarized in Sect. 1.4.

## 1.4 Main Results

### 1.4.1 Innovation Speed

#### 1.4.1.1 Process Design

##### **Ann-Kathrin Onken and Kirsten Tracht\***

The design and development of new products and production processes is time-consuming. For faster design of parts, and hence a higher innovation speed, knowledge about the manufacturing processes, parts and their interdependencies is required. This knowledge also enables the simulation and modeling of processes and process steps.

To speed up the design of parts, one opportunity is the development of a modular design system, as shown for linked parts in Sect. 3.2. Linked parts are left in the material they are made of, for example, foil or wire. The remaining material of the interconnection can be used for the implementation of functions that assist in manufacturing processes. Besides the orientation of the parts, the interconnections are appended with functional elements, which are relevant for the handling, such as for the positioning of parts as concerned in the modular design system.

Basic knowledge about the process parameters and their influence on the workpiece are major results from the CRC 747 and build an important basis for fast adaptation to other products, parts or manufacturing processes.

Laser-based free-form heading (Sect. 2.2) is an alternative process chain in the micro range for the production of conventional upsetting and metal forming. It can be applied on rod and on thin metal sheet. With this method, which only works in the micro range, thermal upsetting relations to 500 are possible. The aim of three hundred line-linked parts per minute are realized, which can be formed in a further step. A validated 3D simulation enables the parameter identification and process analysis for free form heading.

Rotary swaging, which is well implemented in the macro range, for example, for producing parts for the automotive industry, has been adapted to the micro range. The two main variations of the process, infeed and plunge rotary swaging, were investigated in the CRC (Sect. 2.3). In order to increase the productivity in the micro range, the process speed can be increased. However, this could lead to failures, particularly due to inappropriate material flow against the feed direction. The findings show that, with additional measures, both the radial and the axial material flow can be controlled, and in both cases the productivity in micro rotary swaging can be increased by up to a factor of four. Furthermore, adjusting the axial positioning of the workpiece during plunge rotary swaging allows a higher diversity to be achieved for the geometry of the swaged part.

On the basis of rotary swaging, the refining (Sect. 2.4) deals with the conditioning of wire semi-finished products for the subsequent forming processes. The results show how the formability and the geometrical diversity of semi-finished parts are prepared by process modifications in rotary swaging tools and kinematics. These results can be adapted to other forming processes like deep drawing and extrusion.

In the case of single and multistep deep drawing, the prediction of the influence of the process parameters and tools on the geometrical properties of parts is also an aim of the investigations about the process stability (Sect. 2.5). The objective is the definition of the interaction of the tool geometry and the stability of a multi-stage micro-drawing process. The results show how to determine allowable and achievable manufacturing tolerances, and wear of the tools' geometry to ensure a stable manufacturing process while producing very large quantities.

Within the competence field of tools, especially the progress in laser chemical machining (Sect. 4.3) enables precise quality control during the manufacturing of metallic micro forming tools. The combination of thermal modeling to define the temperature regime for a disturbance-free removal and closed-loop quality control to compensate the deviations of quality features opens up the possibility of dimensionally and geometrically flexible micro machining. In addition, a developed machining strategy consisting of roughing and finishing steps is used to improve both the microstructural and the topographical tool quality.

By developing the method of non-linear inverse problems, it was possible to allow optimized process parameters for the manufacturing process of tribologically optimized micro forming dies (Sect. 4.5).

The impact of the process parameters on the material properties is presented by the results of two investigated processes. The results of the PVD sheet production in Sect. 6.3 show how magnetron sputtering is established for the generation of thin foils with high strength and good forming behavior. The results clarify how the thickness of the coating is adjustable by changing the transport speed and the size of the exposure area.

In the micro range, heat treatment in a drop-down tube furnace, where the parts are heat-treated as they are falling, is possible because of the size effects (Sect. 6.4). The investigations make it possible to retain the accuracy of the shape as well as the specific setting of properties. Therefore, parameters like the falling time, temperature areas within the furnace, and quenching medium are considered.

Several manufacturing processes for forming tools with tailored material properties that lengthen the tool lifetime were established. One option is tool manufacturing by selective laser melting [Flo16]. Co-spray forming with selective heat treatment afterwards allows adapted tool steels and properties in the specific regions of the tool, with a gradual material transition in between to ensure good bonding (Sect. 6.2).

