

# Tooling solutions for challenges in cold forging

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## 1 Introduction

It is not quite new in the history of industrial society that from time to time technologies do question their current state, perspective and vision. However, especially in these challenging days characterized by globalization, economical crises, ecological challenges necessarily demanding a rethink and change in industry, such a questioning seems to be more than justified. Cold forging is affected as well, in particular because of its distinct dependence on the automotive industry which is facing a radical change in the next decades especially concerning motor, power unit and driving system. Hence, it is not surprising that the cold forging community, represented by their international and national societies, has started initiatives to think about future and visions. On its plenary meeting in Shanghai on Oct 2009 the ICFG established a new subgroup working on “cold forging 2050” giving a remarkable overview presented by Osakada to the historical development of cold forging in all areas concerned such as process, tooling, coating, machine tools, tribology...., the current state of 2010 and expected and/or expectable developments in the future. However, since just established the outcome of this subgroup work is pending. Independently from this but almost in parallel in Germany the GCFG has organized a workshop on “cold forging 2015” on Jan 2010, prepared and chaired by Th. Herlan with similar objectives, strong participation of German industry, finally messaging concrete results. As the perspectives and the results of the two initiatives mentioned are concerning cold forging as a whole there are many pointers recognizable concerning tools and tooling systems which will be picked up in the present paper. It should be noted that beside these initiatives the cold forging and tooling industry has already responded to the challenges described above, eg by changing company’s strategy in general, in particular its structure and its positioning in the market concerning customers and sub-suppliers. These kinds of measures are by nature not public but individual and specific to the company. However, from a more general point of view the necessary recent and future developments are clearly recognizable: global changes in demands of the market do require corresponding and structural adaption of the tooling industry in order to sustain successfully competitiveness. To meet this challenge, in [Hä06] different areas of activity are identified addressing (1) market and customer, (2) production and processes, (3) products and range of services offered, (4) engineering and innovation, and (5) organization and structures. Each area requires new ideas and new approaches. Hence, such strategic consideration represents another frame to look in detail to recent engineering solutions eg concerning tool and tooling system representing one of the keystones of the whole.

This is the intention of the present paper: focussing on tools and tooling systems, first, in order to identify the trends some examples of challenging products will be presented from which, secondly, the actual challenges for tool layout will be derived; finally, recent approaches towards new and innovative solutions will be discussed. It should be noted that all

the examples and case studies are confined to the realm of the GCFG, representing the view of the authors, and not claiming to be complete.

## 2 Trends

The trends, that require novel tool and process layouts in the cold forging and tooling industry to ensure its future competitiveness, are driven by ecological and economic developments. The ecological trends are mainly caused by legal regulations and customer's ecological awareness, the economic ones, are mainly due to the increasing cost and time pressure in the global competition. The following major trends have become apparent.

### Individualization

A major trend is driven by the market and the customer, respectively, which are increasingly demanding individualized products. This development profoundly affects the car industry and its suppliers. The high diversity of product variants resulting from this need leads to a high diversity of variants to be provided. For the cold forging and tooling industry this means, that a high and still increasing variety of parts and assemblies has to be offered. This results in a higher complexity that has to be managed. In addition, e.g. car companies more and more place niche products on the market that are produced in small quantities. Due to the high tool and tooling system costs, these developments cause especially for the cold forging and tooling industry an important need for cost and time reduction in product and tool development and tool production. The necessity of time reduction is furthermore driven by reduced product life cycle times.

### Lightweight design

As the cold forging industry is an important supplier of the automotive industry, it has to contribute its effort to more efficient cars, e.g. by means of lightweight design. A weight reduction of cold forged parts can be achieved by novel part ranges like hollow shafts or the application of higher-strength workpiece materials that permit the design of parts with reduced wall thicknesses. Due to their excellent mechanical properties forged components own a high lightweight potential. Besides reducing the weight of the final product, lightweight design can also help reducing the materials usage required in the manufacturing process and with it costs and use of energy.

Examples for innovative hollow transmission shafts with a significant weight reduction are illustrated in Figure 1. The figure shows different transmission shafts running in serial production with a hollow layout.

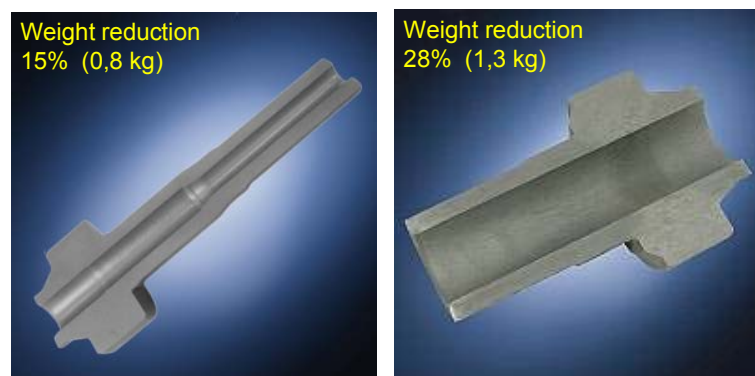


Figure 1: Cold forged hollow transmission shafts – superior mechanical properties permit weight reduction compared to drilled shafts (source: Hirschvogel)

Depending on the possible cavity diameter a weight reduction of 0.8 to 1.3 kg is to be expected for shafts in passenger car transmissions. Hollow forging entails other benefits besides weight reduction. Material is saved and no – or at least significantly reduced – drilling costs arise. The wall thickness of the part can be optimized and varied in accordance to the load and a parallel fibre flow is guaranteed, see also paragraph “Net-shape parts” [Qui09].

### Material utilization

A further trend promising a similar benefit for the cold forging shop is to achieve the highest possible utilization of the raw material volume. Here, ecological as well as cost reasons play an important role as well. In times of increasing demand for resources that leads to increasing costs for raw material, a high utilization of material is an important cost factor. The material utilization can be increased by reducing the workpiece volume removed e.g. by trimming or machining after the forming process.

An example for a high material utilization is shown in Figure 2. Conventionally, hollow transmission shafts are forged as solid shafts and subsequently hollow drilled. This procedure requires maximum material usage, as the entire hollow volume is lost in the form of drilling chips. In hollow forging processes, a shorter bar billet is formed without machining into a thick-walled hollow cylinder. In the following forging stages, the desired hollow shaft geometry is formed [Raedt08]. For further examples cf Figure 3 and 4.

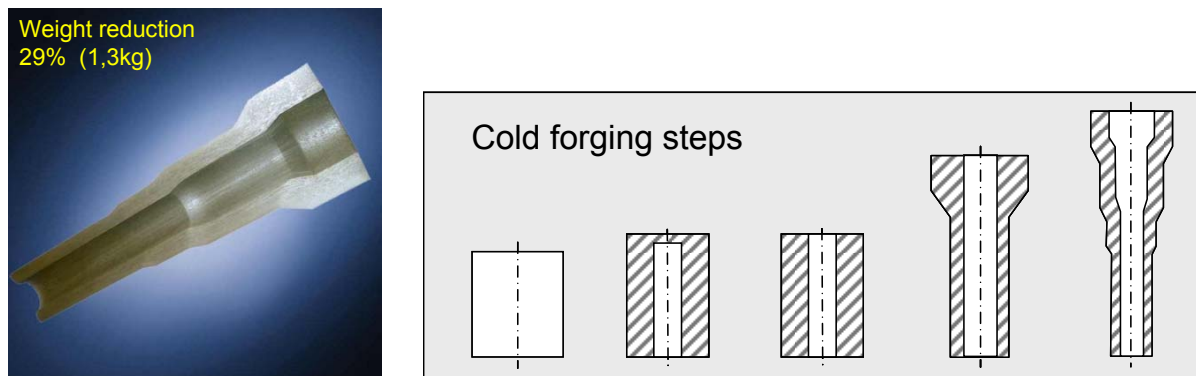


Figure 2: Hollow transmission shaft – hollow forged instead of forged and hollow drilled (source: Hirschvogel)



Figure 3: Roller tappet made from 16MnCr5 (left) – hollow forged (middle) and finished with drilling (right) instead of completely drilled, small wall-thicknesses in the corners cause high forming loads (source: Räuchle)



Figure 4: Spacer disk made from aluminum – forged instead of drilled (source: Rächle)

### Net-shape parts

The trend to net-shape or near net-shape production of parts is also aimed at reducing or even avoiding the subsequent machining steps after the forging process to achieve ready-to-install parts. This approach helps reducing the part production time and the number of processing steps by avoiding machining. This reduction of operations also leads to a cost benefit. The net-shape production can also contribute to lightweight design. Omitting machining keeps the continuous fibre flow from the forging process yielding high workpiece strength. This gain in strength is a decisive advantage especially in cold forging of gears compared to machined gears, Figure 5 [Ho09] and Figures 6-7. Another example can be found in Figure 8 showing a part with a straight spline and a helical gear in gear quality 9, both produced by cold forging.



