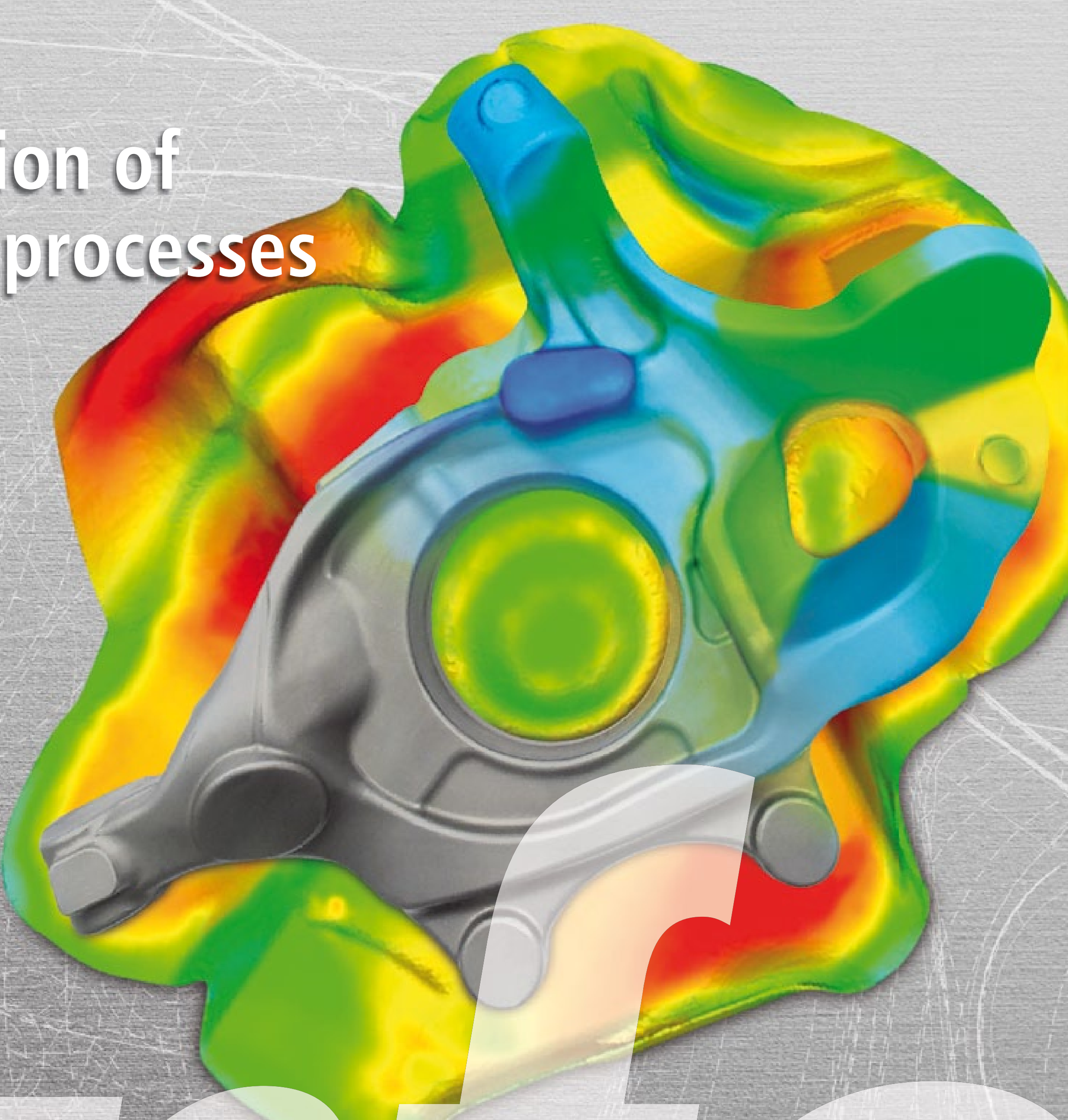
DEUTSCHE
MASSIVUMFORMUNG

Simulation of forging processes



Info
EXTRA

Editor’s Foreword

Modern technical systems – in the automotive, aviation and aerospace sector as well as in mechanical engineering and the field of energy technology – often involve high-performance forged components. Their key role is based on the one hand on their enormous load-bearing capacity required for the transmission of high forces and momentums. On the other hand, it can be observed that in times of increasingly scarce resources there is a growing demand for efficient industrial production processes – as is the case for forging.

Especially in the automotive industry, increasing demands with respect to lightweight design and power density call for the ever more intensive optimization of components, which requires the careful matching of alloy, component geometry and the many parameters along the entire design and manufacturing process chain. By involving the supplier in the product development process and in engineering partnerships early on, favourable conditions are created for finding economical solutions that benefit both parties.

The previous edition of this EXTRA-Info “Simulation in the forging industry“ dealing with simulation described the experience of individual companies and highlighted general solutions based on these case studies. In this second, completely redesigned edition, the editorial advisory board has opted for a different approach.

The numerous areas of application and further development of simulation systems presented in this EXTRA-Info in conjunction with the anticipated research results highlight ongoing progress in the field of virtual tools for forging applications. Particularly noteworthy in this context are developments in the area of basic research aimed at a better understanding of the processes within the workpiece and tool, opening up new possibilities for targeted technical progress.

The description of the use of virtual tools to develop intelligent solutions for the implementation of special features, tolerances and component properties should appeal not only to the forging sector and its customers. Likewise, the intention is also to win over the younger generation – especially technically-minded young people who want to actively participate in future technologies – for the sector. Furthermore, the description of the entire process chain from product development using modern CA and simulation techniques through the selection of materials to determining the design of procedures or combinations of methods can be a valuable aid in apprenticeships and academic studies.

We are pleased to present to all parties interested in forging, by means of the EXTRA-Info documentation as a whole and more specifically with this latest edition, an effective support for issues linked to modern and forward-looking ways of developing products and processes virtually. The greatest tribute to the participants, especially to the editorial board, would be to make frequent and active use of this document.

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1 Introduction

Among other factors, the well-being of modern civilizations is the result of constant innovation, allowing us to manufacture and market more and better products at lower costs and thus to improve the living conditions of the vast majority of people. Some major drivers of this innovation are modern production concepts that optimize resources and expertise across company borders and along the entire process chain from raw material to the finished product. The most efficient approach to optimizing expenditure is inviting suppliers to contribute to the development of new products as soon as possible during the design phase, so that they can contribute their skills at an early stage. This advice stems from the knowledge that the expenditure required to manufacture a product is largely determined during the first stages of the design process: experts estimate that about 80 % of the costs of producing a component are fixed during the first 20 % of its design phase. This brochure shows the multiple and far-reaching possibilities available to the forger by using modern, high-performance IT tools to simulate processes and workpiece properties.

Developing forged parts requires process know-how

For an optimal product design comprehensive knowledge of the manufacturing process is essential for the best utilization of process-related advantages and thus to ensure optimum product characteristics: every designer is familiar with the fact that in practice it is virtually impossible to substitute a production process such as casting by other processes such as forging or welding without having to radically readjust the part geometry, Fig. 2.1 This reflects the recognition that the process "makes" the product. By this we mean that the characteristics of a mechanical component can differ significantly depending on how the process used to form its contours has been implemented. In addition to this, the typical aspects of (large-scale) series production, such as costs quality assurance and minimized resource consumption, are also included, so that the production process and its specifics will finally take on a lead role.

The best advice for the customer's R&D engineers is thus to team up with the supplier's staff in the early stages of the design phase. In principle, this can even be recommended as soon as basic performance requirements with respect to space, interfaces or load conditions, as well as additional requirements, for example with respect to corrosion resistance, are defined. Occasionally it might even make sense in these circumstances to seek the advice of the supplier also with respect to the production process or even to the type of material, especially if additional lightweight aspects play a role. Following the example of the automotive industry, more and more other industrial sectors are therefore inviting their suppliers to participate in the design process early on in the concept phase. This also results in the interaction of two different virtual worlds: the designer's "classic" CAD software packages, which cannot model the local distribution of field variables and properties, versus the supplier's process-oriented simulation tools, which take into account the production process and its numerous peculiarities, including its impact on the properties of the component.

Fig. 2.1: Process-oriented design of the present-day forged aluminium rear axle support (left) for a passenger car as compared to a cast steel version (right)

2.1 Making use of the forger's process expertise

By performing simultaneous engineering together with the forger it is possible to unlock a plethora of capabilities because in the design phase that follows the concept-finding stage the forging specialists have a key advantage. Due to their in-depth knowledge of the limits and advantages of their production process, several "expert systems" are up and running – so to speak – at the back of their head. These automatically check the process technicalities and cost-benefit aspects of their craft. For example, a forging professional will often see at first glance where a radius should be re-examined to determine if it may affect the durability of the forging tool. Likewise, machinability aspects will also be considered, from clamping surfaces and fixtures to questions such as whether a given surface can still be machined with standard tools, or if any special devices may have to be procured for the task. Furthermore, other benefits along the entire process chain up to the end user may materialize, such as achievable weight savings or improved performance characteristics, Fig. 2.2.

Fig. 2.2: Cold forged pinion: simulation result and real part

2.2 Modern simulation tools

The different forging processes and the wide variety of materials make it possible to achieve a highly accurate tune of sometimes quite varying properties in different areas of the same component as well as to optimize expenditure and cost along the downstream supply chain. In order to be able to meet his challenging tasks as an engineering partner, the modern forger can draw on highly sophisticated simulation tools. These mathematically depict the numerous steps in the development and manufacturing process, from the acquisition, modification and generation of CAD data through complex software for simulation and optimization of forging components and processes down to the design of the downstream process chain, Fig. 2.3.

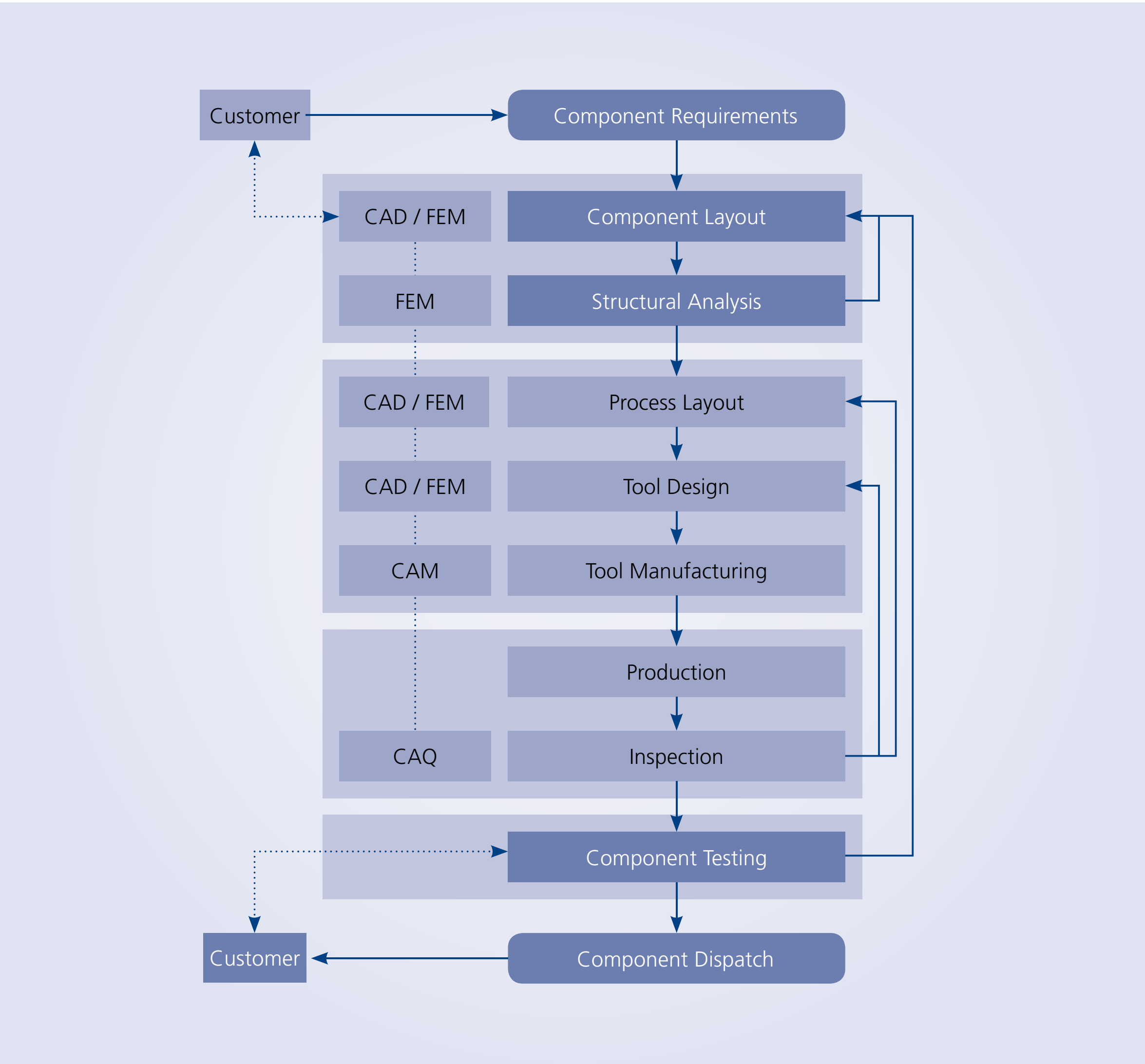


Fig. 2.3: A typical development process chain with the virtual tools used

Depending on the specifics of the given company, working steps such as computer-aided optimization of the component topology, followed by redesign and analysis of component behaviour, may be undertaken using suitable finite element method (FEM) software. Sometimes even more specialized simulation tools are used, e. g. for optimizing gear wheel design or even whole assemblies such as differential gears, for dimensioning constant-velocity joints or for fine tuning piston rod shapes.

2.3 Expertise remains the key factor

Thanks to faster software and more powerful hardware, the mathematical models employed in the software the forger uses to simulate his processes have made great advances with respect to the bandwidth of applications as well as to the accuracy of their forecasts in recent years. Nevertheless, it must be borne in mind that simulation tools are exactly what their name implies, namely tools with specific properties for a particular purpose. The programs currently available are very powerful instruments that enable the forger to provide his customer with significant benefits. The input of data on initial and

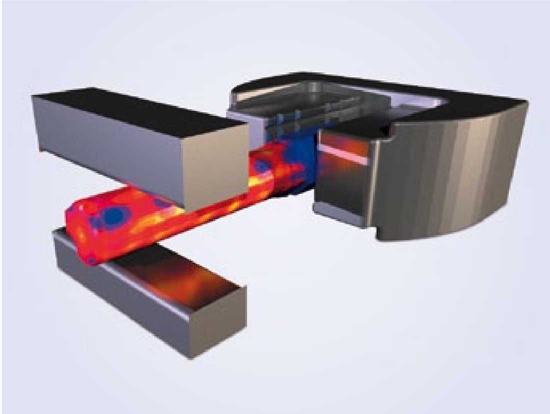


Fig. 2.4: Simulation can depict even intricate kinematics, here to the example of open die forging

boundary conditions as well as material-related information is necessary for the calculation. These material data are often provided by the software house in the form of databases as well as being experimentally determined in the forging companies or by scientific institutes. Moreover, such simulation tools will yield their full benefits only in the hands of an experienced specialist with in-depth knowledge of his processes and the ability to assess the performance of the software. The same specialist should therefore be left to decide for what purpose and to what extent he intends to use these tools for the task in hand, Fig. 2.4.

3

Virtual tools in product development

In the forging sector, product and process development tasks regularly include the use of simulation software. In this respect, a distinction should be made between two basic categories: commercial software based on the finite element method (FEM) as compared to proprietary programs based on analytical approaches that in some cases have been specifically developed within a given company. Such FEM programs not only make it possible to solve mechanical structural problems arising during the product development phase. They can also simulate the evolution and local distribution of thermo-mechanical and elastic characteristics when a manufacturing process is being designed.

The subsequent paragraphs describe basic steps in performing FE analyses. Furthermore, the use of advanced simulation tools in forging companies is discussed and forgers' creativity presented.

3.1 Sequence and scope of FEM simulation applications

When setting up the process model, the first step is to create a 3D CAD representation of the interacting objects, which will then be passed on to the so-called pre-processor of the FE software. Subsequently, the component to be examined or the assembly space to be considered is divided into a multitude of small volume elements with defined dimensions, the so-called finite elements. Furthermore, the boundary conditions are applied to the finite element model and the material data added. Afterwards, the complete model is transferred to the so-called solver, who will compute a solution. Then the results can be viewed and evaluated on-screen in the form of graphics or animations with the help of a so-called post-processor, Fig. 3.1. This

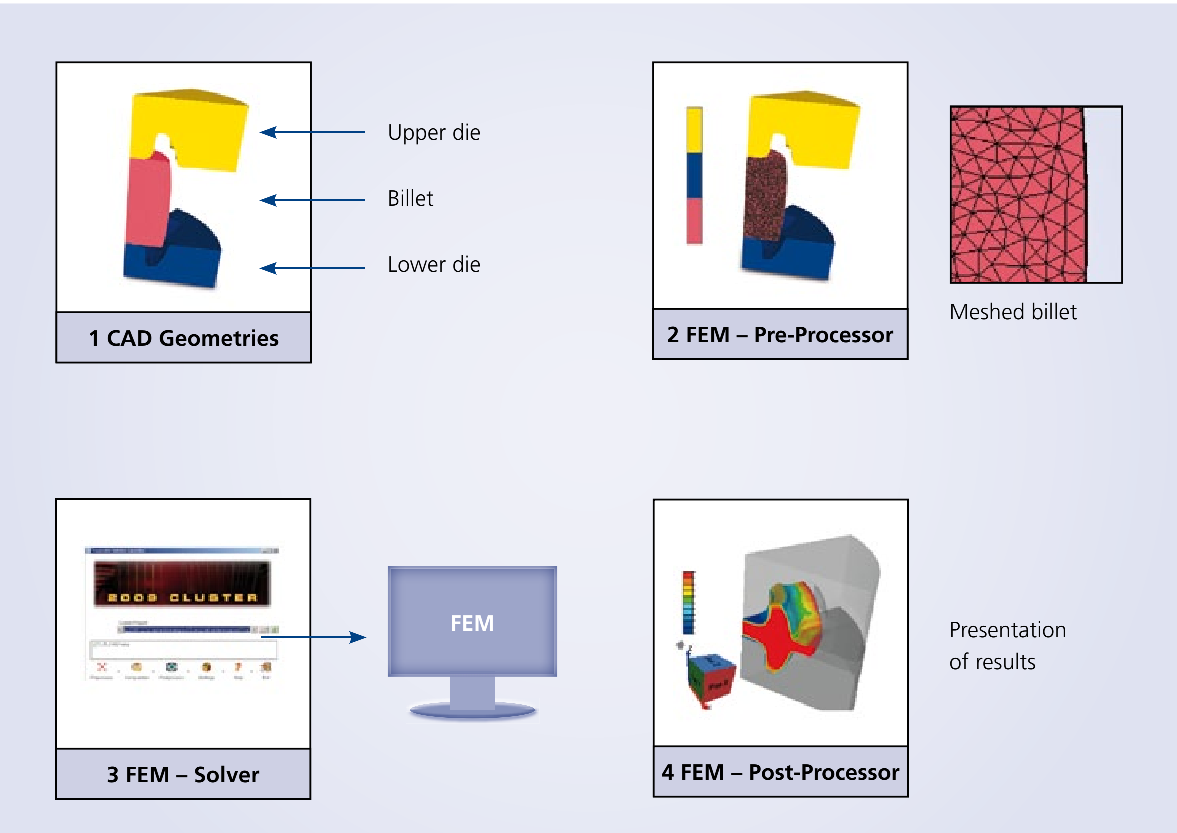


Fig. 3.1: To prepare for the simulation, the three-dimensional CAD image of the billet is subdivided into numerous minuscule volume elements. During calculation the solver "closes" the tool in small steps and calculates the changes for each step

makes it possible to look on while the billet is deformed in the forging process and the material fills the cavity of the die. Although such calculations usually require enormous computing power, thanks to the high performance of modern computer systems and related advances in recent software developments, nowadays they can be performed within acceptable time limits.