### 1.4.1.2 *Design of Production Systems*

#### **Ann-Kathrin Onken and Kirsten Tracht\***

The planning and configuration of process chains constitutes a major factor of success for the industrial production of metallic micromechanical components, due to the occurrence of size effects, the inherently small tolerances, and the small geometrical dimensions of the workpieces. For this reason, methodologies and recommendations for the design of production systems for micro mass production are required. Within this context, CRC 747 focuses on two different aspects with two different perspectives.

The first is the widening of the tolerance field (Sect. 3.2). This methodology follows a super-ordinated point of view on the process chain. Based on measured geometrical dimensions of linked parts, trends occurring that are, for example, caused by wear are used for matching, and design adjustments. Therefore, a reduction of surplus parts as well as the increased durability of tools is achieved. The production of linked parts is crucial for this methodology. Due to the retention of the production order, the parts are measured to identify trends concerning geometrical deviations, which are used for building homogeneous trend sections. These sections are used for matching linked parts for building assemblies. Hence a softening of the tolerances, similar to selective assembly, is achieved. Selective assembly is usually applied to scenarios where processes are hard to control. In micro mass production, this specific matching enables a widening of the tolerance field. The feedback loop to the design stage enables further increases in the outcome by a stepwise adjustment of the nominal value and new combinations of parts. With the adjusted nominal value, the identified sections, and matchings, further batches are produced and assembled.

The second perspective focuses on detailing the interdependencies between and within processes by considering the effects of single parameters on the production result. Small variations in single parameters can have significant influences along the process chain and finally interfere with the compliance with tolerances. For this reason, the  $\mu$ -Process Planning and Analysis methodology (Sect. 3.3) covers all phases from the process and material flow planning to the configuration and evaluation of the processes and process chain models. The process configuration relies on so-called cause–effect networks, subsuming the relevant logistic and technical parameters of the corresponding processes and describing their relationships to each other. By using these networks,  $\mu$ -Process Planning and Analysis enables a fast evaluation of different process configurations (e.g. the use of different materials or different production velocities) already during the planning stages. The networks enable an assessment of the impacts of different choices on the follow-up processes or the production system in general. Thereto,  $\mu$ -Process Planning and Analysis can directly reflect changes to the configuration in the integrated material flow simulation and evaluate these configurations, e.g., regarding work-in-progress levels, lead times or the products' estimated qualities.

## 1.4.2 Micro Mass Forming

### 1.4.2.1 Tribology

**Florian Böhmermann\* and Oltmann Riemer\***

Tribology is one major concern in the development of micro cold forming processes. Size effects lead to changes in the predominant friction mechanism towards adhesion, as well as a reduction of the effectiveness of lubrication. This is associated with an increase of friction and has an impact on the wear behavior. Furthermore, micro forming dies and work pieces show anisotropic behavior in wear or non-predictable malfunctions, as the geometrical features and micro structure are of about the same size. Thus, the development of robust micro cold forming processes presumes an understanding of the mechanisms of friction and wear in the micro regime. The main work within CRC 747 was first to determine the wear mechanisms in micro cold forming processes and to derive measures to avoid and reduce wear (Sect. 4.2). The second area of investigation was the development of dry micro deep drawing processes utilizing textured forming dies. The work here comprised the development of new and geometrically scaled down experimental setups for tribological investigations and the generation and application of textured surfaces with friction-reducing properties (Sect. 4.5).

#### *Investigation and Avoidance of Wear*

The investigation of forming die wear in micro deep drawing was carried out within a combined blanking and deep drawing process on a high dynamic forming press with two linear direct driven axes. Here, up to 300,000 micro cups were machined in a row. Replication techniques were applied to allow for an ex situ forming die wear investigation and the forming die to remain in the machine. The combined blanking and forming die suffered from failure of the cutting edge rather than abrasive wear of the drawing edge radius (see Sect. 4.2). The dies' malfunction was traced back to the comparatively coarse grain of the applied cold working steel. The application of forming dies made from fine-grained tool steel generated by powder metallurgy helped to overcome this issue.

Furthermore, a combined blanking and forming die from the alternative material Stellite was introduced. The die was manufactured by laser selective melting (SLM) and micro grinding for contour finalization. Comparatively high hardness and excellent toughness allowed for the successful forming of 231,000 micro cups in a row (see Sect. 4.5 and [Flo16]).