Figure 5: Output flange – splines in near-net-shape quality (source: Hirschvogel)



Figure 6: Tripodes – splines and holes in net-shape quality (source: TK Presta)



Figure 7: Steering yokes – holes in yoke legs for needle bearings in net-shape quality (source: TK Presta)

### Function integration

Further potential for lightweight design is promised by parts with increased function integration. Objective is to reduce the number of operations as well as the number of assembly parts. Leaving out joining elements and permitting a more compact part layout decreases the part weight. This can entail a cost reduction through reduced production and assembly steps, saving of material and even lower storage costs. However, product integration often leads to complex part geometries. This may counteract the mentioned cost and time benefits by requiring sophisticated and expensive tooling technology as well as complex forging steps.

Figure 8 shows a twin gear drive as example for successful function integration. In the conventional solution (Figure 8, left), the helical gear is produced by milling a disc. Then, the gear profile is milled on the turned bolt. A bearing sleeve is joined with the bolt and finally these components are pressed into the geared disc. Thus, the component consists of three parts. Based on this initial part, an amended solution was developed consisting of one piece only (Figure 8, right). Here, the gear profile is directly pressed on the pin. The profile is passing into the pin via a circumferential radius. This feature helps increasing the stability and, thus, the functional reliability of the part. Moreover, this solution permits a more compact part layout. The helical gear is milled on the flange of the part. The one-piece solution has a reduced weight thanks to its compact layout and an axial drilling. The drilling for weight reduction is only permitted because of the one-piece layout of the part.

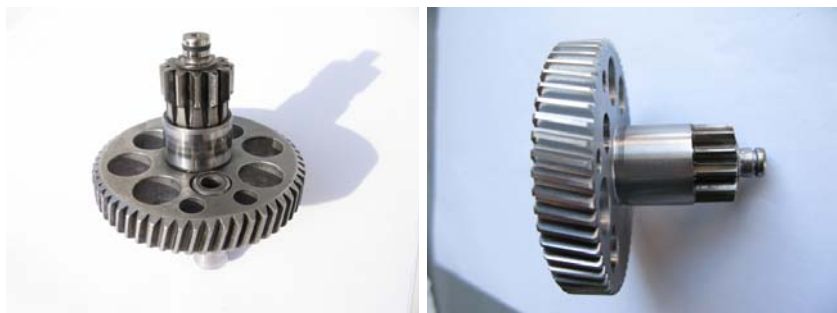


Figure 8: Twin gear drive in three parts complete machined and assembled (left) and in one part, straight gear cold forged in gear quality 9 after case hardening, helical gear machined, both gears with the same ground basis (right) (source: Wezel)

Figure 9 shows a similar one piece twin gear drive. The straight spline is cold forged. In the interim solution on the left, the helical gear is machined. In the final solution on the right, even the helical gear is cold forged with gear quality IT9. This leads to lower costs, higher strength and better functional properties.



Figure 9: Twin gear drive, straight spline cold forged, helical gear machined (left) and straight spline cold forged, helical gear cold forged in gear quality 9 (right) (source: Wezel)

### Efficient process chains

A reduction in costs and production time can also be achieved by rethinking well established production steps. A rearrangement of working sequences can lead to a reduction of single steps. An example is given in Figure 10. With a conventional production of splines by hobbing, both sides of the spline are open. As fit-up aid swellings must be positioned on one end of the spline. This retaining function can be taken over by the inlet area in case of forged splines. Besides the thickening of the teeth after hobbing, also the pre-turning operation of the outside diameter is eliminated by this additional benefit because of the normally unwanted run-in of the forged spline [Ho09]. Further examples are given in Figure 3 and 11.



Figure 10: Hub shaft with forged splines (source: Hirschvogel)

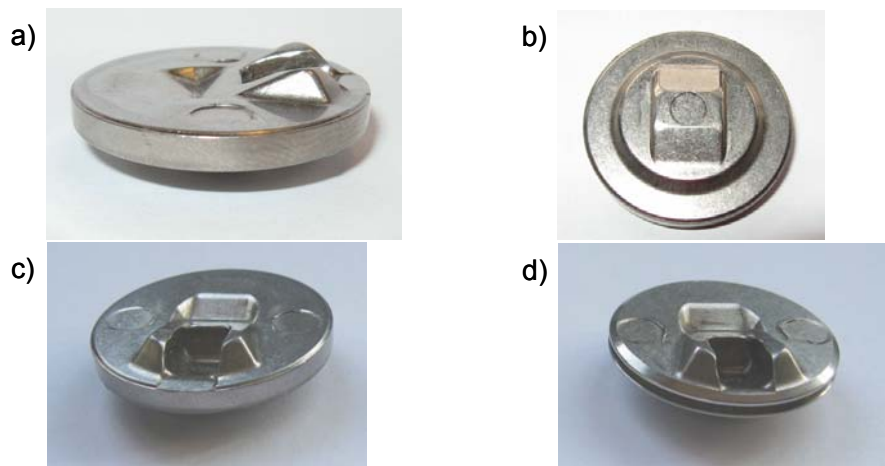


Figure 11: Valve cap made from stainless steel (a) side view (b) bottom view (c) top view after forming and (d) top view after finishing – Forming of lobe with sharp edges requires a highly loadable tool as well as an accurate preform design (source: Röchle)

### **3 Challenges**

The trends mentioned above, requiring challenging products, lead to the following challenges for the cold forging and tooling industry to develop novel approaches for tool and tooling system layouts.

#### **Costs and time**

Although essential objectives for future developments in cold forging are to reduce costs and time, there are several trends, for example net-shape production, high-strength parts or a high amount of function integration, that counteract these targets by causing an increase in costs and time for the tool production. This increase is mainly evoked by the need for higher-strength tool materials and a more complex tool layout. The complication of the tool layout can include, for example, the prestressing system that must resist higher loads requiring several prestress rings or even stripwound containers. In addition, manufacturing the die itself needs increasing costs and time due to the higher part and tool complexity and higher requirements concerning part and, thus, tool accuracy. In addition, increasing complexity already influences cost and time in the early phase of laying out the forging process and tool design. Speeding up the design step, e.g. by a comprehensive use of FE simulation tools, therefore is desirable. Furthermore, an increase in the procurement costs is caused as result of a high and rising global demand for scarce resources.

#### **Increasing loads**

The use of higher-strength workpiece materials leads to steadily growing requirements for the loadability of tools in cold forging because the operative loads on the tools correspondingly will become higher. As a consequence, the failure risk by fatigue is increased, and even the risk of premature failure increases, caused by the critical combinations of load determining factors like billet volume, the material strength itself, and others – even if these are within the tolerance. Not only is the high strength of the workpiece materials, but also the shaping complexity contributing to increased loads on the tool. The development of novel parts, driven e.g. by lightweight design and net-shape design, requires complex geometric features like sharp edges, small radii, filigree shaped elements, gears, hollow design or small cross sections (Figures 3 and 11). Hence, during die filling, the workpiece material is exposed to high strains leading to work hardening and it has to perform large movements relative to the tool surface. Long flow paths and high-strength materials do not only cause increased mechanical loading of the tool, but also lead to critical tribological conditions aggravating tool wear through very high contact normal and friction shear stresses. Besides overload and fatigue, this represents the third crucial reason for tool failure (Figure 12), [Hi08-1].