3.1.1 Integration of two forged parts

T. Feldhaus [FELD 1] describes a well-performed integration of two previously separate forgings to form a single integral part. The starting point of the development project was a assembly for truck axles consisting of two separate forgings, a stub axle and a steering arm, Fig. 3.2. The two parts were joined by two screws. Compared with an integral solution combining the functions of the two separate parts in one monolithic component, this solution entailed several serious disadvantages. All the high dynamic stresses this connection is subjected to run through the screws. To compensate for the fact that, as a result of notch effects, the threads represent a critical factor under dynamic load conditions, their size had been adjusted to the upside. This in turn forced the designers to provide massive walls around the threaded bores and blind holes in order to ensure adequate support. Additionally, both parts had to be forged, machined and tested in separate production processes before being joined by screwing in a quality-assured assembly process that had to comply with specific requirements.

The main reason for this arduous procedure was the fact that in the past, due to the lack of sufficiently powerful tools able to simulate the forging process, the designers were not able to mathematically represent the extremely challenging forging process for the production of this integrated forging with sufficient accuracy of the results. The risk of not being able to produce this part with the high degree of process mastery required for such safety parts was too great. This necessitated many loops in the production process, driving the process costs even higher.

This changed in the 2010s thanks to the increased mastery of such developmental tasks resulting from rapid advances in software to simulate forging processes. So it became possible to design and optimize the elaborate preparatory processes for shaping the forging billet in line with the requirements of the final forging operation on-screen. After a practicable process path had been identified, the next step consisted of defining the optimal component geometry. In this case, optimization of the

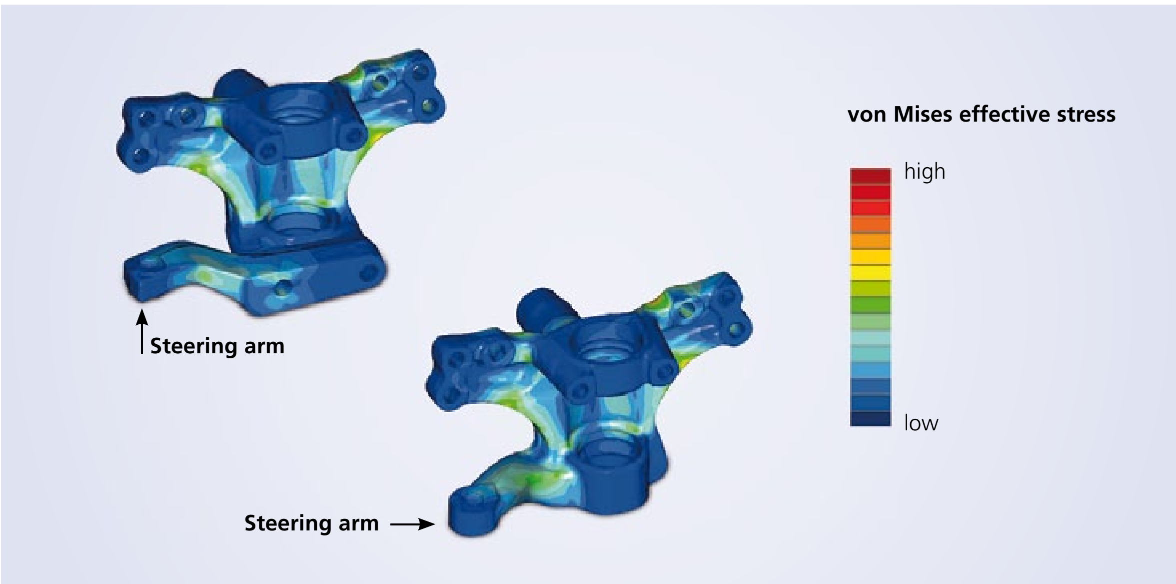


Fig. 3.2: The FEM analysis of a braking load case reveals that in the vicinity of the integrated steering arm the blue areas with low stress levels, indicating oversizing, are significantly reduced

topology was not yet available as a fully automatic software tool. Instead, the designer had to directly establish the geometry by manually performing several iteration loops. For this purpose a reasonably suitable design was generated, which was then subjected to given loads using FEM simulation software. This made it possible to identify areas subjected to particularly high or low stress levels. After any necessary corrections had been made by the designer, the modified geometry was subjected to the same analysis. This iterative procedure was repeated until the results met the developers' expectations. A further important contribution to the realization of this type of integrated part resulted from the truck manufacturer reducing the number of variants in the geometry of the levers he uses. With this refined geometry, the final simulation of the forging process and the design of the tools were tackled. The ultimate success of these actions was a slim integral part that was 25 % lighter than the previous version – a very gratifying contribution to fuel economy and CO_2 reduction, especially in view of the high mileage of heavy trucks. A further bonus comprised substantial savings in machining and assembly costs along the supply chain through to the ready-to-assemble stub axle.

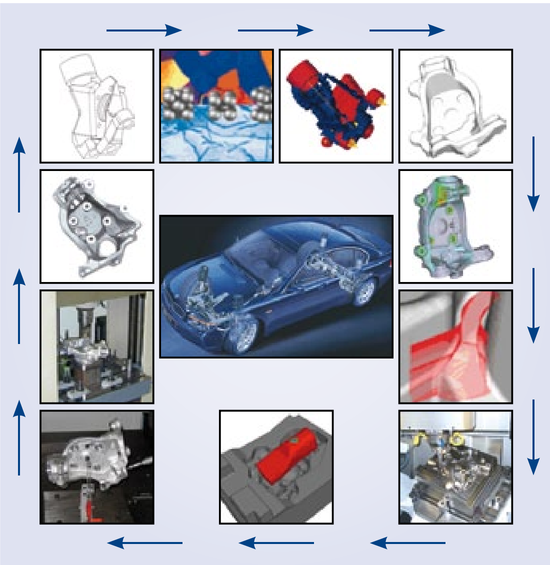


Fig. 3.3: Example of a comprehensive joint development process starting with an initial welded assembly (top left) trough material substitution, topological optimization, CAD model, structural analysis, prototype manufacturing, machining of tools, forging simulation, measurement and testing of aprts to the fished component for a premium segment car producer

3.1.2 Substituting a casting by a forged solution

M. Dahme et al. [HIVO 1] report on a very extensive partnership between a forger and a vehicle manufacturer involving the comprehensive use of simulation tools. The starting point was a request from the customer regarding possible alternatives for a steering knuckle the previous version of which had been designed as a steel casting. Starting from a rough concept designed as a welded structure, the forger was provided with a set of specifications, including the construction space needed, service load cases and additional functions and requirements. The special feature of the inquiry was that the customer was willing to accept advice from his supplier right from the start of the project and was ready to consider an alternative production method and even substituting materials (aluminium alloy instead of steel casting), Fig 3.3.

The first step was a redesign with the aid of software providing automatic topology optimization. With this in mind, the new FE model of the construction space initially included the total volume available. For the subsequent optimization loops this construct was subjected to the given loads and the resulting stress distribution in the material was computed. In areas with low stress levels, "virtual material" was successively removed before initiating the next iteration loops. This procedure was repeated until a relatively uniform stress distribution was achieved throughout the volume of the workpiece. In other words, the material remaining in the component is optimally used in all locations. In performing such tasks modern programs can already allow for manufacturing boundary condition constraints, such as taking into account draft angle or avoiding undercuts, which cannot be achieved by forging.

For the next step, the model resulting from the finite element analysis had to be converted into a CAD model, with the designer taking other manufacturing technicalities, such as rib widths and radii, into account. In this process the forging designer relies on his experience to develop an aluminium steering knuckle that can be produced by forging from the still very immature FE result. But even this solution still leaves room for improvement. For instance, although the material is largely optimally distributed in the component, certain geometric elements should be redesigned, taking account of local stress distributions, which can contribute to a significant reduction of stress peaks. The minimum requirement for shape optimization is that the maximum stress levels predetermined by the choice of material are not exceeded and that elastic deformations of the component remain within prescribed limits. The component model is therefore once again subdivided into finite elements. For the calculation the specified loads are entered as boundary conditions. Only then will the forger use the resulting design model for the next step of designing the actual sequence of stages for a forging process, i. e. the virtual simulation of the forming process on his computer. This step is also supported by simulation. Information obtained in this way can result in further optimization of component design in the course of additional iteration loops.

Only then will prototypes be made and tested – based on the CAD model thus obtained. Furthermore, the model serves as a template for numerous additional simulation computations along the process chain from tool design to the selection of machines and peripherals down to CNC machining processes. Many of these calculations, as well as fatigue testing, are performed in close cooperation with the customer, together with his staff and using his resources. The outcome of such cooperative simultaneous engineering processes is well-designed components as well as production processes that are mastered at a high level and can be ramped up quickly.

3.1.3 Substituting a part made from sheet metal

The successful substitution of a car control arm originally designed as a sheet metal part by a forging is described by M. Bachmann [BACH 1]. The starting point of the development project was an urgent customer request because the original solution had proved to be impractical relatively late in the development process. The forger, acting as a "knight in shining armour" was thus granted only six months for the development (from the first inquiry to the start of production) instead of the usual three-year period. Without resorting to the massive use of simulation software, the forging designers would have stood no chance of making up for this huge delay. Yet the remaining time was not sufficient to come up with an in-depth topology redesign reflecting the particularities of the new manufacturing process. For this reason, the resulting forged part geometry still closely reflects the contours of the original sheet metal design and its large-area, thin-walled geometry is not easy to forge. For example, the thin walls impede the flow of the material in the die. In order to ensure that the tool can be filled satisfactorily in spite of this, the billet has to undergo complex multi-stage operations to predistribute the material prior to the actual forging operation, Fig. 3.4. Thanks to the use of simulation, further special adjustments required were identified in time to include them in the tool design before the start of production.

Another key aspect comprised strict requirements with regard to the behaviour of the components

Fig 3.4: In order to ensure a satisfactory filling of the mold, the billet has to be subjected to a number of sophisticated pre-forming stages prior to the forging process. The entire sequence of production stages consists of 4 rolling passes, bending, flattening, pre-forging, finish forging, trimming/calibration and surface treatment

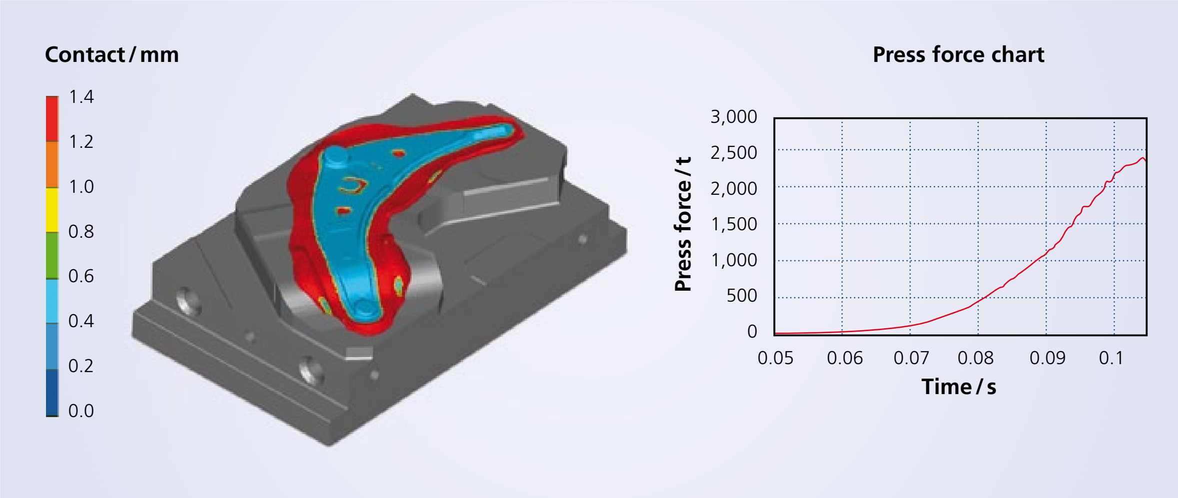


Fig. 3.5: Forming simulation make it possible to accurately predict the pressing forces and thus decide in favour of a smaller and more economical production unit

in the event of abusive overloading. In this respect particularly restrictive requirements prescribed that buckling should occur at a predefined location in order to avoid undue deformations, e.g. in the vicinity of the bearings. Their implementation called for corresponding adjustments in the forging process, for example by narrowing the usual forging tolerances.

Another problem also coming along with the thin-walled geometry was extremely high press forces during the final forging stage. This would have required using much too large a machine, which would have exceeded the limits set by the budget. Here too, the simulation proved beneficial because it could predict the press forces with a high level of accuracy, Fig. 3.5. The computation revealed that the required maximum load would remain just within the tolerance requirements of a smaller and thus more economical machine.

3.1.4 Optimization of spur gears

The successful use of simulation for the optimization of spur gears for the automotive sector is reported by S. Huber et al. [HUBE 1]. The starting point of the development comprised spur gear sets for camshaft drives used in modern engines to replace toothed belts. The focus was on reducing weight by realizing so-called wave-profile connections between the hub and sprocket instead of the usual T-bar profile,

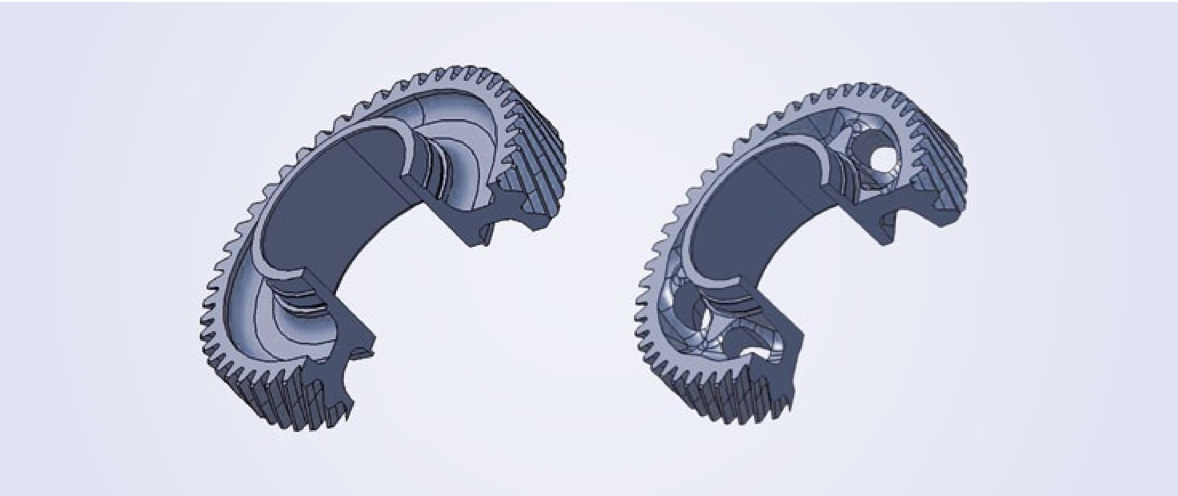


Fig. 3.6: Helical gears with different connection profiles: a T-bar connection (left) and a perforated wave profile connection (right)

Fig. 3.6. The challenge lay in the demanding metal forming technology required to achieve such wave-profiled gears. In particular, this necessitated accurate predistribution of the billet material in the precursory stages in order to avoid wear on the forging tools – especially on the form punch of the final forging stage with the crown or wave contour. An uneven load cases of the forging material on the flanks of the protruding areas of the punch and in the die would put them at particular risk of abrasive wear and fracture. The corresponding forming stages were therefore comprehensively investigated and optimized using simulation software.

Another aspect of this development was to minimize the allowances required when milling the gears in the "green", i. e. non-hardened state. These allowances are required to make up for distortions which the component may sustain as a result of the hardening process prior to the final finishing of the gears by grinding. Since grinding in the hardened state is a very expensive operation, any reduction of the related allowance has a positive impact on costs. Tests showed that with respect to the grinding allowance per tooth, a reduction of 0.05 or 0.1 mm was possible, resulting in significant cost and time savings.

Other benefits were noted when analyzing key characteristics such as the von Mises equivalent stress in the web area between the hub and sprocket, as well as the total deformation in the sprocket area, by means of an FEM analysis, Fig. 3.7. Additional studies revealed that using a wave-profile connection makes it possible to slim down the support area beneath the sprocket teeth. Taking the example of a gear with a diameter of 110 mm and a tooth height of 8 mm, the redesign resulted in weight reduction-values between 60 and 100 g, with a related reduction of the moment of inertia. Depending on the design variant, weight savings of up to 10 % can be achieved.

3.1.5 Optimization of an aluminium wheel

P. Olle [OLLE 1] reports on progress in the development of forged aluminium wheels based on the example of a "historical" classic wheel. Since for this wheel a retro look and modern-day wheel dimensions had to be blended, the striking design of the late 60's had to remain recognizable. In spite of this, the new wheel had to sport an optimally light weight without negatively affecting its fatigue strength. The latter aspect had particularly high priority for the designers, not least with a view to minimizing the unsprung mass of the vehicle in order to enhance driving comfort.

Wheels are safety components that, due to their direct contact with the road surface, are subjected to

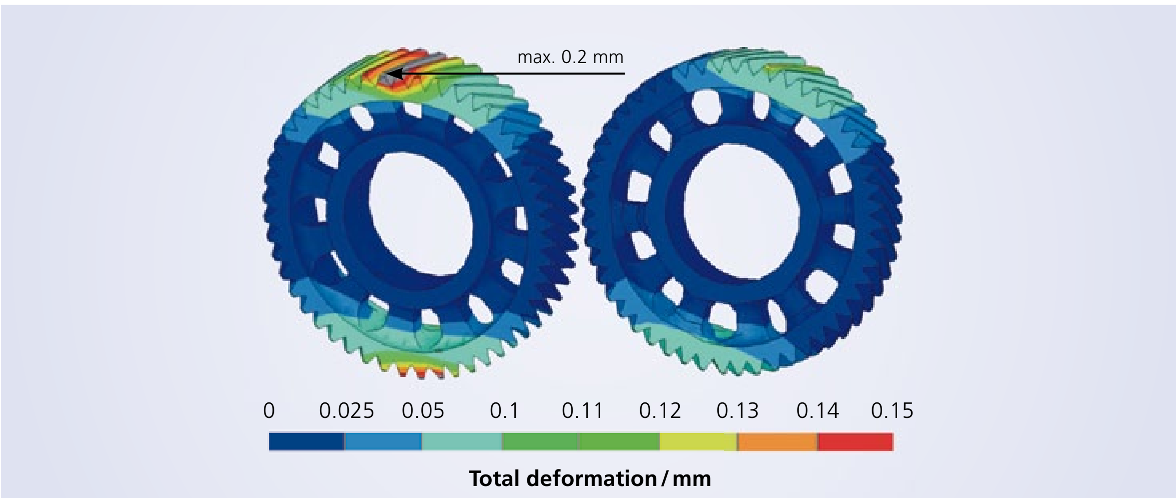


Fig. 3.7: Total deformation in mm: a perforated T-profile (left) and a perforated wave profile (right)

especially high dynamic loads. So their resistance to fatigue had to be proved not once but twice, using two different dynamic test procedures: a classic rotating bending test (UBP) and the biaxial wheel test (ZWARP) developed by the Fraunhofer Institut für Betriebsfestigkeit und Systemzuverlässigkeit (LBF), each performed with load spectra reflecting practical service conditions. Both tests can be simulated using special FEM software. The UBP simulation is modeled, computed and evaluated partly automatically, while the pre-processing of a ZWARP simulation is carried out using simulation tools specially designed for wheels.