With regard to the investigation of adhesive wear in micro rotary swaging, dry machining of aluminum Al99.5 workpieces was carried out. Distinct amounts of cold-welded aluminum were found on the dies after the experiments (Sect. 2.3). With the aim of avoiding adhesion, a fracture-tough, tungsten-doped diamond-like carbon (DLC) hard coating system was developed suitable for the particular application on micro rotary swaging dies with small geometric features (Sect. 6.3).

Subsequent dry micro rotary swaging experiments against aluminum workpieces applying DLC hard coated forming dies showed a distinct reduction in adhesive wear. This allowed the feed velocity to be doubled, achieving higher degrees of deformation in a single process step and increasing the forming die life by a factor of three.

With the aim of providing wear-resistant tool steels with improved and locally adapted mechanical properties, a new material generation process was developed: co-spray forming. In co-spray forming, melts of different materials are sprayed onto a substrate, forming a deposit with the finest microstructure and gradient zones between different material layers. Subsequently, the generated material is hot rolled and heat treated. Micro rotary swaging dies were made from co-sprayed material composed of two different hot working steels. Subsequently, these dies were successfully applied in infeed rotary swaging experiments (Sect. 6.2).

The application of cemented carbides as material for micro forming dies is a promising measure to reduce the abrasive wear and plastic deformation of forming dies. This is due to cemented carbides' significantly higher hardness compared to hardened tool steels, together with their toughness against impact loads. However, machining of cemented carbides in small geometrical dimensions with features sizes down to 100  $\mu\text{m}$  is challenging, e.g. due to strong geometrical limits to the application of grinding. Micro milling applying novel ball endmills with cutting edges from binderless polycrystalline diamond (PCD) is an alternative approach that provides both comparatively high material removal rates and a sufficient surface finish. Machining experiments with binderless PCD ball endmills were carried out on tungsten carbide samples of different compositions. It was found that especially fine-grained materials (grain sizes  $<1 \mu\text{m}$ ) provide the best machining results. Crack-free machining was achieved and ductile inter-crystalline cutting was identified as the predominant material removal mechanism. Further work showed the distinct dependence of the machining result, i.e. the surface roughness, on the machining strategy: this is up- and down-milling. Down-milling provoked distinct chatter and reduced the machining quality. Furthermore, wear mechanisms of the applied micro endmills were identified in dependence on the process parameter feed per tooth. This allowed suitable machining parameters to be derived for the machining of micro forming dies from cemented carbide with a geometrically defined cutting edge (Sect. 4.5).

On top of these measures with respect to channeling and avoiding wear in micro forming, the application of diamond as a tool material has been advanced. The outstanding properties of diamond, with a low friction coefficient in tribological contact with metals, were applied beneficially, and additionally the diamond tool surfaces were micro-structured for friction control. Therefore, a friction polishing process was developed and the principal mechanisms governing the machining of diamond by using thermo-chemical effects were elucidated (Sect. 4.7).

### *Micro Tribometry*

Micro deep drawing processes, obviously, are characterized by only small areas of contact between the tool—this is the die and the blank holder—and the workpiece.



Even though the nominal process forces are low, the reduced interface provokes significant loads on the microscopic level determining friction and wear. Tribological investigation in the micro regime is crucial, for example, for the development of dry deep drawing processes utilizing novel textured forming dies. This requires sensitive instruments and well-developed methodologies to guarantee meaningful results.

For the micro tribological investigation within CRC 747, a new methodology using a micro tribometer in ball-on-plate configuration with balls exhibiting facet areas was developed. Applying the micro tribometer allowed the successful determination of the impact of the micro geometry of textured surfaces on their friction coefficient under dry conditions (Sect. 4.5).

The in-depth tribological investigations of micro deep drawing processes were carried out on a specialized forming press equipped with piezo-electric force measurement equipment to precisely determine the blank holder and punch force in dependence on the punch's position. The aerostatic bearings of the machine, furthermore, helped to minimize the impact of frictional losses during machine movement. Tribological investigations were carried out to determine the impact of the tool geometry, i.e. the drawing edge radius geometrical inaccuracies as a result of the micro machining process, on process forces and the drawing ratio. Furthermore, they were used to confirm the results of the finite element method (FEM)-based development of multistage deep drawing processes (Sect. 2.5).