These mechanical and tribological challenges reach or even exceed the limits of conventional tool layouts. To overcome these obstacles, novel approaches for tools are required. Starting points for an improvement in tool resistance can be the application of new tool materials, the use of innovative tool coatings and surface treatment methods as well as new tooling system layouts.

#### **Reproducibility**

The future trends in cold forging in many cases imply an increasing part, tool and process complexity. This development often leads to a high sensitivity of the process behaviour to various influencing parameters. It can result in a more and more difficult reproducibility concerning workpiece dimensions as well as tool life. Factors that can play a role in this

context are the tolerances and scatter in the tool dimensions, for example the interference fit of the prestressing system or the dimensions of the cavity itself. In addition, scatter of influencing factors like the strength of the workpiece material or the volume of the billet will reduce the reproducibility of the process. Complex geometries like small wall thicknesses or sophisticated and filigree shaped features that are to be formed in the final forging steps also make high demands on the accuracy of the preform design (Figure 11).

### Accuracy

For the same purpose of increased process reproducibility, but also to meet closer tolerances and to achieve net-shape parts (Figure 13), the accuracy requirements are continuously rising. This affects the tool production and finishing processes, of course, but also the tool design step. The high demands regarding workpiece accuracy make it more and more essential to consider the elastic behaviour of tool, tooling system and press during the simulation-based tool and process design. The deflections due to loading in the forging process can have a significant influence on the workpiece dimensions.

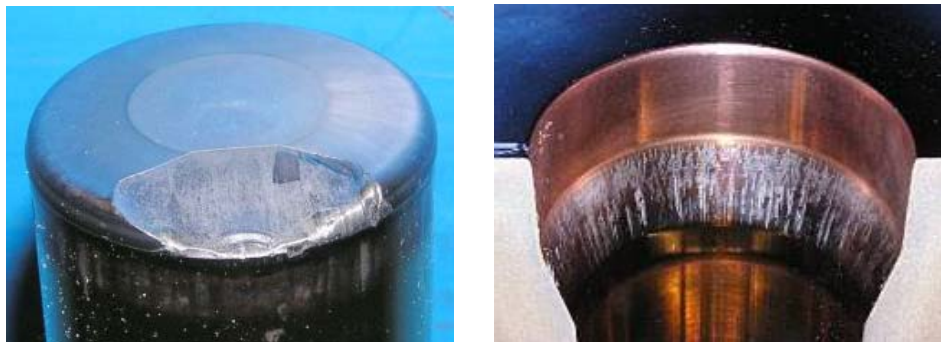


Figure 12: Fatigue on a cold extrusion punch (left) ; wear on a PVD coated cold forging die (right) (source: Hirschvogel)



Figure 13: Steering spider in net-shape quality – trunnions are calibrated with die (source: TK Presta)

## 4 Solutions

### New materials and material characterization

In tooling, materials are playing a key role in facing the challenges outlined above. Looking back to the history, starting with HSS-steels more than 100 years ago, with the introduction of cemented carbides in 1920 and PM-steels only some decades ago, to mention only some milestones, materials development has continuously followed successfully the growing demands in application concerning the loadability of tools in general but in cold forging as well, cf eg [Be10]. Since this is not only a question of material composition and alloying



rather than of new ways of producing the raw material, eg concerning casting, processing wrought alloys, heat treatment and thermo-mechanical solutions, different routes for producing high quality powders for PM-steels, the material represents a field of R&D of high innovation potential – today and in future. As an example, in the field of iron-based alloys the recent development of super clean PM-grades (actually the so called third generation) and Nitrogen-alloyed steels should be mentioned.

Driving force for these developments – in the past and future – is an enhanced loadability of the final tool, targeting to tool life high and reliable as possible. In terms of material properties, the following is required:

- high compressive strength since compressive loads are typical in cold forging
- high hardness to get the wear resistance
- sufficient toughness to withstand fatigue load since fatigue represents the predominating failure mechanism in cold forging.
- high homogeneity of material structure being simultaneously free of any inclusions – which is also due to enhanced fatigue resistance (crack initiation).

Fortunately, compressive strength and hardness go almost hand in hand up or down. However, it is well known that high toughness and fatigue resistance, respectively, can only be reached by diminishing both the other properties.

Accordingly, there are many efforts to improve the situation like – for PM-grades – the development of new routes for manufacturing powders of almost inclusion free quality or new alloying strategies yielding company-specific steels not yet categorized by standards. Similar developments can be observed for the other class of tool materials traditionally applied in cold forging represented by cemented carbides.

These as necessary as beneficial developments lead to another problem being twofold: on the one hand for the customer, the wide range of offers for tool material becomes unclear; on the other hand clear criteria are missing in terms of material properties describing the benefit, respectively, being able to serve as a decision criterion. Many customers, especially SMEs, do stick on a very confined selection of tool materials which they have experienced to be the optimum. An obvious reason is that the description of material provided by the material producer in terms of the above mentioned characteristic values such as compressive strength and hardness is not sufficient to highlight the intrinsic capabilities of new grades. An actual example can be given by the tooling for a hollow shaft which is produced by an automotive company since several decades, using high strength stripwound containers [Gro09], Figure 14.



Figure 14: Cold forged hollow shaft made from 28Cr4 manufactured by an automotive company, Germany – Application of a new hardmetal grade from Japan in combination with STRECON stripwound container increases tool life from 24000 to 33000 parts (source: STRECON)

Whereas the geometry and thus the forming sequence has not changed over the years, the functional demands on the product from steadily more powerful engines have lead to increased strength of the product material, thus, to higher loads on the tools during the forming process, and finally to continuously decreasing tool life, ending at the end at about 6,000 cycles for the previously applied grade of cemented carbide. Several trials with cemented carbides from European manufacturers yielded an increase of the average up to 24.000. The best result - 33.000 parts per die -, however, has been obtained by a grade of a new generation type of hardmetal provided by an Japanese manufacturer (33.000). The peculiarity of this example is that the advantage of the latter can be recognized neither in composition and grain size, nor in mechanical properties as shown in Figure 15. This is why the customer has little orientation in selecting the optimum of tool material for his application.