Developing the new wheel design thus required regular optimization loops between the CAD software, forging simulation and the programs used to evaluate service life. In order to preserve the distinctive look, design changes were only permitted on the brake side of the wheels, Fig. 3.8.So reducing weight without changing the look was achieved by forging topology-optimized pockets as well as by adding blind holes between the mounting holes on the spokes (Fig. 3.9). After each optimization loop the effects on the forgeability of the contour as well as compliance with service life requirements had to be re-checked by computation. From the perspective of the developers it was interesting to note that over the years they were able to not only significantly reduce weight, but moreover – thanks to improved simulation tools – shorten the time required to develop forged aluminium wheels. To a considerable extent this was attributable to the service life computations. Certification tests could therefore be carried out on optimally designed wheels. This made it possible to significantly reduce the amount of work required for service life tests in the lab. Likewise, time-consuming and costly readjustments of the wheel design, which would have necessitated further development loops, could be avoided. Right from the outset, the wheels could be designed with consistently high component utilization. The result is an extremely lightweight product that still meets all safety requirements.

3.2 Using advanced simulation technologies

The more closely the forger is involved in the joint development of new products, the more comprehensive the reach of the advanced software he uses to simulate the characteristics of the product to be designed in order to achieve an optimized solution often becomes. To this end, he relies on his wide-ranging knowledge of the relationship between the functional properties of a component and the characteristics of the production process. Some related examples are presented in the following chapters.

Fig. 3.8: The brake-side CAD view shows the weight-reducing pockets forged in the spokes as well as the additional blind holes on the spokes between the screw-mounting bores

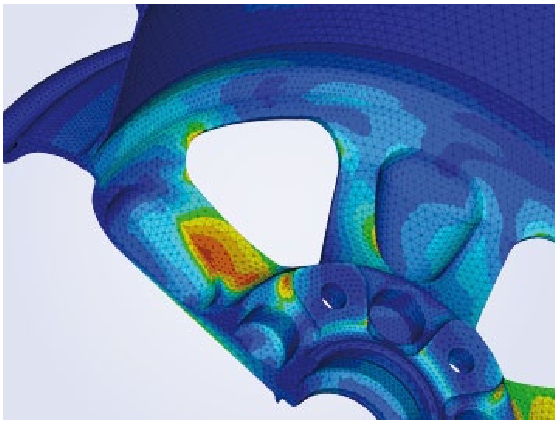


Fig. 3.9: The investigation of the dynamic strength based on an FEM analysis shows that the edges of the weight-reducing pockets had to be designed with special care

3.2.1 Adjusting the design of differential bevel gears

When developing new differential bevel gears, the designer has to find suitable solutions on the basis of customer specifications [RUE 1]. With this in mind, the forger usually receives a description with detailed specifications and requirements regarding construction space, interfaces, load cases to be considered and the maximum total weight. The example presented here deals with a bevel gear that had to be newly designed from scratch. One special feature was an extremely high tolerance to displacements caused by external forces.

The usual procedure in such cases is to create a first rough design of the geometry using a CAD program, with the aim of determining the maximum flank length and load bearing capacity achievable within the prescribed construction space. The variables that have to be considered at this stage of development include, among others, the number of teeth, with the designer's experience playing a major role. For example, he must allow for the fact that not every geometry a CAD system can deliver lends itself to being forged economically later on.

In the next development stage, details of the tooth design have to be studied in order to achieve an optimum load bearing capacity. For these calculations, a DIN calculation program from the Forschungsvereinigung Antriebstechnik is used. Over the years, the forging specialists have added further routines to this standard program, reflecting their special know-how and experience. For the project presented here, some 10,000 variants were designed, computed on the basis of a wide variety of application scenarios and the results assessed. Here too, the forger's special know-how lies in how specifications and constraints should be parameterized and how the best solutions can be identified.

Based on these results, the geometry of the gear is subsequently established using a CAD program. The base geometry is then complemented by diverse subtleties, such as tooth flank crowning, tooth base curvature between the teeth or compensation of the so-called flank entanglement in order to optimize the contact pattern under load. Other important factors, such as the rigidity ratio of bevel pinion and bevel wheel also have to be considered. With all these pre-parameters the project then enters the stage of strength analysis, performed using FE software, Fig. 3.10, where compliance with all requirements is verified.

The next step is the production of a prototype by milling from a solid to evaluate the rolling behaviour, Fig. 3.11. Finally, prototypes are forged that will be tested on the company's own test stand. In the case presented here the forging specialists managed

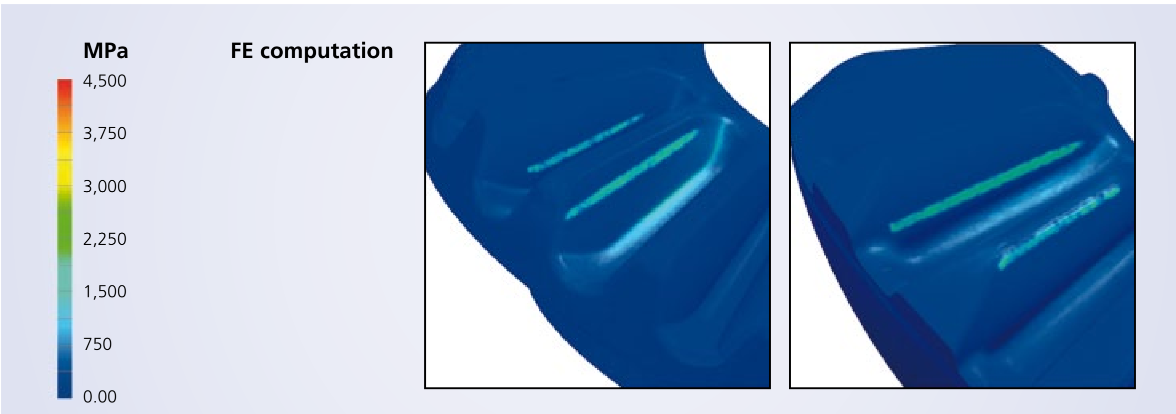


Fig. 3.10: Load-bearing capacity analysis of differential bevel gears using an FE program

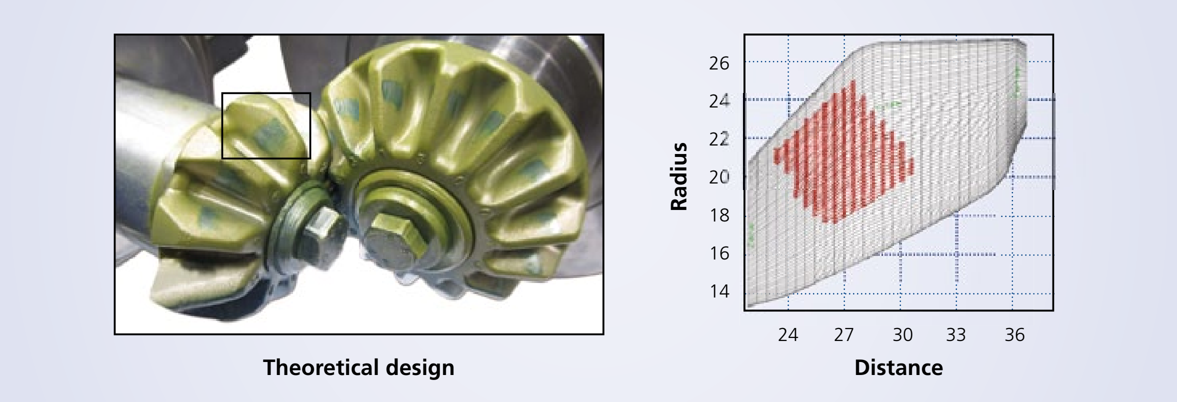


Fig. 3.11: Moment of truth: the test stand reveals whether the computed contact pattern under load is sufficiently consistent with the actual status

to double the expected service life despite having to allow for the problems related to stress-induced displacement.

3.2.2 Simulation-based optimization of a constant-velocity joint

A fine example of how a forger can support his customer's developments is the optimized constant-velocity joint presented below [LEH 1]. Such joints are used, amongst other things, as transmission elements in cardan shafts where – as opposed to universal joints – they ensure that the angular velocity of the entire shaft assembly remains constant even when the assembly is inflected, Fig. 3.12. Basically, the joint consists of two forgings (hub and ring), the balls positioned between them, and a sheet-metal housing.

One special feature of these joint parts produced in large series since 2006 is the fact that the ball tracks of the two main components are forged straight to final shape and do not require any machining after the heat treatment.

A car manufacturer then wanted the load-bearing capacity of this joint to be increased by more than 30 % in order to keep up with the higher performance of new diesel engines, but without increasing its size.

An analysis of the torque path revealed that the diameter of the balls is the key parameter. Closer study of the two forgings showed that the hub could be slimmed down, thereby accommodating larger balls within the joint. The geometry was designed using CAD software while the computations relating to

Fig 3.12: The constant-velocity joint ensures that the angular velocity in Cardan drive shafts remains constant. Basically, it consists of the two forgings, hub and ring, the balls and a sheet metal housing

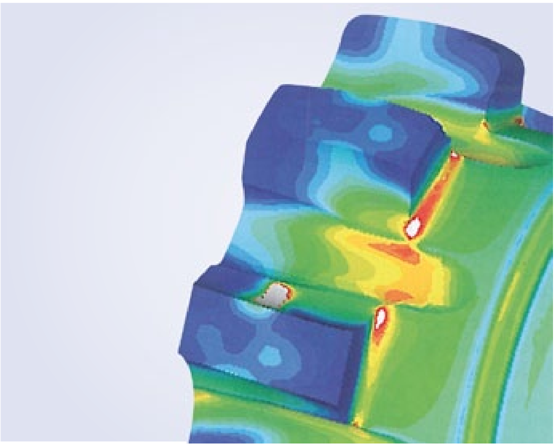


Fig. 3.13: The improved design was subjected to an FEM analysis to check for stress distribution and possible weaknesses

static and dynamic loads were made using FEM programs, Fig. 3.13. The computations were performed using load spectra provided by the customer for the various deflection angle conditions. A further important role was played by process simulation software when it came to assessing the feasibility of a special groove in the hub using the forging process. This groove had to be included in order to be able to insert the balls in the joint during assembly. Finally, further simulations had to be carried out in order to ensure that the hub could be produced with this groove without increasing the risk of fatigue cracks.

3.2.3 Optimizing the design of connecting rods

When new connecting rods have to be designed, the forger ideally receives specifications with the construction space as well as load data, and then creates the design himself [MAH 1]. Typical parameters relate partly to the space requirements – maximum width, piston stroke, distance between piston pin and crankshaft – and partly to service conditions such as the ignition pressure. One of the main tasks of the forging specialist is then to find a design that is as lightweight as possible.

In undertaking this work, the first step consists of designing an initial geometry using industry-standard CAD programs. Subsequent steps are performed using a special design program for connecting rods that has been optimized with regard to the specific loads on the component. Here, computer assistance is used to optimize the cross sections of the connecting rod. The required static strength is determined by a comparison with stresses calculated using an FE analysis. Based on their experience, from the outset the staff allow for feasibility aspects such as radii, draft angles or answering such questions as whether the eye for the piston pin can still be punched or whether it has to be drilled.

The dynamic analysis of the design determined in this way (Fig. 3.14) is usually again conducted by the car manufacturer, as he plays the lead role in development. At this stage there is an intensive exchange of parameters with the supplier. If necessary, the supplier also commands enough expertise to relieve the customer of such tasks on request. After clarification of all theoretical questions the first practical tests are performed, firstly with samples milled from solid and later with forged prototypes.

Beyond this, the overall responsibility of the forging specialists is to support the customer's desire to increase engine power while lowering consumption. This means that the rods must become leaner and lighter, which in turn implies that the limits of the technology have to be gradually expanded. This presupposes that the corresponding limits can be reliably assessed, met during production and consistently observed.

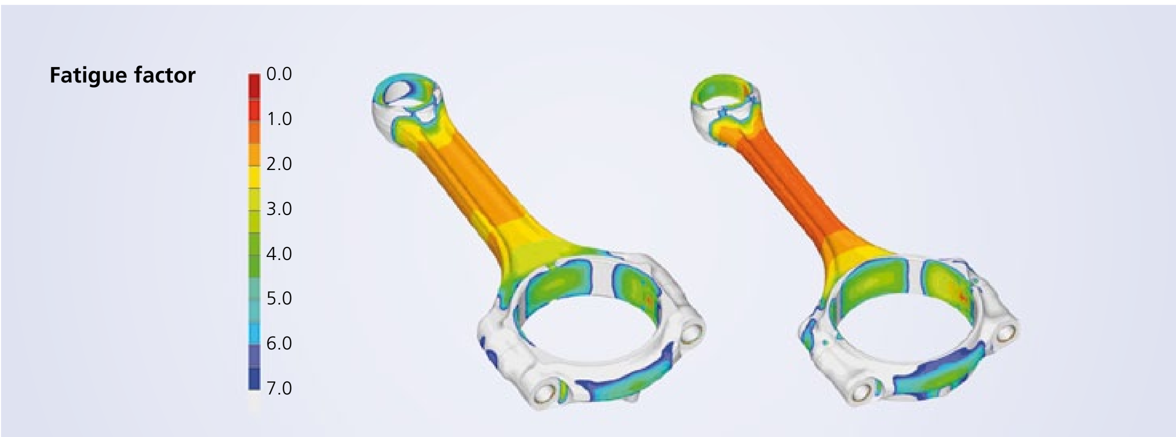


Fig. 3.14: Distribution of fatigue factors in a connecting rod with conventional geometry (left) compared to an optimized connecting rod with a much slimmer shaft (right) at design loading

3.3 No substitute for creativity

As already stated, simulation tools are utensils that belong in the hands of experts. They cannot replace thinking. Human creativity, i.e. smart ideas and the boldness to explore new avenues, remains the key factor for progress. The function of the simulation is then to assist in working out the feasibility and benefits of these ideas. Some examples are presented below.

3.3.1 Advantages of precision forging gear wheels compared of machined ones

Using FEM simulation, today it is possible to create precision-forged geometries (Fig. 3.15) that simply could not be economically produced using conventional processes [GUT 1]. The main aspect here is that gear wheels manufactured by precision forging do not have to be finished by machining. This is made possible thanks to advances in CAM-based technologies for the production of high-precision forging tools on the one hand, and the narrowing of process parameters on the other. The forging process is performed in two stages. In the first stage, the geometry is shaped by hot or warm forging. After controlled cooling and cleaning, the parts are then calibrated by cold coining. The achievable accuracy lies within a few hundredths of a millimeter, so that certain geometry features, such as clutch teeth, do not need any further processing. This has three key advantages: firstly, no runout space for cutting tools has to be provided, and secondly, these clutch teeth can be recessed in relation to the outer sprocket, Fig. 3.16. This makes it possible to design slimmer gears, giving the car designer greater degrees of freedom to develop compact, lightweight transmissions with a larger number of gears. Another advantage is the integration of the clutch teeth in the lower area. This increases the load-bearing capacity of the tooth.

A comparably advantageous effect is obtained by the interconnection of the tooth base of precision-forged bevel gears on the small as well as on the large module, and the optimally shaped transition from the tooth base to its flank, as described by B. Laackmann [LAAC 1], Fig. 3.17. FEM calculations

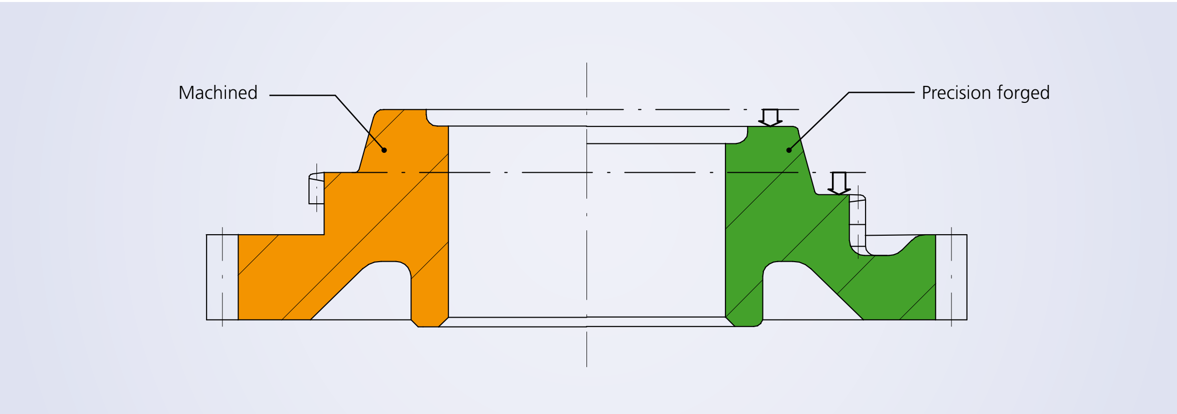


Fig. 3.15: With integrated precision-forged clutch teeth the gear wheel can be made much flatter, thereby saving space

Fig. 3.16: Gear wheel with precision-forged clutch teeth. The integration of the clutch teeth in the lower area increases the load-bearing capacity of the tooth

show that gears with such shapes are able to transmit higher torques compared to ones produced by milling. This in turn allows savings in terms of the weight and size of differentials.

3.3.2 Disk carrier for a transfer clutch

By intelligently combining different forming technologies, nowadays gear teeth can often be produced purely by using forging with such high precision that subsequent machining operations can either be completely eliminated or reduced to a minimum. The advantages of such process combinations are also reflected in the form of significant cost savings [LAND 1].

Such a development has been implemented, for example, on the basis of a disk carrier, Fig. 3.18. This

The base component is first prepared by means of a warm forging operation. The gear teeth are subsequently produced in a cold forming process. Next, the bearing and seal surfaces are machined by turning on a lathe, and some perforations are machined. With the inner toothing within the pot, the strength of the tooth flanks achieved by cold forming is sufficient to withstand even the high specific pressure loads exerted by the narrow clutch lamellae without further treatment.

In such developments, FEM simulation is used on the one hand to fine tune the contours of pre- und intermediate shapes produced using metal forming technologies. On the other hand, it helps determine the ideal stamp outline for the final operation on the inner gearing.