#### *Micro Textured, Tribologically Active Surfaces*

The micro geometry or roughness of interfacing surfaces is of greatest relevance for the development of dry micro deep drawing processes. The micro geometry determines the real area of contact, the predominant friction mechanism—adhesion or abrasion—and thus the friction and the wear behavior. Micro milling, as the most common process for the manufacture of micro forming dies made from hardened tool steels, due to its kinematic and size effects, allows textured surfaces to be generated. The design of these textures is most dependent on the hardness of the machined material, the feed per tooth, and the line pitch. The friction-reducing properties were shown in strip drawing tests and micro tribological investigations using a micro tribometer. It was found for dry strip drawing tests on stainless steel strips that textured surfaces allow the friction to be reduced by up to 20% compared to a polished reference sample. Such textures were also transferred to the surfaces of micro forming dies for the deep drawing of rectangular cups. However, an increase of, for example, the achievable drawing ratio has so far not been found (Sect. 4.5).

The derivation of the most suitable textured surfaces generated by micro milling still remains a research topic. To cover this demand, micro contact and friction modeling is applied. With the purpose of micro modeling, for the first time the combination of a stochastic micro contact model, i.e., the model of Greenwood and Williamson, and feature parameters according to the ISO 25178 standard was shown. This allows for the implantation of actual textured surfaces, e.g., generated by micro milling, into the model and thus the calculation of micro contact conditions in dependence on the normal load. For selected textured surfaces, the contact

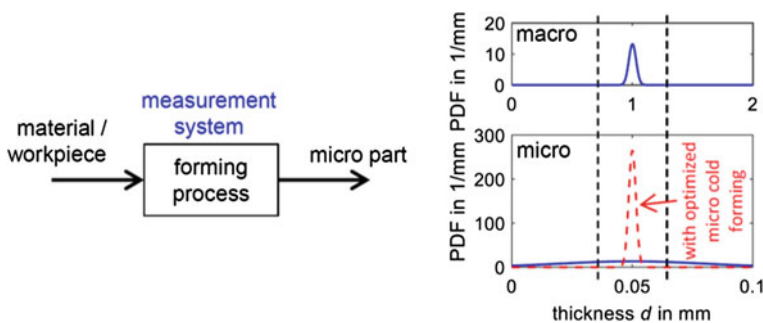
parameter real area of contact and average force acting on a single roughness peak were calculated. The results show excellent correlation with the frictional properties of the surfaces. For the smallest real area of contact, the lowest friction was measured in ball-on-plate tribological experiments. This new expanded Greenwood and Williamson model builds the foundation for the development of a comprehensive friction model for the derivation of the most promising textured surfaces design, allowing the reduction of friction in dry deep drawing. The friction modeling is the subject of ongoing research (Sect. 2.5).

#### 1.4.2.2 Scatter

##### Andreas Fischer\*

Dispersion (or scatter) indicates the distribution of the available data of a physical quantity. It can be characterized by different measures, e.g., variance, standard deviation, quantile or span. Dispersion is quantified and interpreted using stochastic methods (probability theory and statistics). It can be used, for example, to evaluate the stability of processes and process parameters, the uncertainty in the characterization of materials and components, as well as the efficiency of signal processing algorithms.

Due to the increasing influence of the grain structure of metals in micro production, dispersion plays an even more important role than in the production of macro parts. It has to be considered in all components of the micro process chain (see Fig. 1.6).



**Fig. 1.6** Dispersion affects all components of a production process, the geometric or material properties of the workpiece, the process capability, the measuring process, and finally propagates to the quality features of the micro part. Considering the example of producing a foil with the thickness  $d$ , the probability density functions (PDF) shown visualize the scaling effect with respect to the dispersion. When scaling down the macro process (top) to smaller foil thicknesses (bottom), the (also scaled) tolerances (black dashed lines) are exceeded. Since the dispersion of the micro part feature results from the superposed dispersions of the material parameters, the production process and the measurement system, all three components have to be considered in order to minimize the resulting dispersion of the produced micro part and to fulfill given tolerances

Within the CRC, dispersions were considered

- (a) to characterize material properties and processes,
- (b) to optimize process chains, and
- (c) to assess a measuring system for geometric micro features.