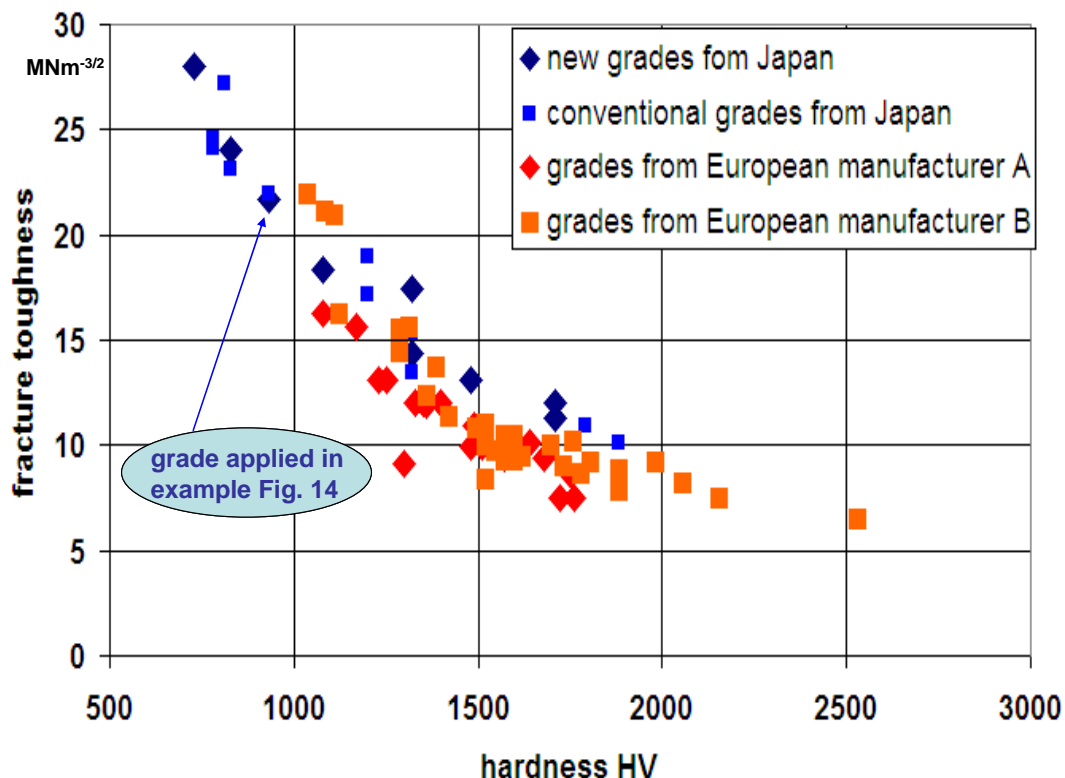


Figure 15: Toughness vs hardness for different hardmetal grades by variation of binder content and grain size; data taken from data sheets published by the manufacturers; methods of determining the characteristic values might be different (source: LFT)

On the other hand it is well known that there are material properties available characterizing the material with respect to its tooling application in a more significant way, such like fatigue resistance which can be described by (stress or strain) Wöhler-diagrams. However, the tests for the determination of such properties are very demanding and expensive. Anyhow, the necessity of such investigations is well recognized. In particular, with respect to PM-steels some new but few projects on this topic has been initiated in Europe recently, mostly based on direct cooperation between industry and research laboratories. Results, however, are not published yet. In Germany, the GCFG has initiated some studies on HSS and PM-steels, starting with static tests. Exemplarily, stress-strain curves from tensile tests and upsetting tests, respectively, are depicted in Figure 16 showing the variety of the different grades and the partly remarkable ductility of tools steels, which in general are characterized by their brittleness.

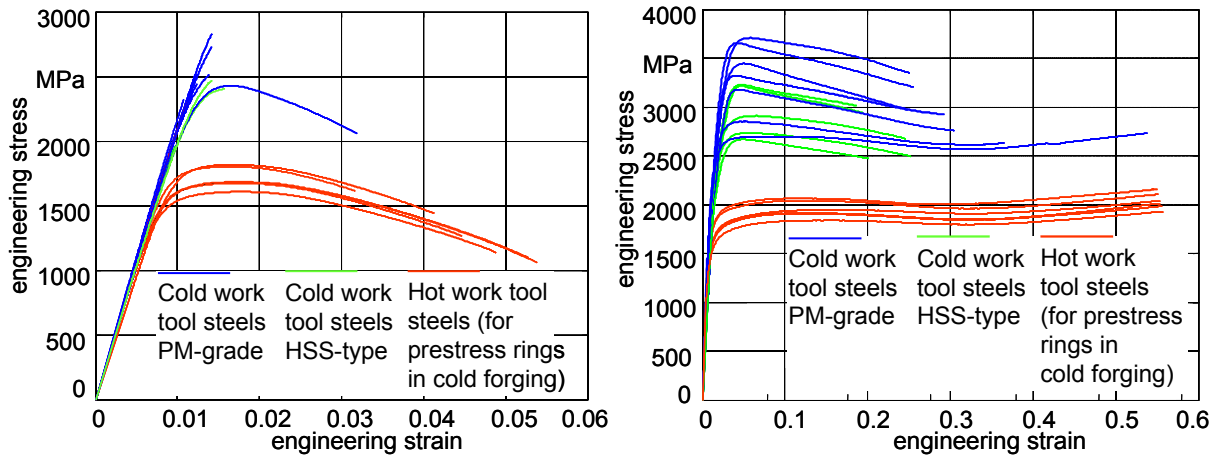


Figure 16: Stress-strain curves from tensile tests (left) and upsetting tests (right) for different tool steels applied in cold forging; differences are due to different grades from different material suppliers but mainly due to the hardness adjusted by different heat treatments (source: LFT / GCFG)

Dynamic tests targeting to Wöhler-diagrams are on the way. First results of some pre-tests on PM grade 1.3344 and another commercial PM-grade characterized by lower content in C, Mo, V, and W, do show the problem of such investigations mentioned above, Figure 17: that is the large scatter, the quantification of which is requiring many experiments on single levels of load amplitude.

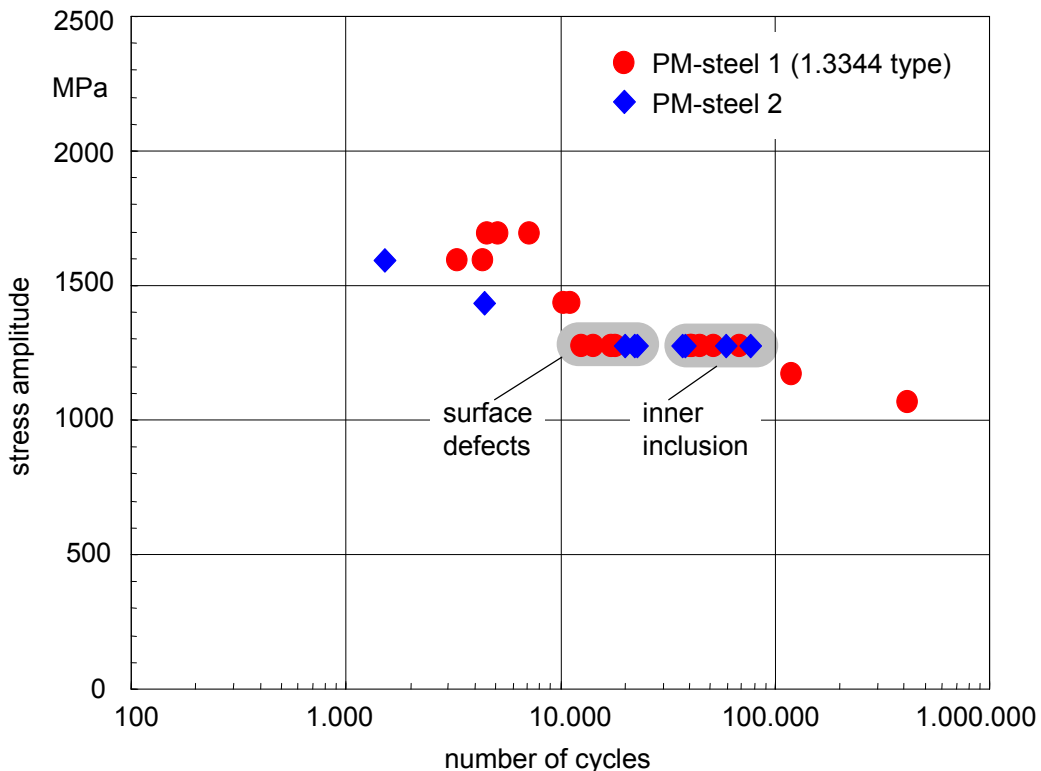


Figure 17: Wöhler-diagram for two typical PM-steels showing exemplarily on level of the marked stress amplitude the distinct scatter of cycles to fracture being due to the fracture origin located either on surface or within the volume but also to size and nature of defects and inclusions, respectively (source : LFT / GCFG)

The scatter on the marked and more extensively tested load level is evidently valid for the other levels as well. The reason for the scatter can be found by looking on the fracture origin by fractography. The majority of failures can be assigned to be of intrinsic nature originated by inclusions, Figure 18. Hence, it can be concluded that the existence, size and shape of such inclusions are mainly controlling the fatigue resistance, once more justifying the efforts to provide “microclean” or “superclean” grades by optimizing the process routes in PM grades production.