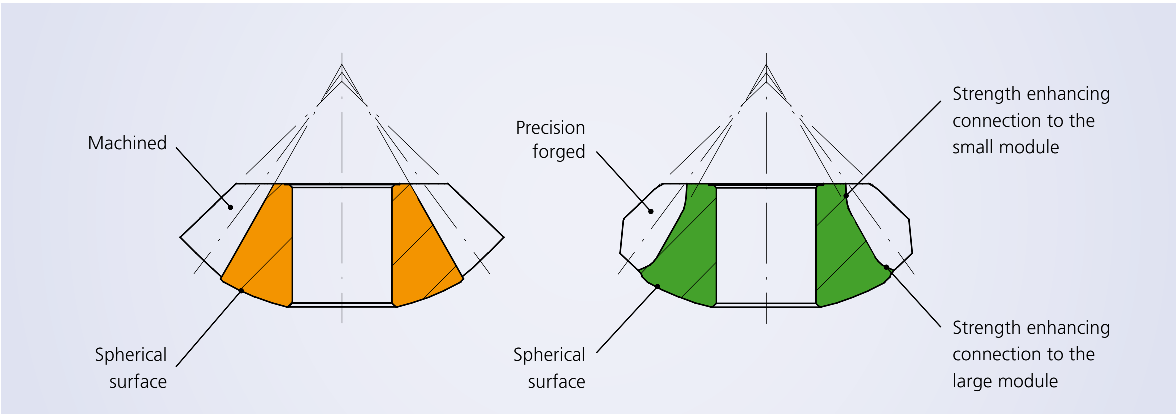


Fig. 3.17: Compared to bevel gears produced by machining, precision forging makes it possible to connect the tooth base of bevel gears to both the small and large module as well as optimally shaping transition from the tooth base to its flank, thereby increasing its load-bearing capacity

is a key component of the transfer clutch for all-wheel drive vehicles. In such vehicles, special lamella clutches adjust the distribution of traction between the front and/or rear axle in line with driving requirements. The disk carrier accommodates the outer sprocket of the lamellae and transmits their revolutions. The toothed lamellae fit alternately into an external or internal gearing. If the lamella package is compressed, it transmits rotational speed and momentum as a result of the friction between them. The power transmitted can be varied by adjusting the contact pressure.

Fig. 3.18: External disk carrier for the distributor clutch of an all-wheel-drive vehicle

Simulation along the forging process chain

Steel is clearly the most commonly used forging material. The process sequence usually applied when forging steel comprises up to 14 individual steps. The "birthplace" of the forged part is the steel mill where the alloy is melted and processed into ingots or continuously cast slabs. These are then further processed by extrusion, hammering, rolling or drawing into semi-finished products in the form of billets, bars or wire. In certain cases, the raw material is peeled to remove surface defects prior to delivery to the forger. In the course of this processing sequence, essential properties of the forging billet such as alloy composition, purity and segregation structure are defined. These have a considerable influence on the properties of the subsequent forging.

At the forge, the process chain starts with the stages of material pre-treatment, cutting und heating before the actual forging takes place. Other stations are machining, heat treatment and surface after-treatment. Depending on the application, a formed part may pass through all of these stages or – especially in the case of cold forming – just some of them.

Simulation software is now available for many of these stages. This makes it possible to virtually model the related process and to compute its effects. The following chapters present the current state of the art taking specific case studies as examples.

4.1. Using simulation in a steel mill

The successful use of different software tools to simulate the processes in a steel mill – from alloy design through casting to rolling – is described by C. Ernst, J.-S. Klung et al. [DUH 1, ERNS 1, ERNS 2, KLUN 1, KLUN 2]. Even before production is started, the design of new or modified alloys is assisted using programs designed to simulate states of thermodynamic equilibrium in the microstructure. In combination with suitable databases, these programs make it possible, for example, to compute the quantity and composition of phases in equilibrium. The software also helps by systematically analyzing the effects of alloying elements, e.g. by modeling the influence of molybdenum on the carbide types in a cold work steel, Fig. 4.1. A further advantage is the calculation of phase diagrams that can be used to identify appropriate temperature ranges for hot forging or for heat treatment processes.

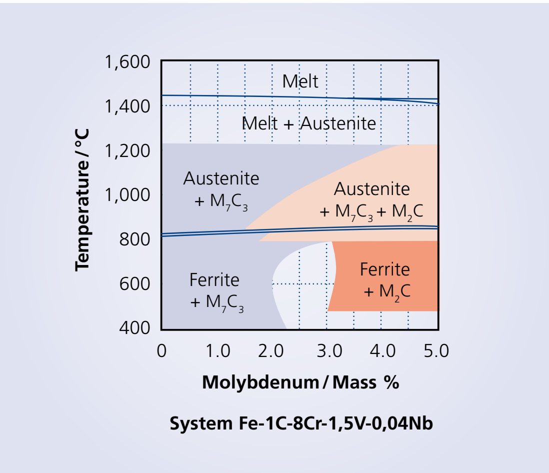


Fig. 4.1: Computation of the influence of molybdenum on the phase diagram

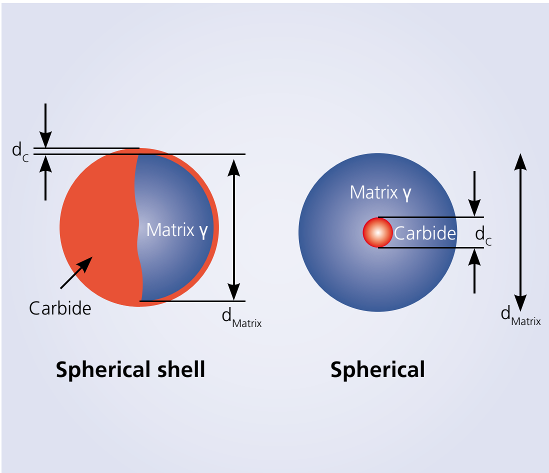


Fig. 4.2: Different geometrical models for the computation of diffusion-driven transformation processes in steels

Another area of application for simulation programs is modeling diffusion-controlled transformations in steels, Fig. 4.2. Of particular importance in this context is the representation of dissolution and precipitation processes in stainless steels, which are computed to determine holding times, holding temperatures and particle sizes. Various geometric models are available for this purpose. In practice, this program has proved to be very helpful in analyzing carbide dissolution in hot work steels, where such calculations have helped optimize the temperatures and holding times required for homogenization annealing.

Simulation software based on FEM is used to simulate processes during casting and solidification in the steel mill as well as during the hot forming of newly developed steel materials. This is particularly important for highly alloyed and thus segregation-prone steels as here macro-segregation, porosity and voids have a significant impact on subsequent manufacturing steps. The segregation processes occurring are depicted using the software. This makes it possible, for example, to analyze the local segregation behaviour for individual alloying elements (Fig. 4.3) and to optimize it by taking appropriate measures.

The next step is to simulate the forging process using another program, Fig. 4.4. During this virtual forging, analyses of material and workpiece are conducted in order to describe temperature, stress and fibre flow patterns as well as the degree of deformation. The program makes it possible to predict the material flow as well as velocity and displacement analyses in order to help identify defects and error sources. For newly developed alloys this simulation helps set up rolling pass schedules along with the necessary intermediate, pre- and post-treatments tailored to the new material.

The objective when using these programs is to complement the traditional experimentally oriented approach to development projects by using simulation tools to calculate casting, forging and heat treatment processes as well as drawing on appropriate material databases focused on steel. Another aim is to enhance the efficiency of the development process. The optimized use of human resources and testing facilities should help reduce the response time to customer requirements and project throughput times while at the same time reducing costs.

Most of the software, database and human resources necessary to implement this concept are either already available or are currently under development. Additionally, external research partnerships with universities, research institutes and industrial partners provide access to further special programs

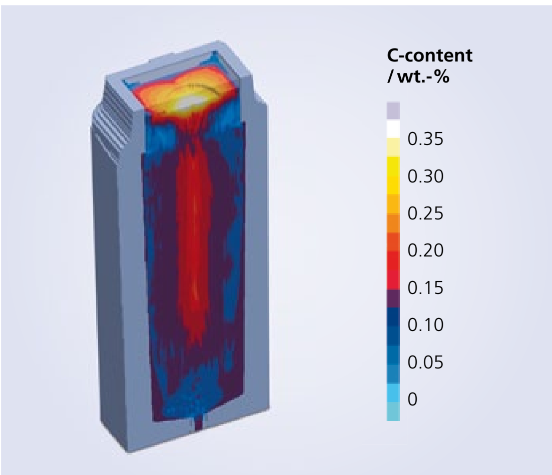


Fig. 4.3: Simulation of carbon segregation during ingot casting

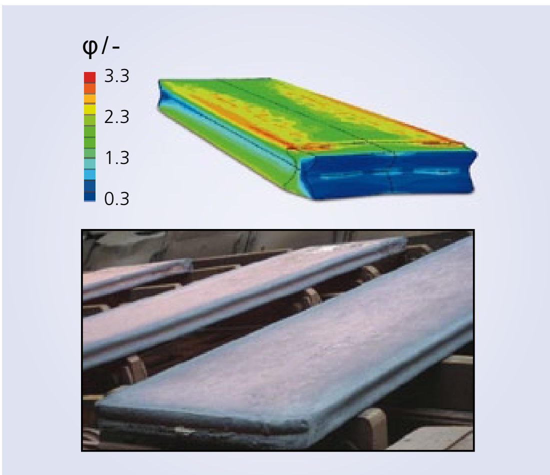


Fig. 4.4: Comparison of the geometry of a rolled billet with the shape calculated by simulation

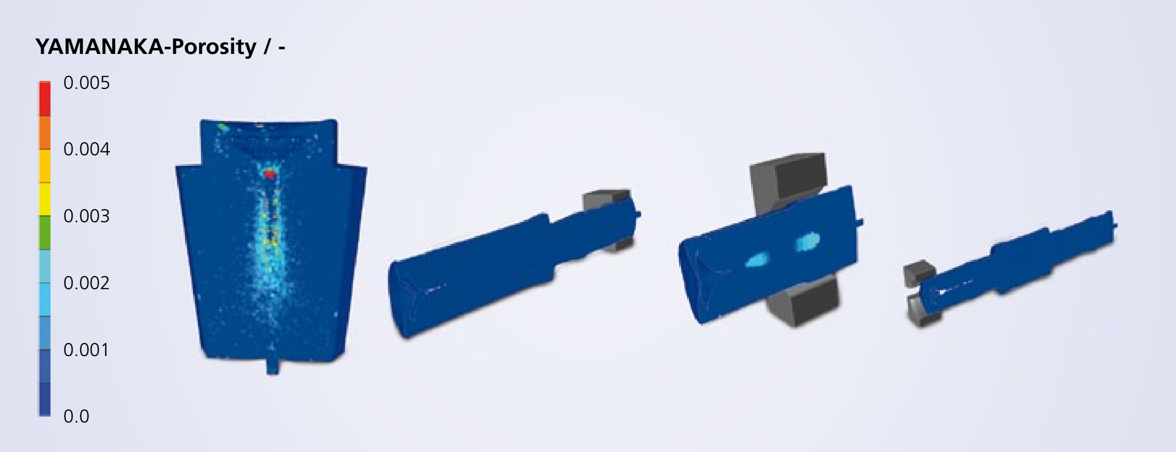


Fig. 4.5: The link-up of casting with forging simulation software makes it possible to follow up the porosities originating during casting of a 1.6 ton ingot during the subsequent stretching operations

and (mainframe) computing capacity. In this way it has become possible to solve even very special and unusual material problems with the aid of external experts and their know-how in simulation technology. In this context, the transfer of knowledge to the company's own materials engineers with a view to continuously upgrading skills is also of considerable importance.

C. Fourment [FOUR 1] describes the successful link-up of the simulation of the casting process for a raw forging ingot with the depiction of the subsequent forging process. This success represents an important breakthrough in joining up two hitherto separate software worlds: simulation of the processes in the liquid state and depiction of the material behaviour during forming in the solid state. In future this will make it possible to use the defects occurring in the ingot or strand during casting (Fig. 4.5), such as shrink holes or segregations, as input parameters for simulation of the subsequent forging. This means that now the entire manufacturing process chain up to the finished forging can be mathematically depicted. Work is currently in progress to refine this link and supplement it with the prediction of additional physical characteristics.

4.2 Material pretreatment

Forging often involves heat treatment and surface treatment in direct succession, which is a prerequisite for the successful implementation of many forging technologies. Heat treatment before or between forming processes makes it possible to achieve a structure facilitating the subsequent deformation as well as a reduction of the flow stress in the workpiece. Furthermore, this helps increase deformability and reduce residual stresses. Under conditions involving high normal stresses and significant surface enlargements (e.g. during cold extrusion of steel), the surface condition of the workpiece is usually improved by additionally applying inorganic or metallic coatings and then applying lubricant. For some forming processes upstream surface treatment of the workpiece can be dispensed with – in these cases lubricants (e.g. graphite-based) are usually applied to the working surface of the tools [LANG 1]. When forming metallic materials, surface treatment and lubrication basically serve three purposes: on the one hand, metallic contact between the workpiece and the tool (with the associated cold welding) is to be avoided. On the other hand, friction losses – and associated requirements with respect to forces and energy requirements – are to be minimized, which in turn helps improve the formability of the workpiece [LANG 2]. A third important effect is the cooling of the tools in order to dissipate the induced heat.

Further preparation methods aimed at improving the surface condition established in the forging sector are drawing and peeling. Drawing is typically applied when wire is used as input material and the main aim is to enhance the geometrical homogeneity (e.g. roundness) of the semi-finished part, especially since this in turn significantly affects the volume consistency in the process. Peeling is used to remove superficial impurities, surface defects or inhomogeneities in the surface layer, thereby helping to generate a higher-quality semi-finished part.

According to G. Adam et al. [ADAM 1], in the forging sector, although simulation technologies constitute an established approach to material pretreatment processes, they tend to be used in an academic context (such as shot peening) or in such cases where a direct influence of relevant condition parameters on subsequent process steps – (e.g. in the case of drawing) can be expected. In order to model the secondary effect of surface hardening during drawing, forging companies explicitly simulate this process step more rarely. Frequently, FEM models of drawn wire sections are already available in libraries as a basis for assessing the impact of this effect on subsequent processes, Fig. 4.6. The boundary conditions set in the specific process (e.g. tribological behaviour) as well as material properties (e.g. work hardening behaviour) are taken into account by simulation models as part of preprocessing.

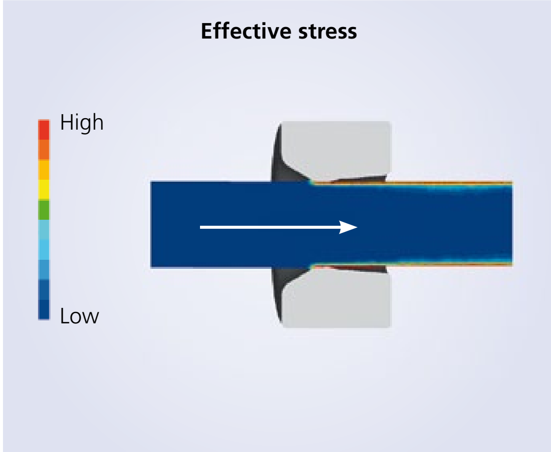


Fig. 4.6: Distribution of the effective stress in a wire after a precision-enhancing processing by drawing

4.3 Separation

Forging processes typically use rod sections or wire as raw material. Separation of the material is usually performed by shearing or sawing. If the process layout is not flawless, shearing off the sections (by means of a flat or round knife) may result in shearing defects, which affect the mass distribution of the billet, Fig. 4.7. During forging this may result in uneven filling of the die cavity, i.e. excessive flash formation on the one hand and incomplete filling on the other. Furthermore, shearing defects may increase wear on the forming tools. For such flaws a distinction must be made between shearing, geometry and volume defects.

Parameter	min.	max.
Temperature in °C	1,000	1,240
Shear gap in mm	0	0.5
Stop angle in °	0	20

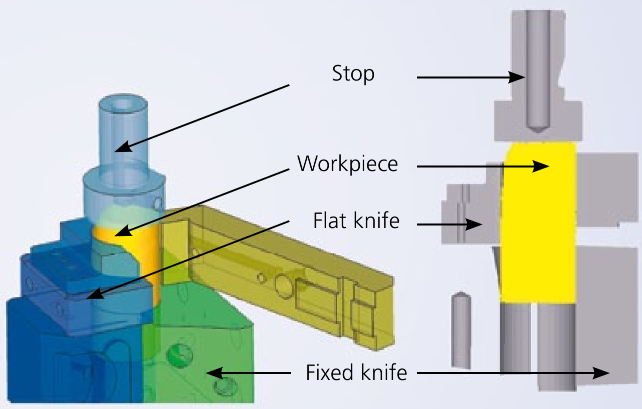


Fig. 4.7: The parameters analyzed by FEM simulation in order to minimize test expenditure

Geometry errors encompass the indentations caused by the pressure of the shearing edges, the axial deformation of the entire billet designated as angularity and the lateral tails. Shear faults include the shear flash as well as the break-outs and angle brackets that give the cut surface a rough, uneven topology. The latter are particularly critical when, after forming, they end up in workpiece areas that have no machining allowance but must meet high demands on surface quality. This can cause problems especially with precision forgings. Volume defects are caused by incorrect adjustment of the stop. They cause over- or under-filling of the die. Correct adjustment of the cut-off process requires extensive operational know-how and is usually adapted to the specific requirements of the product.

P. Guel-López [GUEL 1] and T. Feldhaus [FELD 2] report on research performed using simulation software to study the effects caused by the shear process. In the FEM simulation of the shearing operation, parameters such as shear gap, billet material, workpiece temperature, feed force and stop angle are included in addition to the geometry of the cutting blade and the rod stock material. In order to assess the outcome, a comparison is usually made between the calculated topology and scanned models of a real sheared sample. On a positive note, the impression of the shear blade and the indentation on the opposite side of the billet closely reflect the real situation. However, because the simulated shear surface is not smooth but – due to the mesh size specified – very rough, general differences show up between simulation results and the real specimen, Fig. 4.8. Furthermore, a reduction in the volume of the workpiece can be observed. This phenomenon can be explained by the fact that when the two FEM meshes initially linked to a single unit separate, this is usually done by deleting elements in the shear zone as soon as they achieve a pre-defined damage value.

Due to the complexity of the processes, shear simulations require a lot of processing time. They are therefore not undertaken for each new component. Moreover, the poor quality of the sheared surfaces is still a handicap preventing the everyday use of simulation of the shearing process when developing new forgings. Instead, the results of existing simulations are often systematized and condensed into a library. From this database, optimal values, e. g. for the stop angle and shear gap, can be determined for each material and rod diameter.

Further advances in the field of modeling shear processes would be greatly welcomed, especially since the geometry of the shearing edge and its influence on forming are of great importance for forecasting forging results.

4.4 Heating

In forges, the heating of metal workpieces essentially is performed with the aim of increasing their

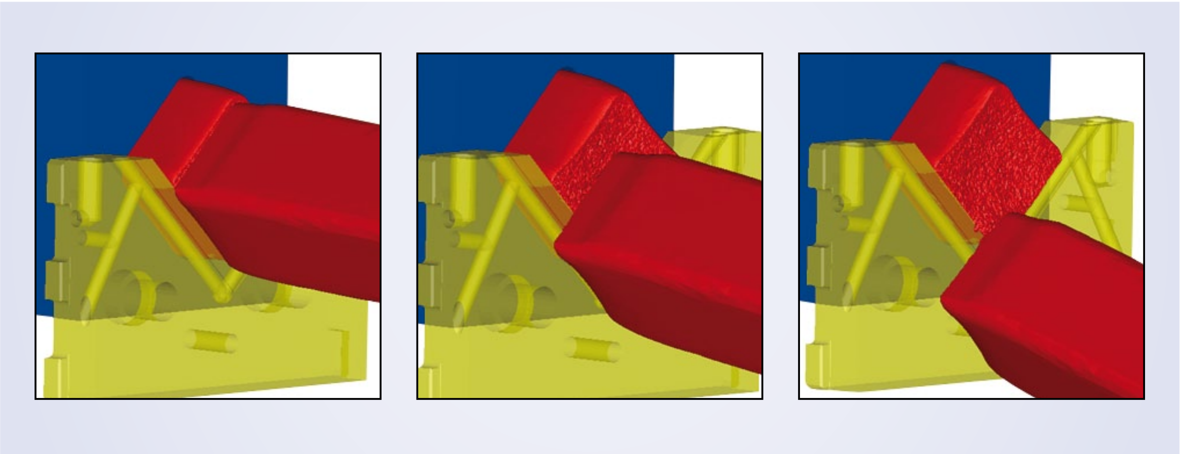


Fig. 4.8: Sequence of images from the simulation of a shearing process with hidden upper shear blade. The roughness of the simulated shearing plane is conspicuous

malleability. At the same time, this lowers the forming force and power requirements as well as generally enhancing formability. Common ways of heating before forging are “warming in furnaces (radiation and convection)“, “warming by eddy currents (induction)“ or “warming through the direct passage of electric current (conduction)“ [LANG 2].