(a) The presentation of the characterization of material properties and processes is chronologically divided into the steps of a general process chain. The dispersion of two primary shaping processes and the material parameters, respectively, are discussed first. The dispersion attributed to the main forming process is described next, followed by the dispersion occurring in a subsequent process step such as heat post-treatment.

In the production of thin foils as semi-finished parts for micro deep drawing, it is of primary importance that the thickness is homogeneously distributed. Indeed, foils, like other components with dimensions of less than one millimeter, are subject to size effects. In particular, the strength and ductility and thus the drawability of thin foils significantly decrease when the thickness is reduced. Therefore, foils with a non-homogeneous thickness distribution may result in a higher number of waste parts in micro deep drawing due to locally weaker drawability. In order to reach a more homogeneous thickness distribution of thin foils, the magnetron sputtering process was optimized by an oscillating or rotating substrate holder (see Sect. 6.3). As a result, the standard deviation of the foil thickness was reduced by a factor of 9 from 4.7 to 0.5  $\mu\text{m}$ .

Laser-based free form heading is a further original forming process, where dispersion effects were identified and reduced. The resulting preforms of the produced parts have a random eccentricity, i.e., the location of the intermediate shape relating to the shaft varies for each workpiece. The eccentricity of the preform depends on the applied laser intensity. For intensities where the absorption can be described by the model of Fresnel, the process design causes more material to melt on the laser beam affected side of the rod and results in a random variation of the eccentricity. When using higher intensities, the absorption over the entire rod cross-section is more uniform due to the keyhole formation and the dispersion of the eccentricity is reduced by about 40%. However, this requires a narrow process window, since the keyhole effect causes higher dynamics within the melt, which can also lead to an eccentric positioning of the solidifying melt (see Sect. 2.2). Independent of the laser process, the span of the eccentricity can also be reduced from a maximum of 100–30  $\mu\text{m}$  by the subsequent forming step. Thus, the impact of the dispersion of the first process stage on the accuracy of the final part geometry is small as a result of the self-calibration during the second process stage.

The interaction between the dies and the workpiece during forming leads to material modifications, e.g., with respect to the microstructure and the mechanical properties. The dispersion of the Martens hardness of the part after micro rotary swaging reaches as much as  $\sim 250 \text{ N/mm}^2$  compared to about  $\sim 160 \text{ N/mm}^2$  before forming (see Sect. 2.3). The increased dispersion occurred because of the

inhomogeneity of the microstructure (austenite soft, strain-induced martensite hard) as well as the distribution of the hardness across the diameter of the cylindrical workpiece. The observed distributions can be explained by the strain being inhomogeneously distributed over the diameter. The results of cyclic tension tests of micro rotary swaged parts show a dispersion over almost 4 decades (see Sect. 5.5). The effect can be explained by a size effect. In small volumes, the appearance of a critical failure is less probable than in a larger volume. The hypothesis is confirmed by the lower fatigue strength of macroscopic swaged parts. As a consequence, the fatigue strength of the micro rotary swaged parts should be defined as the value with a lower probability of failure (e.g. 10%) than the usual 50%.

Finally, it was observed that the heat treatment by means of a drop-down tube furnace produces high dispersions of the micro hardness of the processed micro cups. This finding is also a result of the size effect, as the relation between gravity and flow forces in the process is different for micro cups compared to macro parts. This leads to high variations in the falling time of the parts through the furnace, resulting directly in different material properties. In order to reduce this effect by stabilizing the heat treatment time in the furnace, an opposing gas flow was integrated into the process (Sect. 6.4).

(b) Concerning the optimization of process chains, the high dispersion in process parameters inherent to micro manufacturing leads to additional challenges during the planning of complete manufacturing process chains. For this reason, the method “Micro-Process Planning and Analysis” ( $\mu$ -ProPIAn) was developed that enables process planners to plan and configure stable process chains (Sect. 3.3).  $\mu$ -ProPIAn includes stochastic methods to characterize the expected value and the variance of the input process parameters based on an experimentally obtained dataset. The dispersion of productions can be improved by evaluating different configurations of the entire process chain and by using  $\mu$ -ProPIAn’s so-called cause–effect networks to estimate the required mean values of the input process parameters, as well as the resulting variances of the production output quantities.