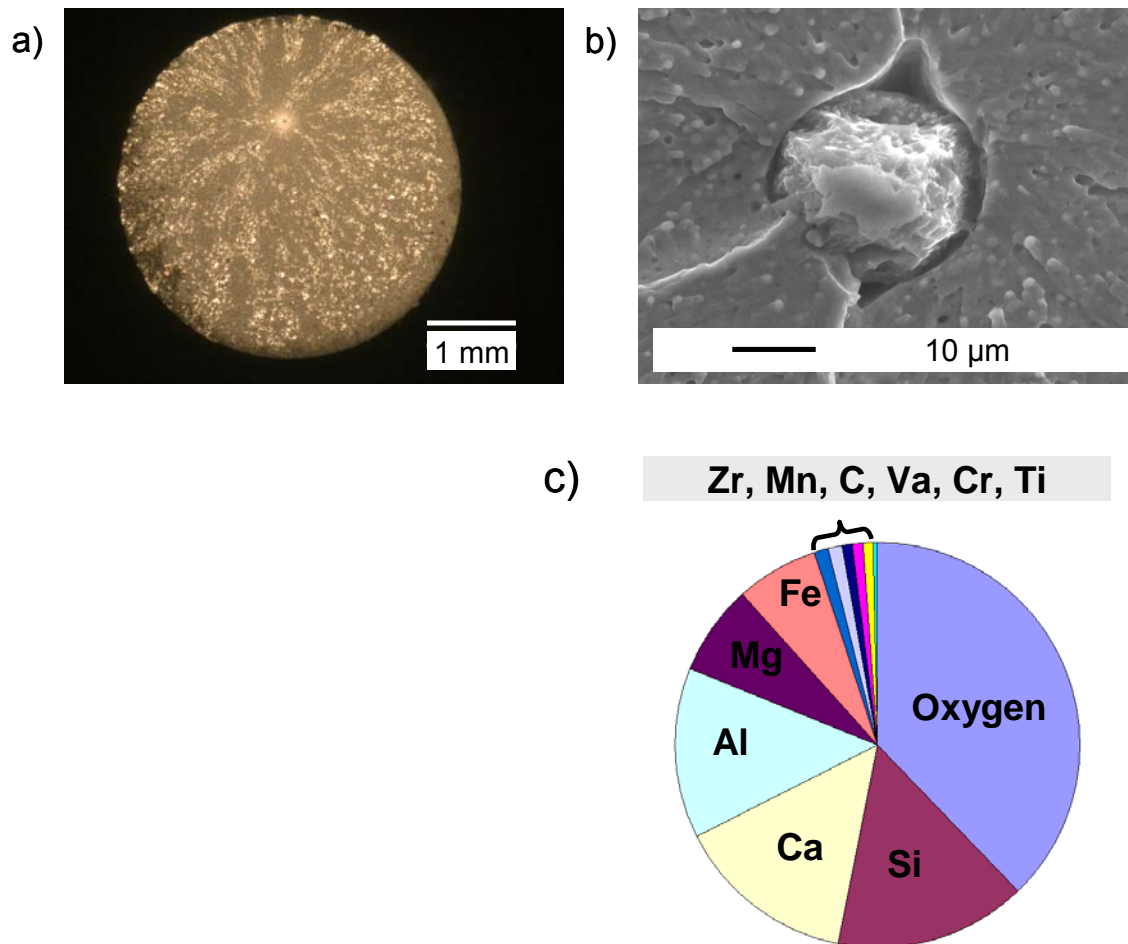


Figure 18: Fatigue fracture initiated by internal inclusion: fracture surface ((a) optical microscopy), inclusion ((b) SEM), inclusion analysis ((c) EDX) being typical for all inner inclusions (source: LFT)

The example above is also to show that in principal there are material tests available – even though being expensive - to characterize fatigue resistance. Based on such tests, the efforts to develop high fatigue resistant tool materials will necessarily be coupled as mentioned above by diminished hardness ie wear resistance. As this contradiction obviously cannot be solved by the material design alone, there are several alternative ways to counteract. One example is to reduce friction by optimizing the surface polishing process. Another one and well experienced measure to add high wear resistance to high fatigue resistant materials is coating. Hence the following three sections are dedicated to polishing, new developments in coating and new solutions of how to characterize wear resistance being not an intrinsic property of the material rather than of the system – actually the cold forging application.

## Surface polishing

The optimal function of tools for cold forging is to a large extent based on a low friction and a low tendency to cold welding (galling) between the active tooling surfaces and the work-piece material. Besides the application of lubrication-technology for the reduction of the friction, a correct surface polishing procedure and surface roughness level are among the most determining factors for a successful cold forging process and for obtaining the required surface quality of the pressed parts [Hi08-2]. Besides this it is known that the surface quality and also the process for achieving the low surface roughness have a significant influence on the service life of the tools.

Due to these requirements the functional surfaces of the active tooling elements – punches and dies – are in general polished to a mirror-like surface quality, as this roughness level is perceived to deliver a good performance of the tools.

Most cold forging tools are today hand-polished by skilled craftsmen using relative simple handheld power-tools and / or wooden sticks with diamond paste, but also processes like extrude honing and vibrating media polishing are applied. The major benefit of the hand-polishing is that a skilled polisher in a very flexible way can obtain a high surface quality on various tooling components with complicated geometries.

On the other hand, the high flexibility of hand polishing in combination with the high number of equal tools required for mass production of cold forged components leads to undesired effects like: variation in polishing quality, variation in service life of the tools, strong dependency of the skills of individual craftsmen, and last but not least, variation in production costs due to variations in service life and tooling related press stops. Besides this the vibrations from hand-held power tools and repeated working movements over a full working day raise critical aspects in relation with working environment and health.

This negative side of the hand-polishing has lead to a demand within tooling manufacture for the development of an automated polishing process that fully, or to a large extent, can replace the traditional hand polishing.

During the last few years a flexible and versatile Robot-Assisted Polishing (RAP) machine has been developed and introduced to the market [Gro08], see Figure 19. At the current development level the RAP machine is able on an industrial level to polish rotational symmetric surfaces on all kind of tool materials.



Figure 19: RAP – Robot Assisted Polishing Machine (source: STRECON)

The roughness level of Ra 0.025 to 0.04  $\mu\text{m}$  as required for cold forging tools can easily be obtained, Figure 20. On-going development activities will make the polishing of simpler 3-D geometries on an industrial level possible by the end of 2010.

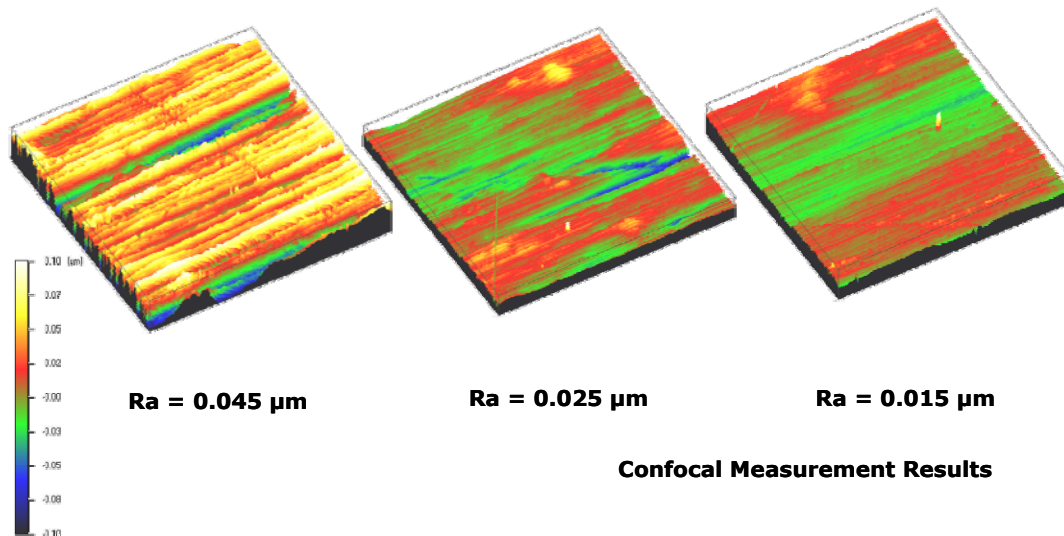


Figure 20: Test polishing of high hardness tool steel to low surface roughness (source: STRECON)

The RAP technology is based on a computer controlled manufacturing environment that eliminates the requirement for knowledge of robot programming for the operator, who thereby can use his skills and knowledge for control and optimisation of the RAP polishing process.