In the process of forging simulation, the flow characteristics – altered by the heating process – are taken into account by assigning them material-specific, temperature-dependent flow curves. For a realistic setting of the temperature distribution in the billets after inductive heating, in order to obtain accurate results forges prefer to adopt the following approaches: a) start from the first forming stage with homogenous, slightly reduced temperature; b) start from the induction heating plant with inhomogeneous temperature distribution, allowing for the transport delay (simulation of the thermal delay) until the first forming stage – see Fig. 4.9. Often the results of the analytical calculation methods applied by equipment manufacturers or values obtained from measuring methods (e. g. using thermocouples and/or pyrometers) are used as a data basis for the latter approach. For the further evaluation of different warming strategies individual software manufacturers (in cooperation with manufacturers of heating plants) have recently been implementing suitable interfaces in their programs, making it possible to adopt the aforementioned time/temperature curves. It future this will mean that it will be possible to also analyze transformation and/or dissolution behaviour (e. g. carbides in the case of a 100Cr6) during the heating process and possibly include them in the subsequent forging simulation. Furthermore, it is worth mentioning that it is not always absolutely necessary to aim at a complete through-heating of the semi-finished material. In some cases targeted, localized heating can prove beneficial not only for process management, but also for achieving locally different component characteristics, according to Wohlmuth et al. [WOHL 1].

4.5 Forging

4.5.1 Designing forging sequences

Against the backdrop of intensifying global competition, intelligently designing technically and economically optimized process chains is gaining in importance. Furthermore, customers increasingly expect

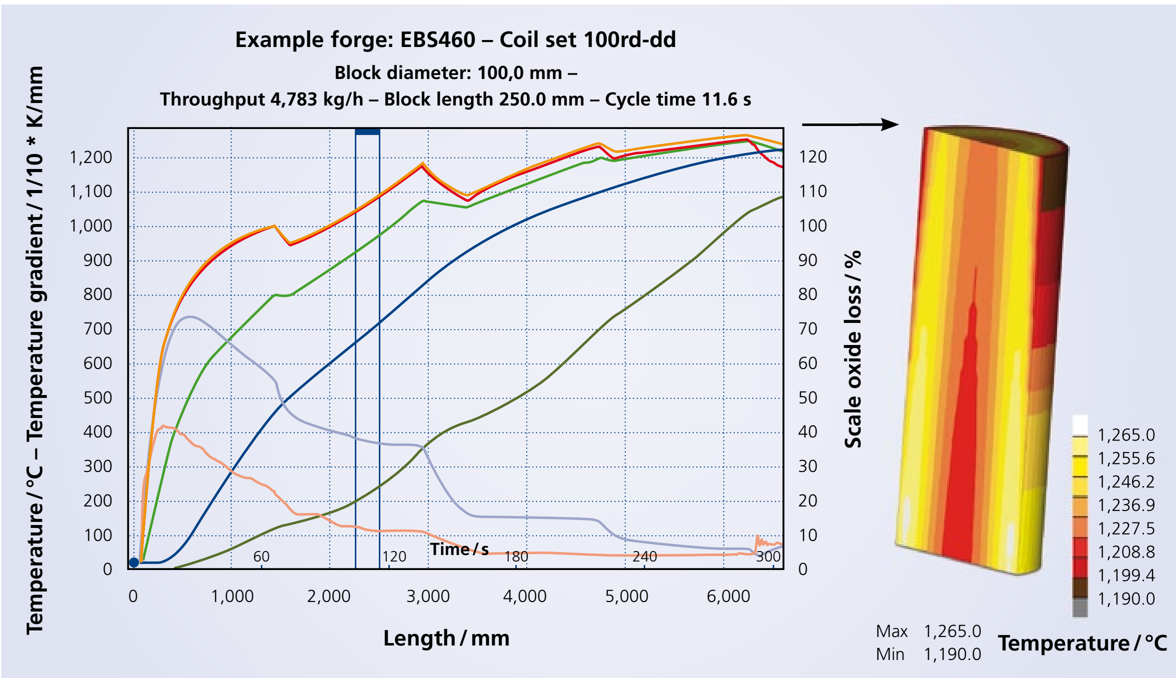


Fig. 4.9: Inhomogeneous temperature distribution after inductive heating as starting condition for the forging simulation

sophisticated, machined and finished components with guaranteed properties. To meet these ever-increasing demands, more and more forging companies are using IT tools for the virtual design and co-ordination of the processing stages. In the following paragraph, J. Heizmann and H.-W. Raedt [Heiz 1] report on the potential for using FEM simulation for this development process step.

After the material, forging technology and heating temperature have been determined, the starting point for further considerations consisted of defining a fibre flow pattern optimally suiting the service loading condition. In this context, reference should be made to the phenomenon of "fibre structure" in forgings. This refers to the fact that during the forming processes transforming continuous casting slabs into ready-to-use rough forging materials, the segregations are stretched and become fibrous. Studies have shown that this fibre structure has a considerable influence on the durability of the forging. For example, components where the fibre flow pattern orientation matches the main stress direction have a significantly higher dynamic strength than those in which the fiber direction runs crossways to the stress. Modern simulation systems are able to take this aspect into account when modeling the forming process. Thus, already at the simulation stage the forger can form an impression of how the fibre flow pattern will be oriented in the component later on – in relation to a specific orientation of the rough forging before the forging process is performed, Fig. 4.10. In the course of designing the process in line with load conditions of the component this knowledge then again influences further considerations with respect to the impact of subsequent processing steps (for example, if surfaces have to be machined).

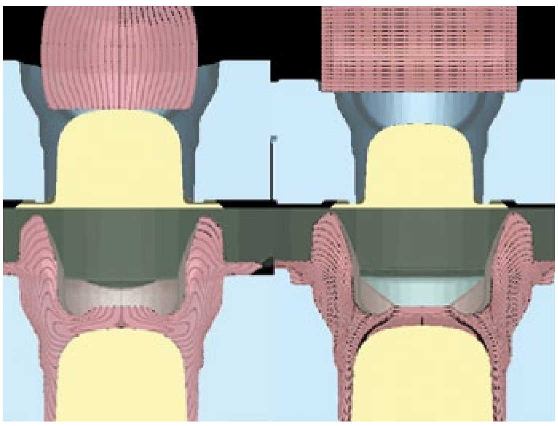


Fig. 4.10: Fibre flow pattern during vertical (left) and horizontal forging operation

Further focal points are the reliable filling of the die cavity together with the dependable prevention of forging defects. Here too, simulation helps detect any unfavourable filling behaviour and/or insufficient filling of the die cavity and compensates for this, for example by adjusting upstream production stages. Similarly, the current commercially available FEM programs help predict forging defects (such as wrinkle formation) and assess the adequacy of corrective actions. At this point, the increases in the efficiency of hardware and software achieved in recent years have contributed enormously to the timely identification of potential problem areas.

Further advantages result from the use of simulation in terms of efforts being made to reduce the use of raw material. In view of the fact that commodity prices in particular have increased dramatically in recent years, the raw material weight, i.e. corrective actions aimed at its reduction in the course of process optimization, are of key importance.

4.5.2 Analysis of tool-related defects

S. Binder [BIND 1] describes the successful use of a program for forming simulation and determining the cause of dimensional variations on a flange. With this part produced by hot forging, the first prototype production run sometimes revealed major variations in thickness, especially in its central region. In some places the specified dimension was exceeded by up to one millimeter. In the search for the cause it was first decided to check the entire geometry of the die in the measuring room. However, this showed that the deviations of the two die halves from the specified geometry were merely within a few hundredths of a millimeter. Examination of the thermal effects on the shrinkage behaviour did not reveal any significant differences as well.

In the next step, a simulation was carried out which focused not only on analysis of mass flows, but also included the tool load, Fig. 4.11, since a possible "dodging" of the tools was suspected. With the help of this advanced simulation, it was quickly found that the forming process led to tool deformations caused by classic springback mechanisms. In this particular case, this not only involved one die half being bent: but compression of the core of upper die, fig. 4.12, by up to one millimeter in the forging process. This was not a permanent plastic deformation, but was caused by an elastic reaction, with the tools returning to their original shape again after each stroke. Once this had been recognized, simulation helped in designing appropriate corrections to the tool geometry. After tests with the corrected tools provided positive results, the project could be released for series production.

4.5.3 Trimming / punching and coining / sizing

H.-J. Britzger et al. [BRIT 1] report on the motivation for performing calculations in the field of the punching/trimming and coining/calibration process steps. In hot forging processes these operations usually take place immediately after the last main forming step. Trimming differs from punching in the way that removal of excess material (i.e. flash) is performed beyond the active geometry of the part.

To do this, the component is forced through a cut plate by means of a punch. Punching, by contrast, involves the removal of excess material from the interior of the component using a cutting punch.

Simulation of trimming/punching has now been included in the standard repertoire of forging simulation. Basically, from the viewpoint of simulation the same boundary conditions apply as to the "separation" process step described in section 4.3. Furthermore, simulation of these operations can be expected to be relatively complex. Nevertheless, the trimming/punching operations are more important than cut-off as these final forming operations may result in undesirable deformation of the components. This in turn can lead to deviations from specified tolerances causing unwanted mechanical post-processing or even non-correctable geometric defects. In these cases, simulation enables the designer to reduce problems typical of these process steps as early as the design phase. Furthermore, simulation makes a contribution to a better understanding of the intervention or operation of tools. On top of this, the additional expenditure is justified by the more accurate depiction of the process chain or several consecutive parts thereof. Here, the in-

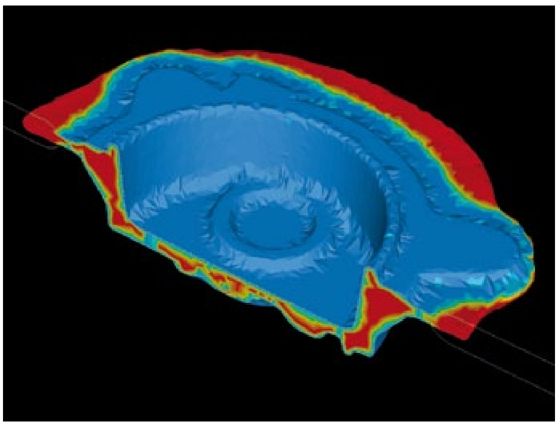


Fig. 4.11: Only with the help of expanded simulation was it evident that tool deformations resulting from classic springback effects occurred during the forging process

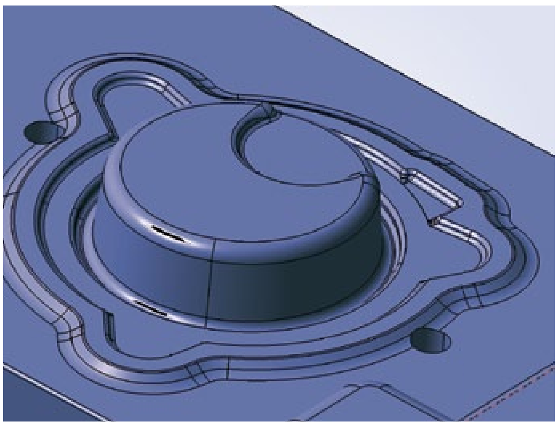


Fig. 4.12: The main cause of the problem was the core in the upper die, which was compressed by up to one millimeter in the forging process

crease in accuracy can be attributed to generating accurate geometries and/or realistic temperature profiles for calculating follow-up operations. Such an application case occurs, for example, when examination of the forming process is followed by an analysis of the heat treatment, Fig. 4.13.

When coining or sizing, a fundamental distinction has to be made between forming the workpiece at forging temperature (warm sizing) or at room temperature (cold sizing). Warm sizing is usually performed in order to reduce the scatter of measures or to improve shape and location accuracy, and usually has no lasting impact on stress distribution in the workpiece. Cold sizing tends to be performed on selected surfaces, with the aim of increasing dimensional accuracy, surface quality and/or shape and location accuracy. Due to the local application of forming forces, sizing often implies high stresses and noticeable strains on the tools. Furthermore, increases of local strength in the surface area of the part can be achieved by targeted strain hardening (which forms part of cold sizing).

The simulation of coining/calibration operations is performed with a view to obtaining important information about interactions between the component and the tool concept. Here on the one hand calibration simulation helps ensure the precision of the final geometry of the workpiece and realization of extremely fine geometric details in advance on the computer. On the other hand, simulation allows the forger to significantly enhance the service performance of the calibration tools. Furthermore, simulation makes it much easier to estimate the required strain hardening when locally higher strengths have to be achieved on the component surface.

4.6 Machining forged parts

The influences on the machinability of forging materials are manifold. Starting from the conduct of the heat, they extend through the chemical composition and the forming process up to the heat treatment. Evaluating the machinability of a material is often based on the criteria of "tool wear", "cutting forces", "chip shape" and "surface quality".

Companies in the forging sector do not usually conduct simulation-based studies on the impact of problems related to chip shape, which are very difficult to influence. Instead, such evaluations are carried out on a practical basis (e. g. assessment of different so-called "chip breakers"). Conversely, the evaluation of different clamping and stop concepts is indeed the subject of simulation-based analysis – according to G. Triesch et al. [TRI 1]. This is typically performed

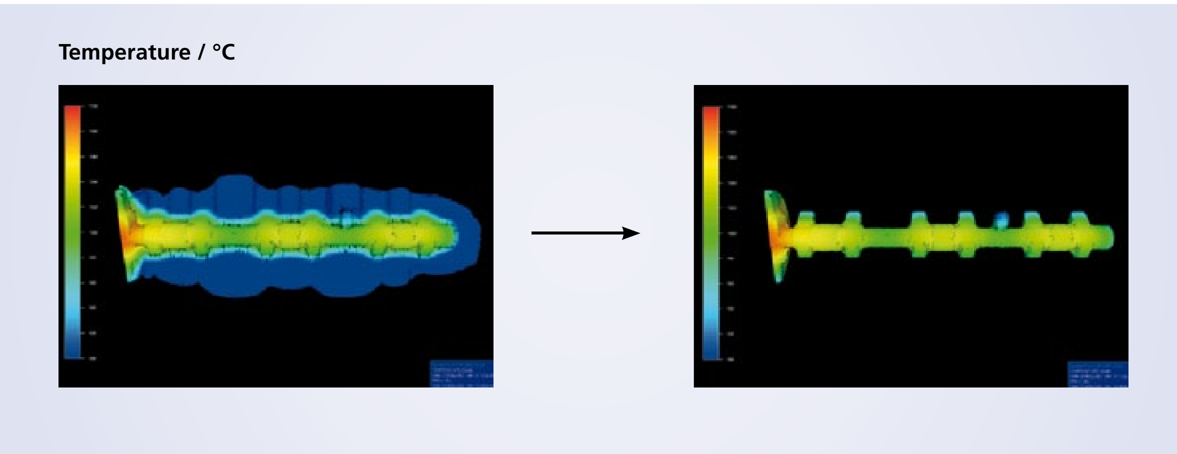


Abbildung 4.13: Simulation of the trimming process as starting point for a subsequent thermal computation

by evaluating the deformation of components using different clamping systems and/or forces, 4.14.

Furthermore, forgings are distinguished by their outstanding dynamic component properties – among other characteristics. At this point, in addition to the component strength and the setting of fibre orientation, the residual stresses the component inside or on the component surface after machining are also of particular importance. The success of different measures again can be evaluated using simulation methods. Thus, for example, the influence of different temperature profiles in the component during forming and possibly of the machining operations on heat treatment results can be evaluated qualitatively.

4.7 Heat Treatment

In the past years, with respect to comprehension of interactions between boundary conditions and material properties, in the field of heat treatment considerable progress has been made. Concurrently commercial software adapted for simulation of operations within the respective scope have availed themselves from the extended state of knowledge – as per K. Heeß et al. [HEES 1]. For process developments in the field of heat treatment, these advances open up the possibility in future of already making initial assessments for process management on the simulation computer. Furthermore, realistic input parameters offer considerable potential in the field of process optimization. Simulation is generally suitable for indicating trends, for parametric studies and impact analyses, as well as for significantly improving understanding of the closely linked processes occurring during heat treatment. For this purpose the temporal and spatial development of temperatures, structural transformations, deformations and stresses, as well as interactions occurring in these processes, have to be determined mathematically in order to proceed to numerical simulation, as illustrated schematically in Fig. 4.15, based on the example of hardening steel components.

4.7.1 Hardening and tempering

O. Oehler [Oehl 1] reports on the use of simulation in the context of identifying weaknesses in the design of a hardening and tempering process. Here particular attention was paid to the "hardening" process step. With this in mind, the behaviour of a cold extruded component during quenching in oil was studied as some parts failed due to quench stress cracking. The evaluation of simulation results revealed that the cooling rate of the component is highest at its thinnest cross-section, thus locally falling below the martensite start temperature. This resulted in a largely martensitic transformation of the microstructure in this area – while the remaining part of the component was markedly austenitic. At the same

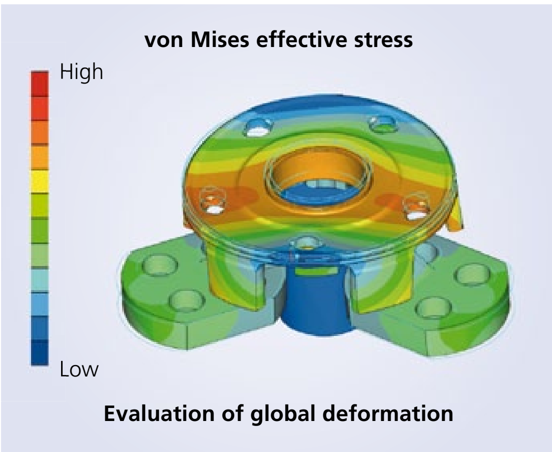


Fig. 4.14: Influence of the clamping concept on the deformation of delicate components during machining

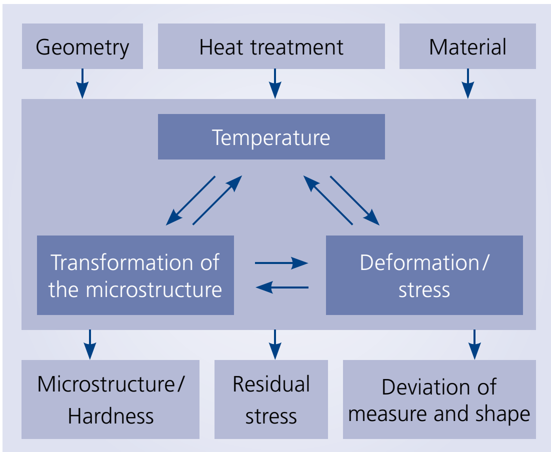
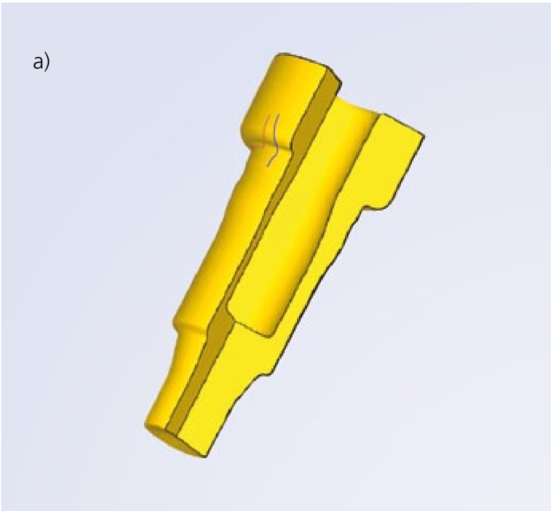


Fig. 4.15: Input and output data as well as interacting partial processes during the simulation of heat treatment processes

time, as a result of the volume jump caused by the transformation of austenite to martensite, tensile stresses (>260 MPa) could be observed at the junction of this section to a much larger cross-sectional area, see Fig. 4.16. These tensions were considered to be critical, especially since they occurred at temperatures of approximately 340 °C (martensite start temperature "Ms"). The stress gradients occurring in this critical area were mitigated by geometrically adjusting the cross-sectional transitions, resulting in a substantial reduction of the reject ratio. For variant parts these findings could be included in the component design.