The stochastic modeling approach in  $\mu$ -ProPIAn is mainly based on a forward model of the process chain. In order to find suitable process parameters for a given production aim (e.g. the specified geometrical features of the product), however, the forward model has to be inverted. Since many forward models are ill-posed, meaning they cannot be inverted as they are non-injective or tend to amplify small deviations in the output, regularization methods such as Tikhonov regularization from the area of inverse problems are applied. In addition, existing, classical approaches have been altered to consider uncertainties when solving the inverse problem. As a result, process parameters can be identified that not only fulfill a given expected output but also stay within a given range (tolerance). Further information on this topic can be found in Sects. 4.5 and 4.6.

(c) Beside the manufacturing processes, dispersion also plays an important role in quality inspection. The dispersion of the measurement results is characterized by the measurement uncertainty. In micro production, the proportion of the geometric feature of the workpiece to be measured to its tolerance and the measurement

uncertainty is different compared with the inspection of macro parts. In addition, high aspect ratios in small dimensions, steep surfaces and gradients, as well as a limited accessibility are challenging for the acquisition and evaluation of surface measurement data. To cope with these boundary conditions, a measurement system was developed within the CRC, which captures the part's three-dimensional surface with a digital holographic microscope setup and automatically evaluates its geometric features by a holistic approximation, as well as surface defects by means of a convolutional neural network. The details of this system are described in Sects. 5.2 and 5.3. Increased uncertainties in the evaluation of incomplete geometric features are reduced by acquiring as much as possible of the part's surface out of 4 directions in one shot. Another problem is the holographic reconstruction of optically rough surfaces, if the height variations exceed one quarter of the wavelength. Therefore, the two-wavelength contouring technique was applied. In addition, a method to reduce speckle decorrelation noise was implemented based on averaging the results obtained from multiple measurements with varying directions of illumination. Finally, by applying convolution-based low pass filtering, the standard deviation of the depth measurement could be reduced from 4.4 to 1.5  $\mu\text{m}$ . Regarding the subsequent automatic evaluation of geometric parameters out of the surface point cloud of a micro cup, the holistic approximation approach was verified to yield measurement uncertainties below 0.5  $\mu\text{m}$ .

## 1.4.3 Mastered Production

### 1.4.3.1 Measurement and Quality Control

#### Ralf B. Bergmann\*

At the start of the CRC, there was no method available that enabled the measurement of the shape or deformation of micro parts with a complex geometry that is at the same time precise (low measurement uncertainty in the  $\mu\text{m}$  or sub- $\mu\text{m}$  range), fast (typically less than a second) and robust (capable of operating outside a measurement lab). In the course of the CRC, a digital holographic measurement system was realized that uses four simultaneous directions of observation and enables optical measurement to be done within approx. 120 ms. The measurement and fully automated evaluation of 3D geometry and surface defects of a micro cup proceed within around 12 s. The dominant time fraction of 11 s is required for data transfer and hologram analysis to obtain the 3D point cloud which is used as input for geometry and surface defect analysis. Next, measurement algorithms are used for an automatic evaluation of dimensional deviations by combining a least squares approximation with an optimal decomposition of the point cloud into elementary geometries and for an automated recognition of surface defects. The system achieves an axial measurement uncertainty of 5  $\mu\text{m}$  and a lateral resolution of 2  $\mu\text{m}$ . In the framework of a transfer project, another holographic measurement

technique was set up, that enables the detection of defects with a minimum lateral extent of 2  $\mu\text{m}$  and a minimum depth of 5  $\mu\text{m}$  within cavities of the micro formed parts investigated. For further details refer to Sects. 5.2 and 5.3.

The characterization of the laser chemical machining (LCM) quality as well as its comparison with competing processes were defined as key objectives toward widespread industrial acceptance. Using confocal microscopy in combination with the holistic approximation approach of the CRC to quantify geometric features, it was demonstrated that LCM is particularly suited for the manufacture of micro cavities with dimensions  $< 200 \mu\text{m}$ . In comparison with micro milling, laser chemical machining shows higher shape and dimensional accuracy due to sharp edge contours with mean edge radii of  $(11.2 \pm 1.3) \mu\text{m}$ . However, the surface finish quality of micro milling (with  $S_a = 0.2 \mu\text{m}$ ) could not be achieved due to the remaining surface waviness, which limits the LCM finishing to  $S_a > 0.7 \mu\text{m}$ . For further details refer to Sect. 4.3.