By varying the RAP polishing on specific areas of the tools where it is most critical, the RAP process has demonstrated its potential in improving the performance and service of industrial tools for demanding cold forging, Figure 21.

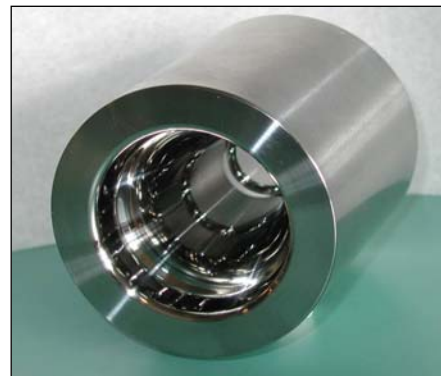


Figure 21: RAP polished tool  $\varnothing 95 \times 120$  for demanding cold forging operation (source: STRECON)

## Coatings

In order to improve wear resistance, the coating has a long tradition in general but for cold forging tools as well. Accordingly high is the diversity of coating technologies and layers composition. The following is focused to PVD only since this seems to represent the most promising technique for the future. The most important reason for that is not only that hard layers of almost arbitrary composition can be realized but in particular the low processing temperature. Processing below  $500^{\circ}\text{C}$  does not affect the properties of the substrate as adjusted by foregoing heat-treatments. Looking to the required tolerances of cold forging tools, this is quite an important aspect since any subsequent operation of tempering would lead to not acceptable distortions. In terms of coating composition hard layers of type TiN or TiCN are state of the art. High wear resistance of such layers is due to the hardness and low

adhesivity. The combination of different layers towards so called multi-layer coatings can be regarded also as state of the art. Examples are multi-layers of type TiAlCN.

What is relatively new is the introduction of nano-layer coatings the high performance of which are proved in basic investigations [Bo04], in application to machining tools [KI09], but only punctually tested for cold forging tool application. The reason for the retarded introduction and acceptance of new coatings in cold forging might be addressed to the same problem as discussed above: characteristic values like hardness or friction coefficient provided by the coatings producers do give little information about wear resistance required by the specific conditions characterizing the wear load in cold forging. A promising test to assess the wear resistance of cold forging tools has been actually developed by the LFT, the qualification of which has been supported by the GCFG. Operation mode and capability of this test are discussed in the following section.

### CPFE-test for wear investigation on coated tools

A comprehensive characterization of coated tools in cold forging is essential to utilize fully the capabilities of common and new coatings for an increased tool life and workpiece quality. Various types of PVD-coatings, like TiN or TiAlCN, are already in use in many cold forging companies to reduce wear. Further new coatings are developed continuously. Nevertheless, their selection and application in the industry is mainly based on empiric data in the respective shop depending on the application. To adapt a coating appropriately to the particular process, a substantial characterization of its properties is required.

There are several wear tests for this kind of coatings like the pin-on-disk test, but they do not represent the particular loading conditions like high contact normal stress, long sliding paths and high workpiece deformations, occurring in the real cold forging process. To characterize coatings for the use in cold forging, a new tribological test for the investigation of wear on coated tools was developed at the Chair of Manufacturing Technology [Sch10]. With the so called combined punching-forward extrusion (CPFE-) test it is possible to investigate the behaviour of coated dies and punches under process relevant conditions. In the CPFE-test a punching and a forward extrusion process are carried out under conditions which are typical of cold forging processes (Figure 22). High contact pressures, long sliding paths and high deformation of the workpiece are realized.

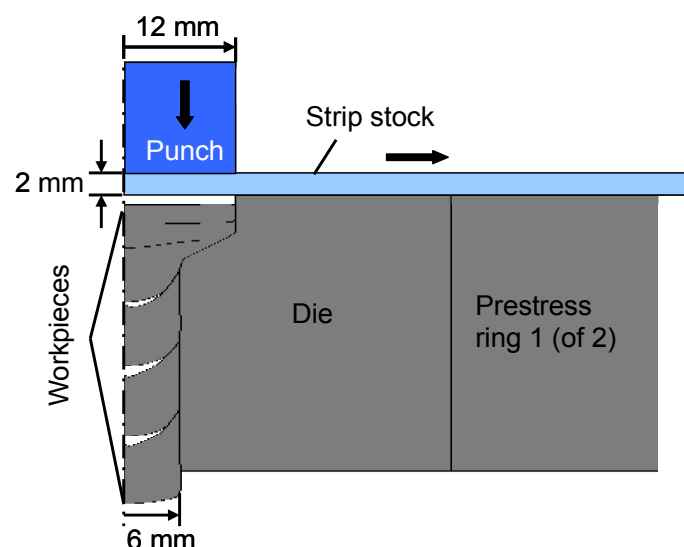


Figure 22: Schematic drawing of the CPFE-test (source: LFT)

In the test each single punch stroke involves a cutting process and a contribution to a forward extrusion process. A coated punch cuts circular specimens out of strip stock and directly stacks them into a die. The stacked material simulates a bulk workpiece and is forward extruded gradually by the punch through a coated die. Due to the stepped feed and the test set-up the tests can be carried out with a relatively high velocity and with comparatively minor waste of material. It is possible to test coated dies and punches simultaneously. Wear is monitored by an optical microscope before the CPFE-test and after fixed intervals of several thousands of strokes. As wear mainly occurs in the die shoulder, only this section is considered in the following.

Investigations on a TiN coating and a new AlCrN coating show different wear characteristics on the die shoulder after 7000 strokes. The mono-layer coating TiN shows deep grooves of wear in radial direction that reach into the substrate (Figure 23 left). Wear of the die shoulder coated with AlCrN is shown in Figure 23 right as example for a nano-layer coating. There are only minor traces of wear observable, like tiny pittings on the die shoulder.

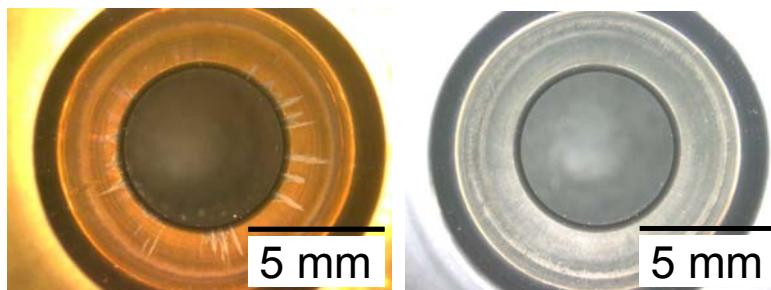


Figure 23: Wear after 7000 strokes on the die shoulder coated with monolayer TiN (left) and nanolayer AlCrN (right) (source: LFT)

These results show that the newly developed CPFE-test is qualified for an evaluation of the wear resistance of coatings for cold forging tools under realistic conditions. Depending on the investigated coating, different wear characteristics were observed. A comparison of the results of the CPFE-test and wear behaviour of the coatings in industrial applications is planned.

### Selective surface treatment

The two damage causes fatigue and wear are dominating in terms of limiting tool life. Fatigue is caused by the cyclic loading of the tool. Even at a very early stage fatigue cracks can lead to disruption at the tool surface and then to tool failure. Wear is caused by high contact stress in combination with a cumulating sliding length and affects the accuracy and surface quality of the workpiece. Thus, the tool surface is of particular importance to find approaches for an increased tool life.

Depending on the process, both mentioned damaging mechanisms of fatigue and wear can act concurrently at different locations of a cold forging die. According to this local loading, a locally selected surface treatment against these damaging mechanisms offers the potential to increase tool life. Among these methods locally adapted to the tool load, hard roller burnishing and surface heat treatment by laser are of particular importance.