4.7.2 Case hardening

O. Oehler [OEHL 2], M. Herrmann and M. Fiderer [HERR 1] write about a specific application of simulation to case hardening – in the course of manufacturing input hubs for dual-clutch transmissions. In this case the focus was on precision-formed teeth as the central element of the component. These are subjected to a quenching process in the course of case hardening treatment. The problem was that after this process step the parts exhibited a deviation from the intended geometry of about 25 microns (negative crowning detected by two-ball testing) over the entire gearing length. In a first attempt, no satisfactory cure could be achieved despite several practical tests in the form of variations of the heat treatment. In connection with subsequent investigations by simulation, the analysis focused on developing an im-



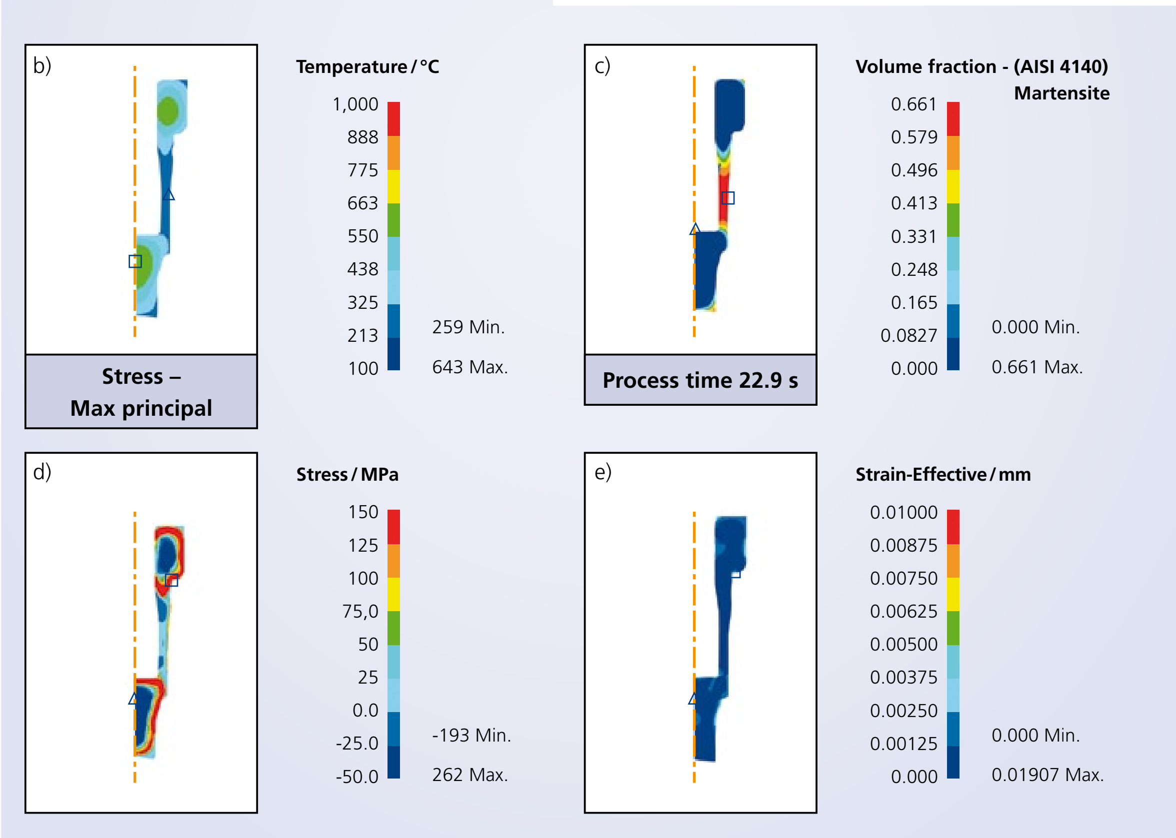


Fig. 4.16: Failure location (a), temperature distribution (b), martensite share (c), 1st main normal stress (d) and effective stress (e) during quenching

proved understanding of the processg. In turn, new solution approaches were generated on this basis. In order to achieve a virtual representation of what was going on in the component, metal forming and heat treatment simulation had to be linked up. The essential characteristic of this operation comprised passing on residual stresses stemming from the "gearing by pressing" process step and initializing the deformation ratio after reaching the austenitizing temperature. Finally, it is worth mentioning that component hardness is often used to assess the quality of simulation results in the field of heat treatment: in the case presented here, a good coincidence was identified between the hardness profile actually measured and the visualized curve established by the simulation, see Fig. 4.17.

4.7.3 Induction hardening

The induction hardening of a crankshaft has been investigated by D. Cardinaux et al. [CARD 1]. In practice the intention is to achieve a predefined gradient of mechanical properties within the workpiece by means of local inductive heating with subsequent quenching in water. This hardens the surface of the component in the desired areas to a pre-defined depth. The results are improved service characteristics in terms of fatigue strength and wear.

The process is modeled in two stages. The first stage involves the induction heating of the component to complete austenitization of the desired areas. The second stage of modeling concerns the quenching process.

In the course of developing a suitable finite element model to describe local quenching, numerous coupled physical processes in the fields of electromagnetism, heat conduction, mechanical properties and metallurgical processes have to be taken into account.

After suitable mathematical models had been set up, spatial discretization and time integration had to

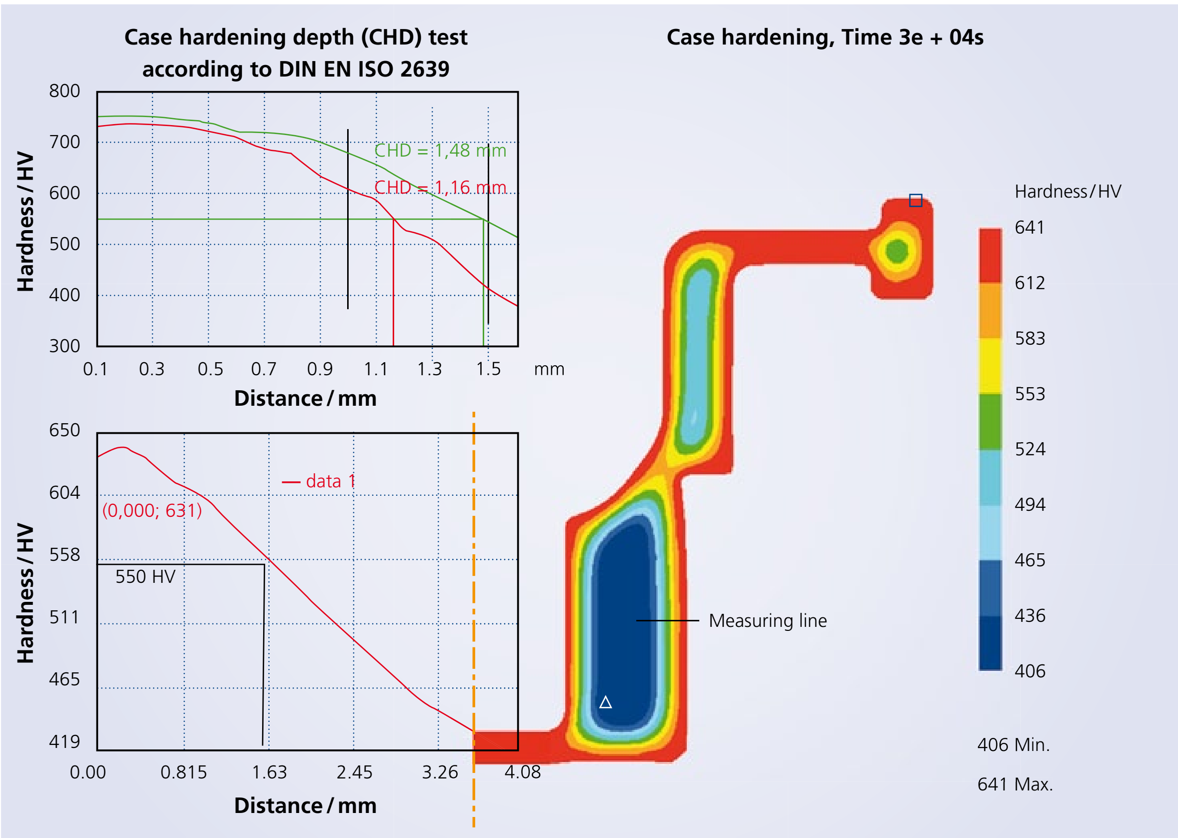


Fig. 4.17: Comparison of the Case Hardening Depth (CHD) computed by simulation (lower diagram) with experimental results (upper diagram)

be defined. Linear tetrahedrons were used to compute the heat transfer, mechanics and metallurgy, while Nedelec FEM elements were used to describe the electromagnetic processes. The results calculated for an automobile crankshaft are shown in Fig. 4.18.

4.8 Post-processing surface treatment

The surfaces of forgings are usually treated in order to clean them. Other treatments are frequently performed to increase fatigue strength or protect surfaces. When a surface is cleaned, the oxide layer that has formed on the component surface in the course of hot forming or heat treatment operations is removed. This is usually done by shot blasting, drum grinding or pickling. The fatigue life of dynamically loaded components is influenced not only by design, material and heat treatment, but in particular by the state of the surface – especially since the highest loads usually occur on the surface of the part. A significant increase in dynamic characteristics can be achieved by heat treatment processes (e.g. nitriding) as well as by processes resulting in surface hardening (e.g. roll hardening or shot peening). Protection against chemical alteration of a clean metallic surface (e.g. by rusting) – and with some restrictions also against mechanical damage – can be achieved by means of coating or electrolytic and chemical depositions, according to W. Adlof et al. [ADL 1].

The effect of strength-increasing roll hardening is based on the strain hardening of the surface edge zone and the formation of compressive residual stresses. For example, the service life of undercarriage components can often be enhanced to a much higher degree by roll hardening stress-critical transition radii than would be possible by increasing yield strength. As a result of shot peening, a thin surface layer is work-hardened while at the same time compressive residual stresses are indu-

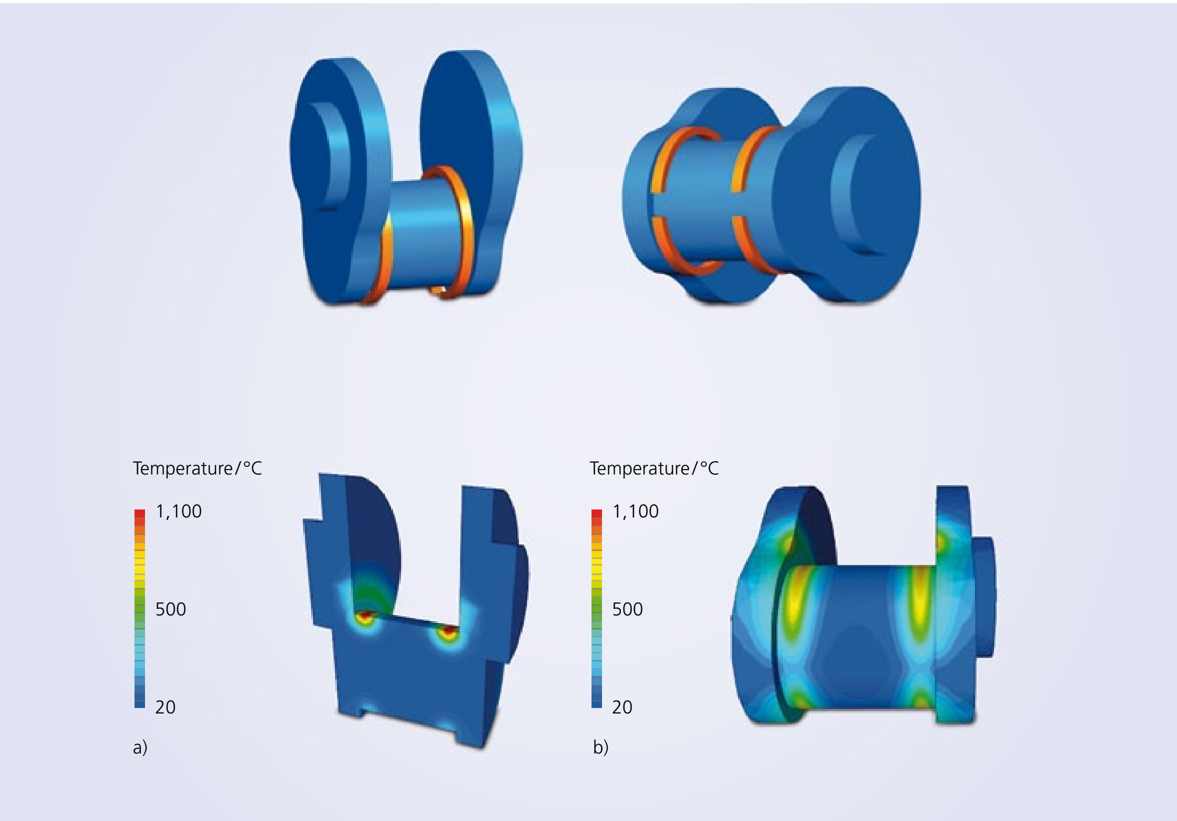


Fig. 4.18: Inductive heating of a crankshaft using two coils (orange) and the simulated computation of temperature distribution after 15 s on the inside (a) as well as on the surface (b)

ced. The impact of various parameter settings for applying these strength-enhancing mechanisms is often studied by means of simulation, Fig. 4.19. During surface rolling, for example, the contact pressure of the rolling tool or the spacing between the overrun lines is varied – according to J. Heizmann [HEIZ 2].

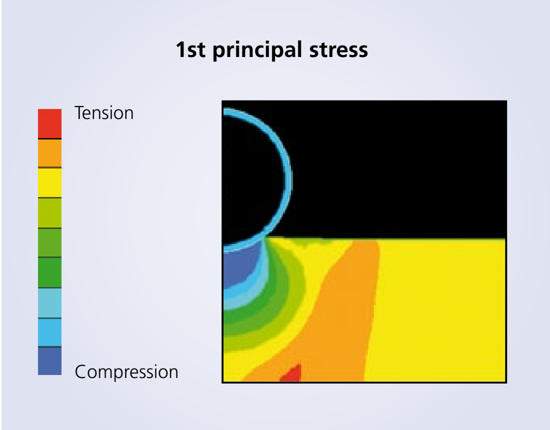


Fig. 4.19: Influence of diameter and impact velocity of shot grains on the stress distribution of the surface

5 Advances in the field of simulation

5.1 Development trends

Authors from among providers of related software solutions are paying particular attention to ongoing developments in the field of simulation in forging [WOHL-2], [PERE 1], [DUCL1], [WALT 1], [DOKT 1], [TWIC 1], [VLAS 1]. The following paragraphs are intended to provide a summary of the main trends in this field. The main requirements of the market to be met by providers of simulation software are above all:

- improved accuracy of the results,
- modeling of the interaction between tool and machine,
- simulation of the entire process chain,
- prediction of component properties based on models of microstructure development,
- minimization of computing time,
- automatic optimization of manufacturing concepts,
- use of expert systems.

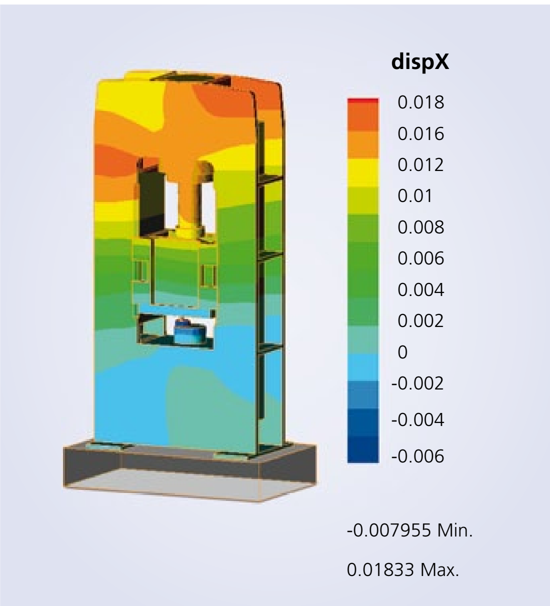


Fig. 5.1: Horizontal deformation of the frame of a forging press resulting from an eccentric position of the die

5.1.1 Improved accuracy of calculation results

One of the top priorities for all software developers is to improve the quality of the results of FEM calculations. Among other things, this involves better element formulations as well as the revision of physical models describing the process parameters. Moreover, new approaches to the development of failure mechanisms – with respect to tools as well as workpieces – are in the making. Furthermore, a great deal of attention is being paid to the processes taking place in the "interaction interstice" between workpiece and tool with the aim of modeling the corresponding tribological system and optimizing it through simulation.

5.1.2 Modeling the interaction between tools and machine

Another field of considerable interest is work aimed at extending forming simulation by adding models that allow for the interaction between forming machine and tool. A major aspect in this context is the consistent consideration of elastic effects in the process as they have a significant impact. Overall elasticity comprises the elasticities of the workpiece, the tools and the machine. While inclusion of the former can now be considered standard, so far the modeling of elastic tools has turned out to be much more challenging in practice – at least in 3D. The main reasons for this are the complex simulation models with their "multi-body contact" both between the workpiece and tooling and between the individual components of the tool – especially in the case of demanding tools reinforced by shrinkage rings, as used in cold forming, for example.

The main obstacles for a wider application are extremely long computation times and significant challenges with respect to the numerical stability of the models. The situation is further aggravated by the fact that for a highly accurate simulation result it is often necessary to realistically depict springs as optional tool assembly elements within the simulation model. For this task it is important that the modeling of all variants of different types of springs and spring concepts is made as user-friendly as possible.