Tool wear is usually measured by using optical measurements directly on the tool. The challenge is, however, to determine the tool wear from a measurement of the forming product. In this case, experiments in lateral micro upsetting were carried out in which the tool wear is reproduced on the formed wire. The reproduced tool geometry on the wire was analyzed and compared to the original geometry of the tool. Both the tool and the wire were measured with a confocal microscope with the same measurement conditions. The development of this technique allows the measurement of the tool wear history on the wire reproductions with a forming accuracy of down to 1.5  $\mu\text{m}$ . For further details refer to Sect. 4.2.

Prior to the CRC it was not possible to perform tensile tests or fatigue tests for micro swaged wires with enhanced strength, since the wires tend to break in the clamping device as a consequence of stress peaks. It was not possible to glue adequate tubes to the samples ends to enhance the diameter of the shafts, since for a sufficiently strong bond it is necessary to cure the adhesive at 180  $^{\circ}\text{C}$ , which leads to an unwanted heat treatment of the sample. Within the project a special clamping device for wires, following the approach for fibers, was constructed. The extreme strength of the wires demands a very high surface hardness of the device, which was implemented by a nitriding heat treatment. For further details refer to Sect. 5.5.

For the determination of a forming limit diagram, the ISO standard defines the dimensions of the experimental setup. The ISO standard is, however, created for material testing in the macro range and material thicknesses above 300  $\mu\text{m}$ . Within the CRC, a test was developed to measure the forming limit diagram for thicknesses below 200  $\mu\text{m}$ . For the detection of localized deformation, which occurs in the micro range, the test setup was scaled down to a diameter of 6 mm for the forming area. Thus the lateral resolution of the optical strain measurement is in the range of the grain size and localized deformation can be measured. The optical measurement method is based on a stereo camera system that uses digital image correlation for the strain measurement. Due to the new measurement method, the determination of the forming limit diagram in the micro range is simplified and the accuracy is increased. For further details refer to Sect. 2.5.

### **1.4.3.2 Handling**

#### **Ann-Kathrin Onken and Kirsten Tracht\***

Micro mass production with conventional handling technologies like vibratory conveyors is limited by the sticking effects and small tolerances that occur. Basic functions for handling parts in bulk are functions like separation, orientation, positioning, and transfer. Hence, handling micro parts in bulk slows down the manufacturing and assembly of micro parts. For this reason, the preparation of micro parts has a major impact on the ability to produce micro parts in large quantities. The handling of micro parts is simplified and sped up by interconnecting the parts. Therefore, the linked parts are left in the material, such as foil or wire. While manufacturing linked parts, handling functions such as orientation, separation, and positioning is already covered by the application of the linked parts production method. The basic material of the parts offers the possibility of implementing assisting elements for subsequent production stages.

Technologies for the handling of linked micro parts are speeding up their manufacturing and assembly (Sect. 3.2). A fast transportation is enabled by specific conveyor technologies, which transport parts at rates of up to 500 parts/minute. In combination with referencing of the parts, a fast synchronization of pre-assemblies is implemented. The storage of micro parts is also simplified by the interconnection. Concepts ensure the safe buffering and long-term storage. For long-term storage, the well-known concept of coiling is combined with the usage of layers between the linked parts. This ensures fast and deformation-free storage. Buffering between the stations facilitates especially the required flexibility. Due to the retention of the orientation and position, simple concepts like extending the conveying distance using guiding rollers are applicable.

The production as linked parts offers several advantages, simplifies the handling, and significantly speeds up parts transport, but new challenges also result from the linking of the parts. This has been investigated in cooperation with the processes of laser melting (Sect. 2.2) and rotary swaging (Sect. 2.3). It was shown that the application of the feeder to the tasks of transport, positioning and eventual feed during processing results in different requirements, between which a compromise is needed. Further, the structural connection of the parts leads to a transfer of forces and the processes change the structure. The effects that occur are shown and measured to deal with the resulting challenges.