### Hard roller burnishing

The primary objective of hard roller burnishing is to improve fatigue resistance of the tool surface. The process consists of a ceramic ball that is rolled on the machined tool surface under high pressure, flattening the topography by local plastification. The ball is hydrostatically supported to roll with low friction. The predefined burnishing pressure is



directly proportional to the burnishing force. The burnishing speed depends on the rotation speed of the axially symmetric tool in the turning lathe. The burnishing feed rate has to be set in the turning lathe as well.

In the process, due to the local plastification, a surface layer of a certain depth will be subjected to work hardening which leads to residual compressive stresses. This stress condition can be achieved even if tensile residual stresses exist due to a prior machining. The maximum compressive stress typically occurs in a depth of 120  $\mu\text{m}$  below the surface. Hard roller burnishing also inhibits crack initiation and propagation by closing micro cracks on the surface. Flattening can be observed even at surfaces with high initial hardness. However, a further gain in hardness and compressive residual stresses is difficult to achieve on tool materials with high initial hardness (ca.  $\geq 60$  HRC).

In a case study in [Wa08], hard roller burnishing was applied on a full-forward extrusion die at the radius above the shoulder to improve tool life (Figure 24). During the forging process, this area is subjected to high cyclic axial stresses yielding finally failure by fatigue. The superposition of compressive residual stresses to the axial stress, diminishing the resulting equivalent stress, lead in combination with flattening of the topography to an extended relative tool lifetime of the die up to 160%.

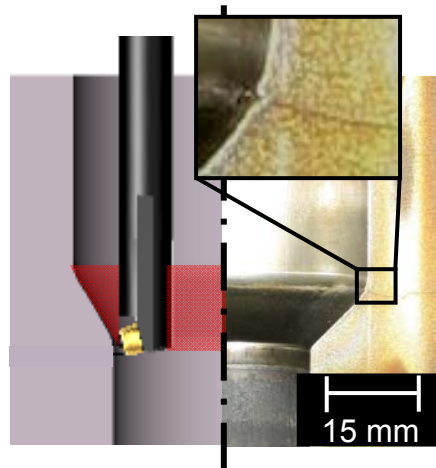


Figure 24: Surface treatment of a full-forward extrusion die by a hard roller burnishing tool (l.); critical tool region subjected to fatigue (r.) (source: LFT)

### Surface heat treatment by laser

Laser heat treatment is a flexible method to modify tool surface properties selectively by martensitic transformation yielding locally improved wear resistance. The laser spot moves along a predefined track to cover the tool area that is to be hardened. Depending on speed and power of the laser spot, the tool surface is heated up locally at a high heating rate. During the immediately following self-quenching process, the heated regions transform from austenite to martensite yielding the high hardness [Ku01]. Besides the hardening, local annealing can also be realized either by hardening an uncritical region in the neighbourhood using the annealing effect in the border areas of the focal spot, or directly by an appropriate choice of operation mode of laser irradiation. This locally applied annealing can be used on purpose to decrease locally the hardness, thus increasing the toughness in order to achieve a positive influence on tool life in areas subjected to fatigue. The laser heat treatment can be carried out on coated as well as uncoated tool surfaces (Figure 25) [Wa08].

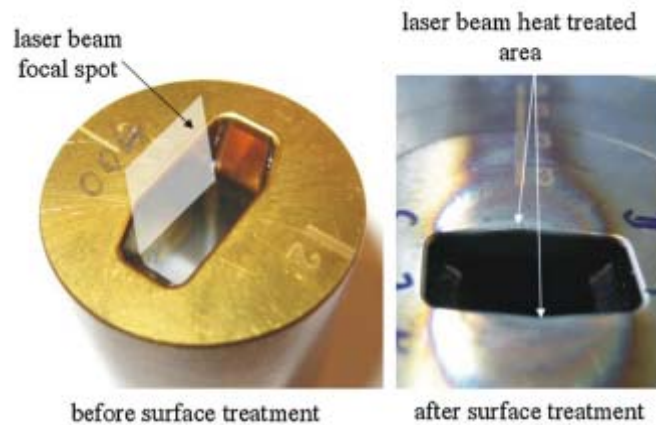


Figure 25: TiN-coated cold forging die with position of laser spot (left); die after heat treatment by laser (right) with annealed areas at the border of the spot (source: LFT)

### New processes

The actual challenges in cold forging may also be countered by rethinking of established processes or even by developing completely new approaches. Two quite different examples are given in the following. Whereas the first is focussed on an alternative solution for a specific product, the second comprises the idea of combining the potentials of cold forging with those of sheet metal forming which will open up a new and promising field of cold forging processes in future. In both cases, new tooling solutions are required.

### Thread forming

Thread manufacturing has a long tradition and conventional methods like thread rolling must not be discussed here. However, the new developments in cold forging even require questioning such well-known processes. Sieber forming solutions has developed a novel method for thread manufacturing, the so-called thread forming [Ge10] that helps to meet several of the crucial future trends identified before.

The tooling system for thread forming consists of a die split into three jaws (Figure 26, left). The thread is formed during closing the jaws. To eject the formed workpiece, the jaws are opened again. To avoid material flow into the gaps between the die segments, the billet must feature an adjusted, non-circular shape at the contact areas of the closing die. The cross section of the billet can consist of a circle with three cut-outs, for example, but a lot of billet cross sections are possible. However, an important design rule is to maintain that no material is pressed between the jaws. This can be ensured by laying out the billet geometry in simulation. The cut-outs of the billet geometry appear in axial direction of the part after the forming process. The resulting reduction in the tensile stress area by ca. 1-2% is practically negligible.

Hollow threaded parts are often produced by machining. Hence, it is a decisive advantage of the thread forming process, that external threads can not only be formed on massive parts, but also on hollow parts in a similar way (Figure 26, right). In this case, first the jaws are closed and then the thread is pressed by moving a pin into the hollow billet. Substituting the machining of hollow threaded parts through a cost-saving forming step promises a significant cost and time reduction. As a consequence, the whole part can be produced by cold forging. Ideally, the thread forming is integrated into the last stage of the press. Compared to a transfer to the machining, this simplifies part handling and reduces production time. Omitting machining also leads to an increased material utilization.



Figure 26: Segmented tools for thread forming (left); Besides massive parts, even hollow parts with external threads can be formed without machining (right) (source: Sieber Forming solutions)

Besides the mentioned cost and time reduction, thread forming offers additional benefits in terms of function integration compared to conventional methods. Due to the segmented tool design, threads with non-circular shape can be manufactured, for example if a polygon shape is required for self-cutting ability. The parts can also feature a slotted outline contour, even combined with a hollow cross section. Conical shapes of the threads, combinations of different kinds of threads and as well as geared or knurled threads are possible. The beginning of the thread can be located just after the screw head. Compared to thread rolling, the crest of thread is always rounded and does not show a wrinkle. A consequence is high impact-resistance of the threads and a better suitability for coatings. The axial cut-out at the die segmentation can be used for chip and paint removal or for taking off air, oil or other mediums. Threads similar to a lock washer permit a self-locking effect of the screw, wavy ones help eliminating clearance. Thus, the thread forming is a paradigm for coping with the major challenges resulting from the global future trends in cold forging.

### Sheet-bulk metal forming

As in the past certainly there can be found some singular examples for combining sheet and bulk metal forming in specific application, the actual research is targeting to exploiting the potentials of such a combination starting from a fundamental and interdisciplinary approach. For this objective, in Germany a Collaborative Research Centre supported by the German Research Foundation DFG has been established in 2009 promising new solutions on this field, which will not only be restricted to short termed, singular applications but will open up new areas of general applications in future [TR73, Me09]. One short example for the problems arising looking on a product exemplarily shown in Figure 27 is given in the following.