Another critical factor is still consideration of the elasticity of the whole machine (Fig. 5.1), especially in the case of multi-stage presses, where tilting behaviour also has to be depicted. Different models are available for this purpose, which are generally described as replacement spring stiffnesses. Problems here relate in particular to defining the parameters necessary to describe the behaviour of the respective machine (e.g. tilting stiffness) or their supply by the machine manufacturer. Furthermore, software houses are also working on the inclusion of guiding clearances, e.g. between ram and crosshead guiding.

An important step towards the realistic depiction of machine behaviour is also the correct representation of the kinematics, which, as experience shows, has a significant impact on the quality of the result of a process simulation. Whereas in the past the description of the kinematics partly still involved some extreme simplifications, nowadays numerous kinematics can be depicted with a good level of accuracy. Today powerful simulation systems even include the process-dependent control of production, e.g. for ring rolling or open-die and radial forging.

5.1.3 Simulation of the entire process chain

Integration of the individual simulations of various manufacturing processes along the process chain is one of the main demands of the market. This involves handing over the process-related characteristics of a production operation to the next process step. For example, the data of a component strengthened by cold-working can be handed over to a final structural analysis. Another example is the simulation of an open-die forging process, which builds on the results of a casting simulation performed during production of the forging billet, and whose data will in turn be made available to the downstream machining and final heat treatment operations. Such simulations are also of interest when it comes to assessing the effects of residual stresses induced by forging and heat treatment on the deformation of the component after machining, Fig. 5.2).

Simulating complete process chains still poses several challenges. For example, data and parameters must be passed on from one simulation model to the next, which requires the use of powerful mapping algorithms. It should be noted that in doing this the data have to be readapted to sometimes completely different network topologies as the various systems for process simulation – such as forming, welding, crash testing or structural analysis – often

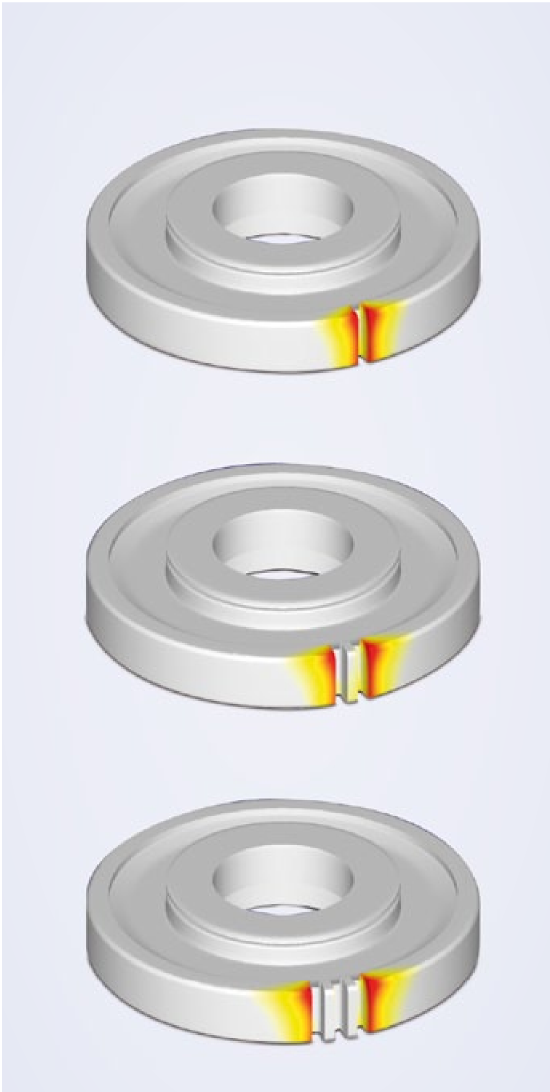


Fig. 5.2: Deformation of a forged disk during the broaching of slots in the wheel face. The stress fields and thus the deformation patterns change with each machining pass

use completely different networks and element types. Another problem arises from the question as to which data should be selected for transfer, i. e. what relevance they have for the next process step. Here software developers still face numerous challenges.

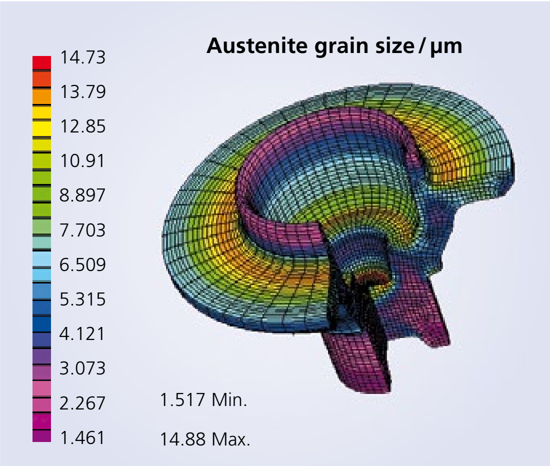


Fig 5.3: The distribution of grain sizes in the forging analyzed on the basis of the simulated dislocation density

5.1.4 Predicting component properties

Apart from the classic result sets of forming simulation, such as material flow, force requirements, distribution of stresses and the degree of deformation, as well as stressing on the tool, users are increasingly focussing on the actual prediction of component properties.

Special emphasis is put on mechanical properties such as the distribution of hardness and strength through to notch impact toughness or fatigue strength. Ultimately, these properties can be attributed to the structural composition and the distribution of the various metallurgical phases within the component, implying that these specifications also have to be computed both in the course of simulating the forming process and during subsequent heat treatment. This in turn requires modeling at a microscopic level, allowing for mechanisms such

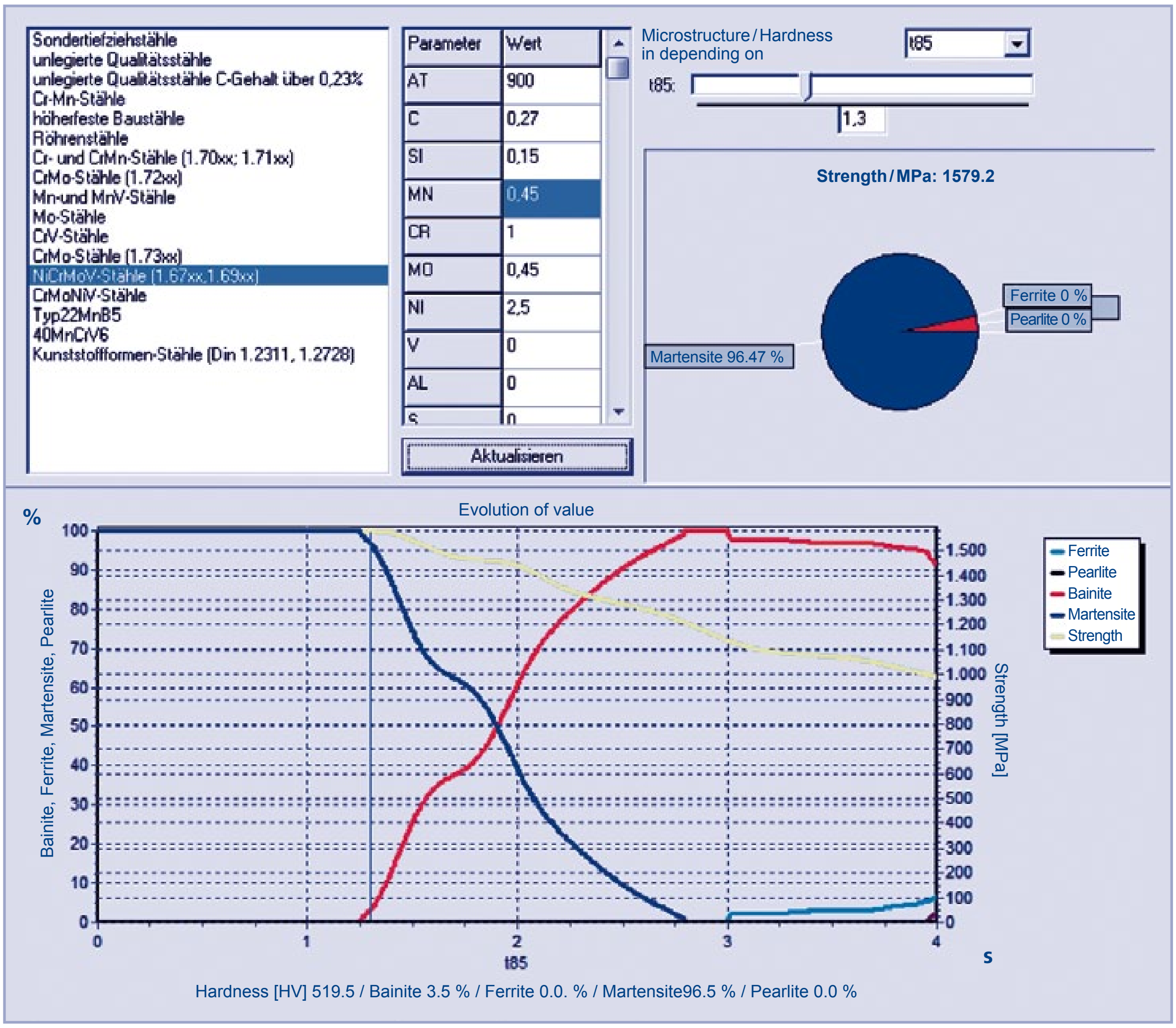


Fig. 5.4: Quantitative microstructure chart of a NiCrMo steel with 0.27 % Cr and 2.5 % Ni

as dislocation reactions, recrystallization, precipitation formation and microstructural transformation. Structure models already exist for the simulation of dynamic and static recrystallization and a great deal of work is being done to develop them further, Fig. 5.3. In the case of hot forging, this determination of the crystalline structure and the related properties by means of simulation already has a longer tradition, for example in the open-die forging of large generator shafts, where simulation of the phase transition based on TTT diagrams is already established.

Other approaches are based on modeling by means of neural networks, which first have to be trained after their configuration. Upon successful completion of this phase it becomes possible to estimate the expected microstructure of various steel compositions within a very short time, Fig. 5.4. Even inhomogeneities, such as those occurring in forging ingots, could be considered locally.

5.1.5 Minimizing computation times

Computation times still remain a critical factor. While the power of modern computer systems is still rapidly increasing, the computation requirements of modern simulation tools is also soaring as a result of growing demands with respect to performance bandwidth and the quality of results. Both factors tend to balance each other out.

The most important step to counter this stalemate has proved to be increasing the computational speed by parallelization of computational models so that several computers can work in parallel on the same model, Fig. 5.5. This approach, which has long since proved its merits in the field of structural analysis, could only later be used for forging simulation because the mandatory fully automatic remeshing it requires makes parallelizing much more difficult. In the area of actual forging simulation this strategy is now de facto state of the art. Nevertheless, software houses are still trying to enhance the speed and flexibility of the related strategies and mathematical models and to further increase the number of processors that can be used in parallel. "Parallel computing" of complex models, including the tools, holds major potential, Fig. 5.6. In such cases, for example, different tool parts may be assigned to different domains and then either processed on different CPUs or cores, or themselves parallelized once again.

5.1.6 Automatic optimization of manufacturing concepts

Process simulation in manufacturing technology often comes down to virtual testing with multiple test cycles. The optimization of development processes that involve such procedures is the objective of intensive efforts by developers of IT tools for the simulation of forging processes. Up to now, the com-

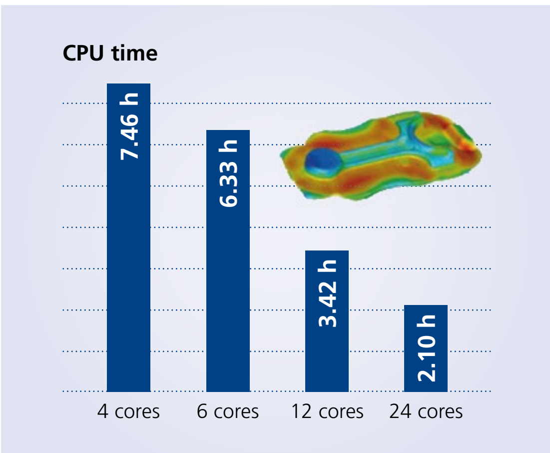


Fig. 5.5: The more cores, the higher the computational speed. Graphic representation of the speed gain for a 3 stage connecting rod forging simulation

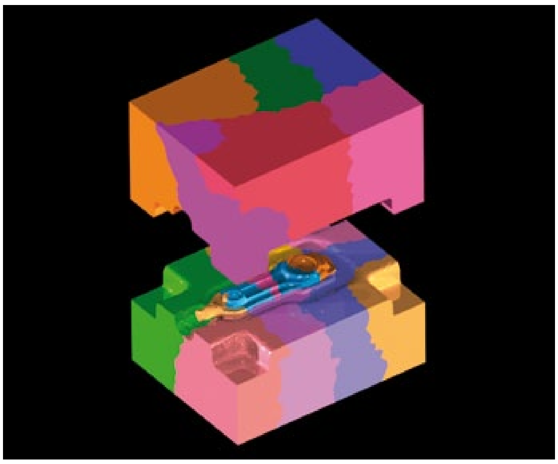


Fig. 5.6: Break-up of a simulation model into several CPU partitions taking into account the linear-elastic characteristic of the die blocks

puter-assisted automatic optimization of these steps was precluded by the amount of computation this required. However, thanks to modern high-powered computers and the improved performance of the simulation programs, the computing times required for such approaches are now drawing closer to a reasonable order of magnitude.

Automated optimization is also intended to increase the quality and reliability of simulation results. This can be achieved by minimizing a target function by means of several automatic simulation calculations in order to find the optimum for one or more parameters.

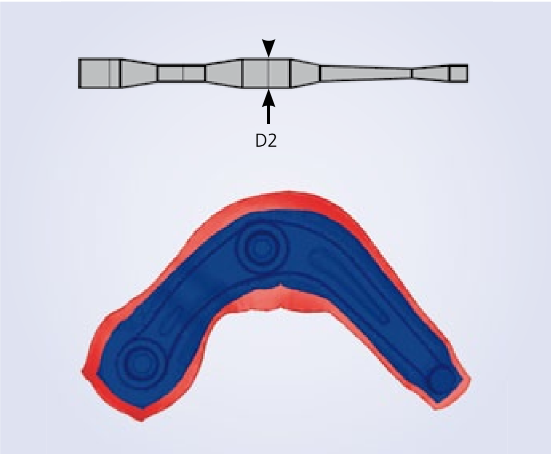


Fig. 5.7: The integrated optimization routine automatically linking simulation software and CAD system makes it possible to reduce the mass of the rough forging by 10 %. The red area depicts the contour of the flash before optimization while the result after optimization is shown in blue

In this context, an important aim is also to objectify decisions on design changes in a process or tools, even for complex forming processes, in order to avoid risky "gut decisions". This also makes it easier to assign such tasks to younger employees with less experience and also allows for the fact that the process window limits are becoming ever narrower, both technologically and with respect to development time.

This automatic optimization makes it possible to adapt process parameters such as friction factors to real process conditions. Furthermore, the task is to accurately comprehend the material flow while at the same time reducing forming loads and/or distributing them among the individual forming stages in a more advantageous manner by modifying tool radii and tool draft. In addition, automatic optimization makes it possible to significantly reduce the weight of the forging billet, thus saving material and costs, Fig. 5.7.

When automatically modifying tool geometries, a close tie-in with the existing CAD environment is vital. Moreover, the description of the shaping geometry has to lend itself to full parametrization, which is not necessarily the case for the free-form surfaces typical of a forging die. Here a lot more development work is necessary – also by CAD software providers.

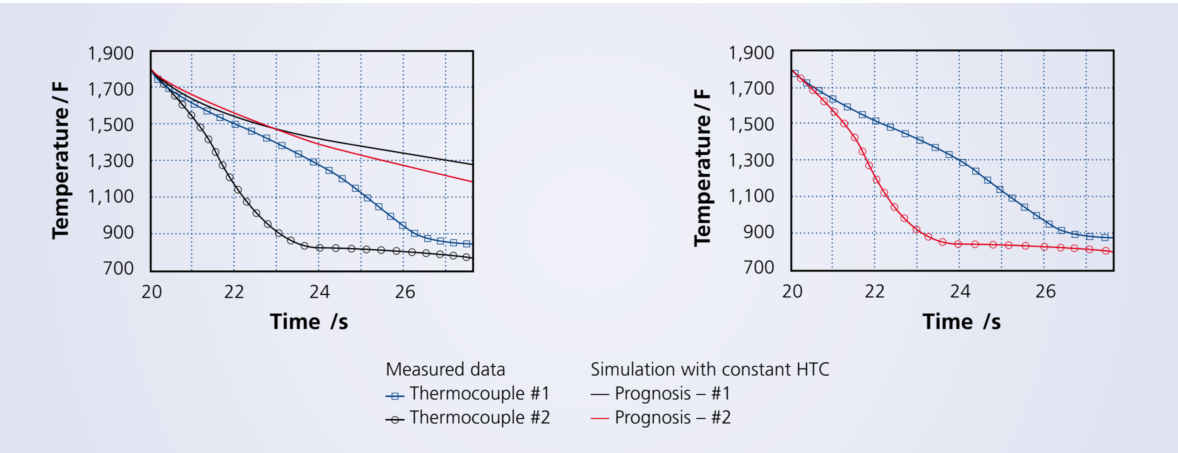


Fig. 5.8: The cooling curves predicted by simulation are depicted for two locations (left). They differ significantly from the experimental data represented by symbols. After an iterative development of HTCs (Heat Transfer Coefficients) simulation and experiment coincide quite neatly (right)

Another branch of optimization development deals with determining the thermophysical characteristics of an alloy required for simulation of the forming process. In the past this was mostly expensive and time consuming. In the meantime, simulation tools for the step-by-step calculation of the heat transfer coefficient (HTC) using an inverse method have become available. Their starting point is experimentally determined temperature-time data gained from a real process using thermocouples. Subsequently, the software performs several simulation loops using an optimization routine to determine the HTC (as a function of temperature). This optimization is iteratively repeated until the calculated curve becomes consistent with the experimentally determined data, Fig. 5.8.

5.1.7 Use of expert systems

The future functionalities of simulation software will increasingly also include expert systems that go beyond predicting the performance characteristics of the component with the maximum possible accuracy. These are intended to make it easier for staff to make targeted use of forging simulation. The key driver of this development is increasing staff fluctuation. As a result of this mobility, factors such as work experience and the experience of individual employees, for example with respect to fine-tuning materials and the related design of the tool, are tending to decline. The expert system is intended to compensate for this negative trend. The minimum requirement for such a system is management of the history of all simulations conducted in the company and easy access to these data based on predefined criteria, Fig. 5.9.

The system should be structured according to the range of component types occurring and should be able to identify the type of component and provide suitable proposals concerning the parameters of the forging process, the rules for the tool concept and the requirements and boundary conditions for an optimization.

As a rule, such an expert system is capable of learning, which means that it constantly expands its experience by including all new simulations carried out in the company. For this it requires access to the new communication systems available today in order to be used for result analyses or group meetings of simulation experts, for example using tablet computers.