### **1.4.3.3 Thermal Aspects**

#### **Frank Vollertsen\***

Within the current research on micro forming, questions of thermal aspects were mainly those where special effects occurred due to the upscaling of the production rate. Higher production rates very often lead to shorter processing time, while the

total work (energy for a specific plastic deformation) per workpiece is held constant. This results in an increased process power, which has to be transferred by the tool. As a consequence of the dissipation of heat, which is the biggest share of energy consumption in metal forming processes, the input power into the tools is increased. As the tool dimensions and the tool material, i.e. its physical properties like thermal conductivity and other, are held constant, the conditions for cooling are unchanged. Only higher thermal gradients due to heating up to higher temperatures will enhance the apparent cooling power, but in spite of that, higher temperatures will result in tools and even in workpieces when scaling up the production rate. The increased temperature of the workpieces and tools can have many different effects. An increased tool temperature can have detrimental effects on tool wear, the workpiece material might have another plastic deformation behavior, and the increased temperature could affect lubricated and unlubricated friction. In order to master this, the temperature fields in tools and workpieces, the damage mechanisms and the development of the microstructure all have to be controlled. Therefore, research has been done in two main fields to control the thermal aspects. First, methods for the measurement, prediction and control of thermal fields were developed. Second, detailed questions, which were mainly induced by the higher production rates, were solved.

Within the first task, i.e., mastering thermal fields in micro metal forming, experimental, analytical and numerical methods were developed. The process of laser-induced chemical etching, which has already been used for two-dimensional processing like cutting and drilling, had to be extended to three-dimensional processing, i.e. to a process similar to free-form milling. As the basic chemical reaction of the process is very sensitive to the local temperature, the temperature fields should be known. Due to the difficulties of direct temperature measurements, the temperature field was calculated. An analytical model was developed (Sect. 4.3) that helps to keep the temperature above the threshold limit (typically in the range of 65 °C for the given materials) and below the limit above which some disturbances of the process occur, like boiling of the electrolyte leading to inferior workpiece quality (slightly above 100 °C).

A method for the numerical simulation of a thermal process, e.g., thermal upsetting, was also developed. Thermal upsetting of wire and sheet material to get intermediate stages of the desired part was introduced within the research work. This process does not need any solid tools. It uses local melting of the raw part and the effect of surface tension, which is the dominant force component in the given range of workpiece sizes. A multiphase simulation was developed for the analysis of the thermal field during heating and cooling of the solid, liquid and gaseous material. Using an experimental determination of the solidification speed (Sect. 2.2), the anticipated transport mechanisms for the heat transfer were validated. In addition, the influence of the method for the absorption of the energy (heat conduction mode or keyhole mode) could be assessed concerning its influence on the overall cycle time (Sect. 2.2).



Within the second task, the thermal impacts due to higher production rates were analyzed with respect to the heat development, the impact on the microstructure of tool and workpiece material, and also wear and fatigue properties.

Measurements of the frictional heat due to a misalignment of tool components in deep drawing (Sect. 4.2) showed that the thermal impact can be measured, but is rather low (temperature increase below 5 K) and will not affect the process or the workpiece properties. Also, no critical effect on the tools was seen in rotary swaging. The tool temperature induced by the process heat in rotary swaging was as high as 300 °C (see Sect. 2.3), but an influence on the tool wear was excluded. This is because the annealing temperature of the tool materials used is above 500 °C (Sect. 6.2). For that reason, any impact on the tool properties, especially the wear properties, was excluded.

Significant influences of the time–temperature course were observed in the development of the microstructures of both the tool steel and workpiece materials. Tool steels were produced by spray forming. The substrate was initially a flat plate, which, in combination with spray forming of graded materials, led to excessive heating and coarsening of carbides. By changing the shape of the substrate to the form of a ring and thus increasing the surface during deposition, the cooling could be enhanced and finer carbides resulted (Sect. 6.2).

While the heating of the tools in rotary swaging did not affect the tool wear, the heating of the workpiece could have a significant influence on the workpiece properties, e.g. hardness and fatigue behavior. This was seen after measuring the material properties for samples which were processed by rotary swaging. Using a high feed-forward speed results in a lower hardness and endurance limit. The primary influences were strain hardening and strain-induced martensite formation and therewith the resulting martensite content, which was lower after forming at a higher speed (Sect. 5.5). Different mechanisms are discussed for this effect observed for high alloyed steel. One assumption is that a slow, stepwise deformation leads to higher martensite content than deformation in a few steps. The other assumption is that a higher feed-forward speed increases the mean temperature of the workpiece. This in turn leads to less strain-induced martensite (Sect. 2.3), which can be fully suppressed at slightly elevated temperatures.

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