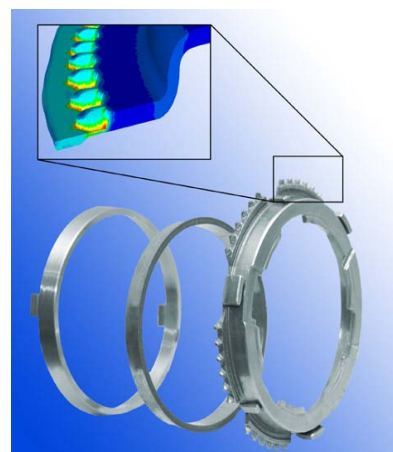


Figure 27: Synchronizer ring with high-precision shape elements formed by sheet bulk metal forming (source: LFT, Diehl)

With regard to complex functional components, sheet-bulk metal forming has the potential for manufacturing of high-precision elements in the range of the sheet thickness with close geometrical tolerances. The direct forming of three-dimensional shapes using blanks as semi-finished parts offers several challenges. Complex interactions between regions of high and low strains and three-dimensional stress-states in the sheet plane, which are characteristic for sheet-bulk metal forming class and mainly responsible for the resulting workpiece characteristics, are widely unknown [Me10]. Due to large contact areas, the achievement of the required mold filling, e.g. for the manufacturing of synchronizer rings, at acceptable forming forces is critical in most cases. In order to meet this challenge, different approaches are actually investigated. Forming of components with complex geometries and small variants using sheet-bulk metal forming can be enhanced by a pre-distribution of material in the blank in order to improve the material flow. Furthermore new tool geometries and forming strategies have been developed to control local material flow for a defined filling of target regions. As a consequence, the tool components are modified by several flow-restrictions, which lead to a significant improved mould filling. However, the comparatively large contact area between tool and workpiece and additional low sheet thickness causes high process forces. Using multilevel forming processes, a step-by-step material flow caused by different sequenced tools is achieved. Using this proceeding, the contact area and thus process force is reduced equally [Me10].

For the improvement of the geometric accuracy and mould filling, several methods have been investigated. Process adapted semi-finished products, flow-orientated tool design and special forming strategies are a promising ways for the optimization of sheet-bulk metal forming processes.

### **System approach**

Solutions as discussed above are targeting mostly on specific problems not considering interactions, respectively, the impact of single enhancements on other elements of the whole forming system. In order to get to an optimum in future, a holistic view seems to be necessary, ie taking into account the whole forming system or at least the most decisive elements of the system in which tooling is playing an important part. This is particularly true for using new solutions in the phase of laying out the process. An example picking up the keywords of “high complexity”, “high tool loads”, “high precision” is given in the following.

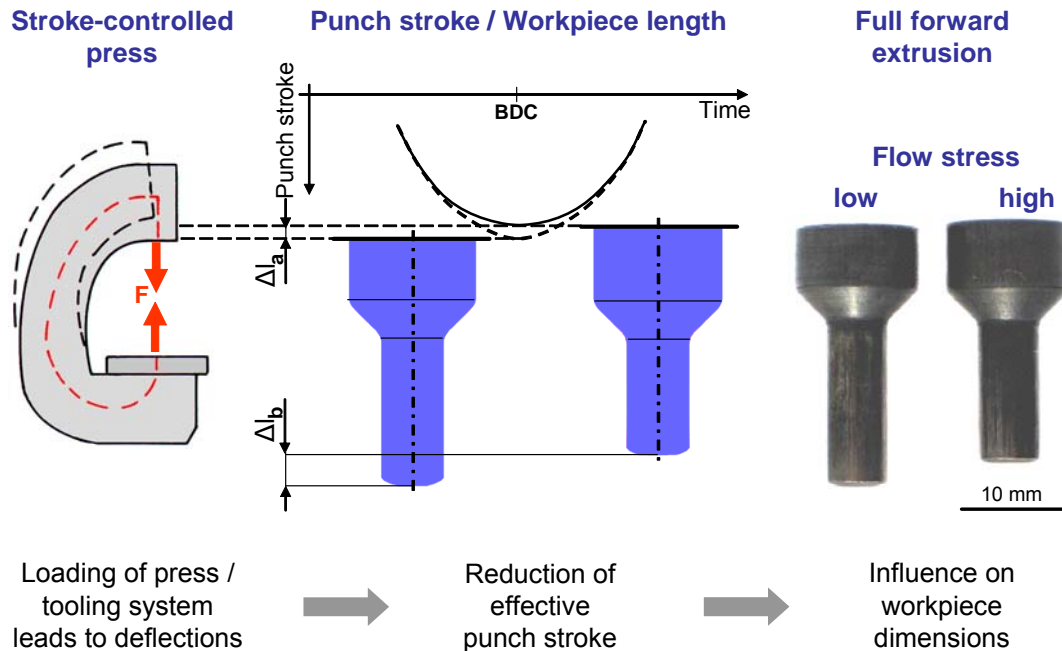
### **Process-Tool-Machine Interactions**

The demand for parts with high precision (net-shape design) as well as high strength, both of them being major trends in cold forging, requires enhancing the scope during the FE-based tool design from the process itself to a consideration of the whole system including tooling system and press. The reason for this need lies, to a great extent, in the high flow stresses of these materials. The resulting high loading of tool and press can cause considerable deflections of these components and, in turn, dimensional deviations of the workpiece. The displacement of a stroke-controlled press under load, for example, directly leads to a reduced actual punch stroke and dimensional deviations of the workpiece.

These interactions between process, press and tooling system complicate the optimization of the tool and process design. Thus, to obtain high workpiece accuracy without subsequent adjusting effort, this behaviour already should be taken into account during the FE-based tool and process layout. This enhanced modelling even becomes more essential with increasing accuracy and complexity demands which lead to reduced reproducibility of the real process.

For the coupled simulation of forming process and the characteristic of press and tooling system, the following classification into three approaches can be made [Gr99]: offline-coupling, co-simulation and model integration. The offline-coupling does not feature an active interaction between process and press model. The co-simulation in different simulation environments consists of a process simulation, usually FEM, and a machine model, e.g. in a multi-body simulation. The two simulations interact by means of a coupling tool with a data exchange after each increment [Br08] or cyclically after a full simulation run [Be08]. In contrast, in the model integration forging simulation and machine / tooling system are modelled in the same environment. In this integrated model, process, tooling system and press can interact directly. The deflection characteristic can be modelled with elastic FE-bodies or spring elements [Gr08; En08].

The investigation of Process-Tool-Machine Interactions is subject of the Priority Program 1180 of the German Research Foundation “Prediction and Manipulation of Interactions between Structure and Process” [SPP1180]. In [Kr10], considering the axial displacement characteristic of tooling system and stroke-controlled press in the FE simulation of a full-forward extrusion process lead to a significant increase in simulation accuracy. Compared to experimental results of the extrusion process, the deviations in workpiece length were reduced from up to 17.7 % for a conventional FE process simulation (die and prestress system modelled elastically) to 0.1 % for the comprehensive FE model considering tooling system and press characteristic. The model permits the calculation of a parametric process model including the Process-Tool-Machine interactions. Based on this, an optimization of influencing factors can be carried out to achieve high workpiece accuracy in production without try-out (Figure 28).



BDC: Bottom Dead Center

Figure 28: Deflection of stroke-controlled press and its influence on the workpiece dimensions using full forward extrusion as example (source: LFT)

## 5 Outlook

To sum up, cold forging technology faces manifold trends like focus on individualization, lightweight design, material utilization, net-shape parts, function integration and efficient process chains. These trends lead to steadily increasing challenges on the tooling system – challenges that require further improvements as well as novel solutions in tool design, including advanced FE analysis, materials, tool manufacturing and polishing, surface treatment and coating, and other factors influencing tool life and tool quality. This paper could only spotlight some of the various activities in both academic and industrial R&D which contribute to extending today's limits, and which will lead to new processes, tooling and products in cold forging. Finally, within this context, the significance of the activities of the national and international associations of the cold forging community should be stressed, observing and documenting the ongoing developments, thus representing an important and promising basis for future developments and visions (cf eg [ICFG02, ICFG04, ICFG06]).

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