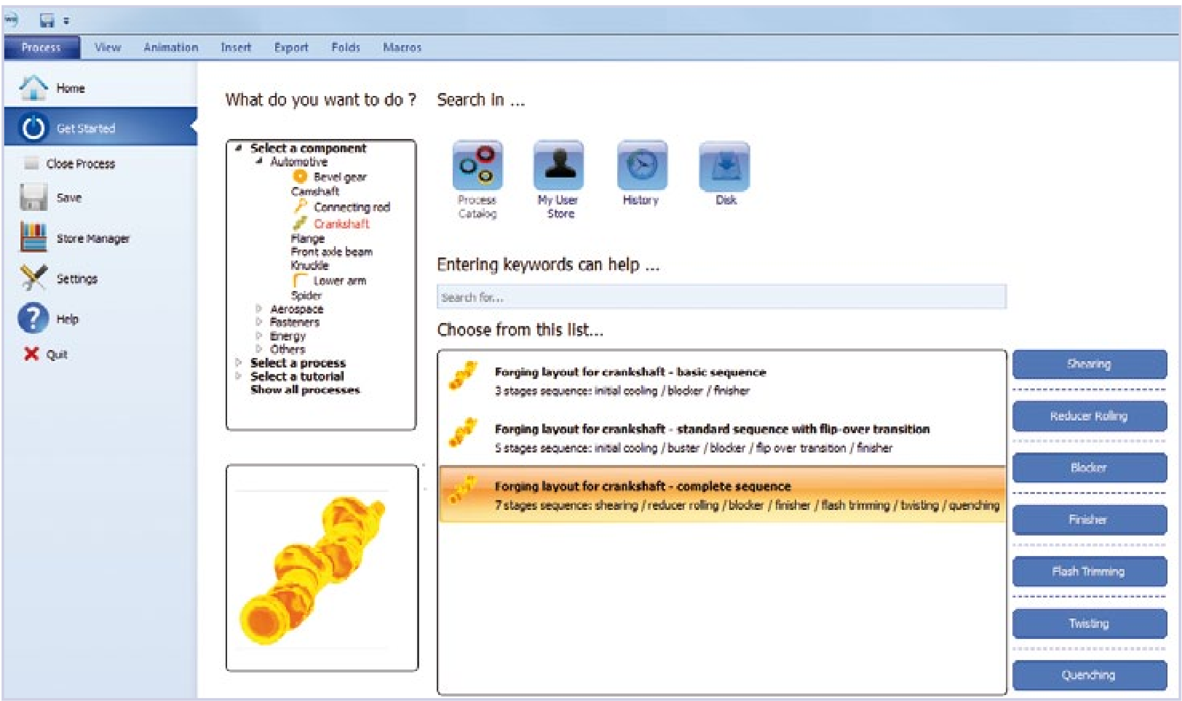


Fig. 5.9: Input menu of a process database drawing based on the know-how of a software provider

5.2 Progress in understanding basic principles

Together with software providers and forging companies, many technical and scientific institutions, such as universities, are engaged in developing new simulation techniques and/or improving existing ones by participating in numerous research projects. The current focus is on investigating basic knowledge, developing improved models and including further simulation tools in simulation systems. The cause-and-effect diagram (Fig. 5.10) highlights the main emphasis of current development directions in research projects with regard to the usefulness of simulation. Selected projects are presented below.

5.2.1 Alloy database using steel alloys as an example

One prerequisite for the successful simulation of forming processes is the availability of reliable data on the thermophysical properties and transformation behaviour of the materials used. These can be acquired from various useful sources. In the following chapter, U. Diekmann [DIEK 1, DIEK 2] presents the example of a steel database maintained by the Steel Institute of the VDEh, which is the official database of the European steel registry. Alongside references to standards, delivery conditions, product forms and manufacturers, it especially contains technical data sets acquired from material testing. The database offers search, visualization and analysis capabilities. In addition to the usual information such as material number, chemical composition and mechanical properties, the system also provides temperature-dependent properties in conformity with SEW 310 for about 450 materials, as well as links to other data sets, such as TTT/TTA charts, metal sheet specifications and the forming flow curves that are indispensable for forming simulation, Fig. 5.11.

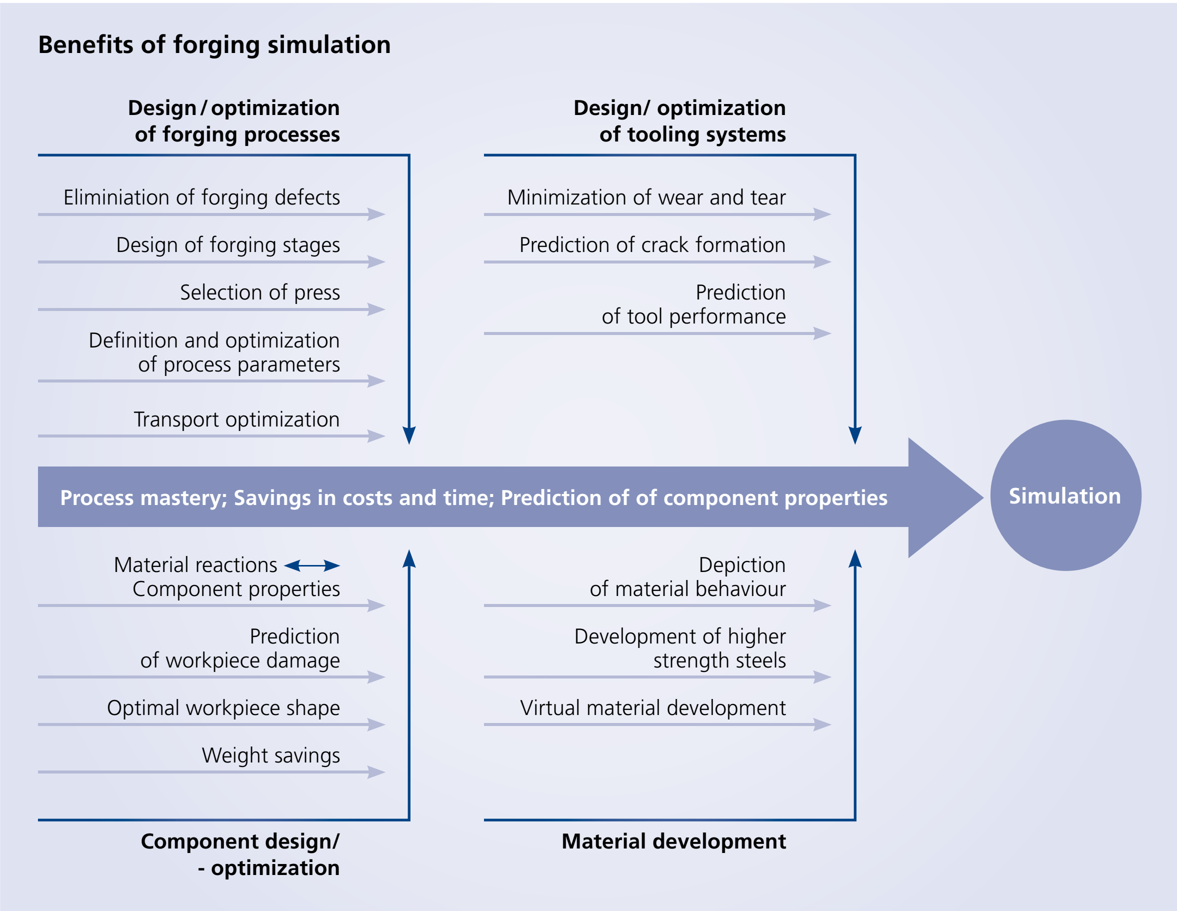


Fig. 5.10: Major development paths of research projects in the field of scientific and technical institutions

To complement this, a software package (even here there are different systems) makes it possible to calculate material properties as a function of chemical composition and process control. Using a well-established thermodynamic basis (CalPhaD), the software features different models for the calculation of material properties such as thermophysical data. For the generation of data sets, such as the TTT diagram shown here, (Fig. 5.12), the models use a physical basis. The material properties computed are used especially in the FE simulation of casting, forming and heat treatment processes.

5.2.2 Influence of the heating rate on the formability of steel and aluminium

For metallic alloys, fast heating or reheating can lead to inhomogeneities in the microstructure and thus to divergences of the microstructural state from that of the thermodynamic equilibrium. The microstructural state and grain size for different heating rates during the austenitizing of steel can be determined using a time-temperature austenitizing diagram (Fig. 5.13). High heating rates (e.g. 20 K/s or 41 K/s) above the transition temperature Ac_3 may result in a microstructure whose austenite grains are inhomogeneously enriched with carbon. Conversely, a slowly heated microstructure (e.g. 1 K/s) usually consists of largely homogenized austenite. Furthermore, with increasing holding time progressive grain growth can be expected.

Recent investigations by R. Kawalla and G. Korpala [KAWA 1], which focused on the influence of different heating methods and heating rates on the formability of steel (20MnCr6, 40CrMo5 and 100Cr6) and aluminium (AlSiMgMn), aimed at exploring the applicability limits of standard stress strain curves to simulate forming processes. Both fast inductive and conductive and slow convective heating technologies were compared.

As expected, a strong dependence of the measured yield stress on the heating rate was recorded in all materials. For the steels examined, for example, a significantly higher flow resistance could be identified if heating to a forming temperature of 850 °C had been performed rapidly (as compared to slow heating). Further analyses can be expected following discussion of the results presented here.

5.2.3 Alloy and process design using thermodynamics and microstructure modeling

In the field of hot forging of steels, deformation, temperature profile and development of the microstructure are usually subjected to substantial interactions. In currently available approaches to the modeling of steel forming, as a rule only limited attention is paid to this phenomenon. As part of the research performed by L. Mosecker [MOSE 1] and K. Schacht [SCHA 1] at the Institute of Ferrous Metallurgy, RWTH Aachen, a metal physical model

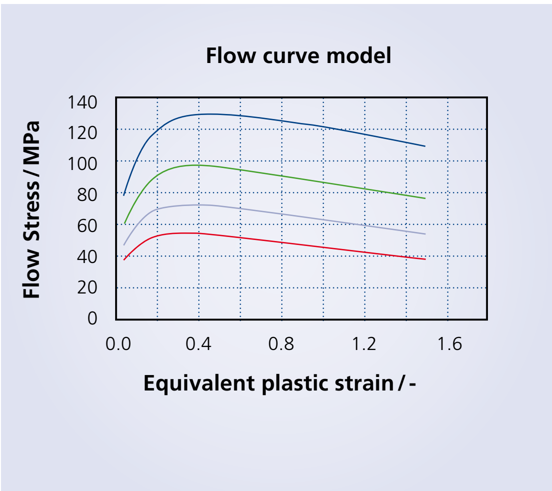


Fig. 5.11: Examples of a hot flow curve for a steel

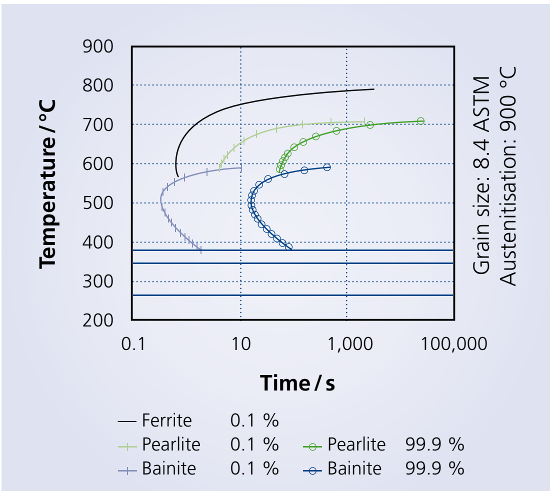


Fig. 5.12: A TTT diagram of a heat-treatable steel computed using the software

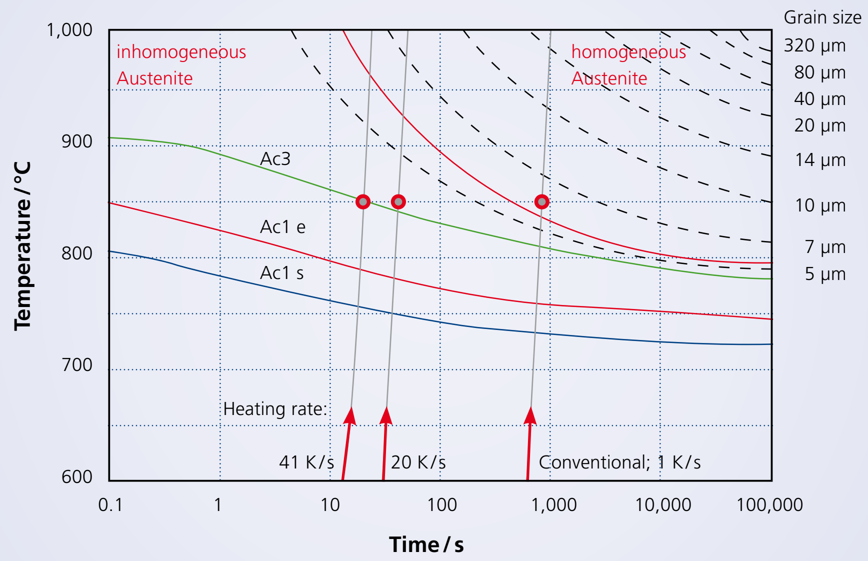


Fig. 5.13: Example of a time-temperature austenitization (TTA) diagram of a steel for different heating rates. The red and black dots indicate different initial states of the forming process at the same temperature

has been developed to improve depiction of local flow properties, Fig. 5.14. The investigation focused on microalloyed forging steels such as precipitation-hardening ferritic-pearlitic (AFP) steels.

The introduction of internal structural variables (such as dislocation density) make it possible to describe metal physical phenomena such as recovery and recrystallization, as well as precipitation behaviour and grain growth on the basis of empirical approaches and to quantify their influence on the mechanical behaviour. The core of the material model is a mathematical description of the evolution of dislocation density. This in turn is used to compute static and dynamic recrystallization and calculate precipitations.

The microstructure-based approach is expected to permit improved simulation of material flows (e.g. for predicting possible forging defects) as well as a prognosis with respect to the state of the microstructure. At this stage, the phase transformation to ferrite and pearlite occurring after forging is not yet depicted. Current investigations relate to linking the microstructure model with the thermodynamic description of the development of precipitations. In this context, the influence of various micro-alloying element (MLE) systems on material behaviour is described as a function of dislocation density and the type and mass fraction of MLE. Another aim is to formulate a dependence on the chemical composition for as many model parameters as possible of the approach so far formulated. Here use is made of the absolute melting temperature, which in turn can be predicted by means of thermodynamic databases. Furthermore, the integration of billet-reheat contributes to the development of a continuous virtual process chain.

5.2.4 Robustness of the modeling of microstructures when designing a drop forging process

Within the framework of ongoing research at the Institute of Bildsame Formgebung (IBF) of the RWTH Aachen University, T. Henke et al. [Henk 1] focused on developing statistical methods to quantify variations in material behaviour, as they arise, for example, due to batch variations and inhomogeneities, and their inclusion in microstructure-based material models. The background motivation for this work was the desire to be able to make predictions with respect to the robustness of the subsequent production process, in addition to the integrative prediction of process parameters and product properties. For this reason, statistical methods are increasingly

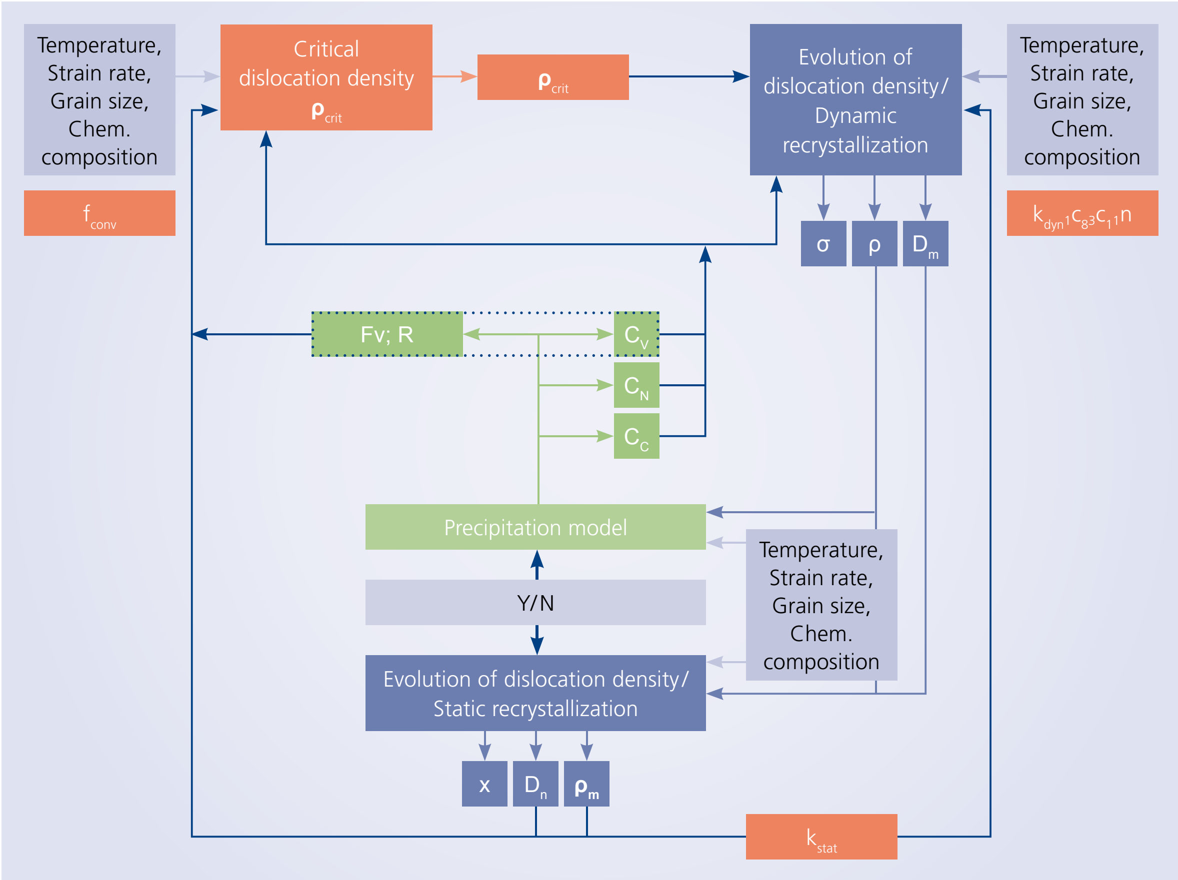


Fig. 5.14: Logical link-up of the different modules for a microstructure-based computation of multi-stage forming processes

being used in process design. However, every robustness analysis requires knowledge of the variations in the input data of the model used for the design, but these variations are usually estimated since they are hard to measure.

In the design of metal forming processes, the behaviour of the material has a major impact on the process parameters and the properties of the product. Simulation models describing the behaviour of the material are therefore increasingly selected in view of their aptness for integratively depicting flow properties and the development of the microstructure. For this purpose, with the aid of a modular material model developed at the IBF, both physical, dislocation-density-based and semi-empirical approaches to the description of hardening and softening as a result of recovery and recrystallization can be combined almost at will.

The statistical methods now developed at the IBF to take material variations into account are based on the so-called "re-sampling" method. Using such a material model to describe fluctuations when designing a drop forging process for the production of a bevel gear from a microalloyed steel 25MoCr4-Nb-Ti, it was possible to predict the variations of the microstructure scatter that could be expected in the real process in distribution functions. Conversely, a comparison with the microstructure distribution of gears actually produced (Fig. 5.15) showed that if a conventional non-fluctuation-adapted model is used, this may result in underestimating the real grain sizes. The confidence limits of the calculated distribution functions on the other hand reliably included the grain sizes of the experiment.

5.2.5 Modeling the friction between workpiece and tool

The feasibility and the force and energy requirements of the forming process critically depend, above all, on the ability of the tribological system to keep tool and workpiece separate in the course of the forming process and to maintain good lubrication in order to minimize wear resulting from shear forces.

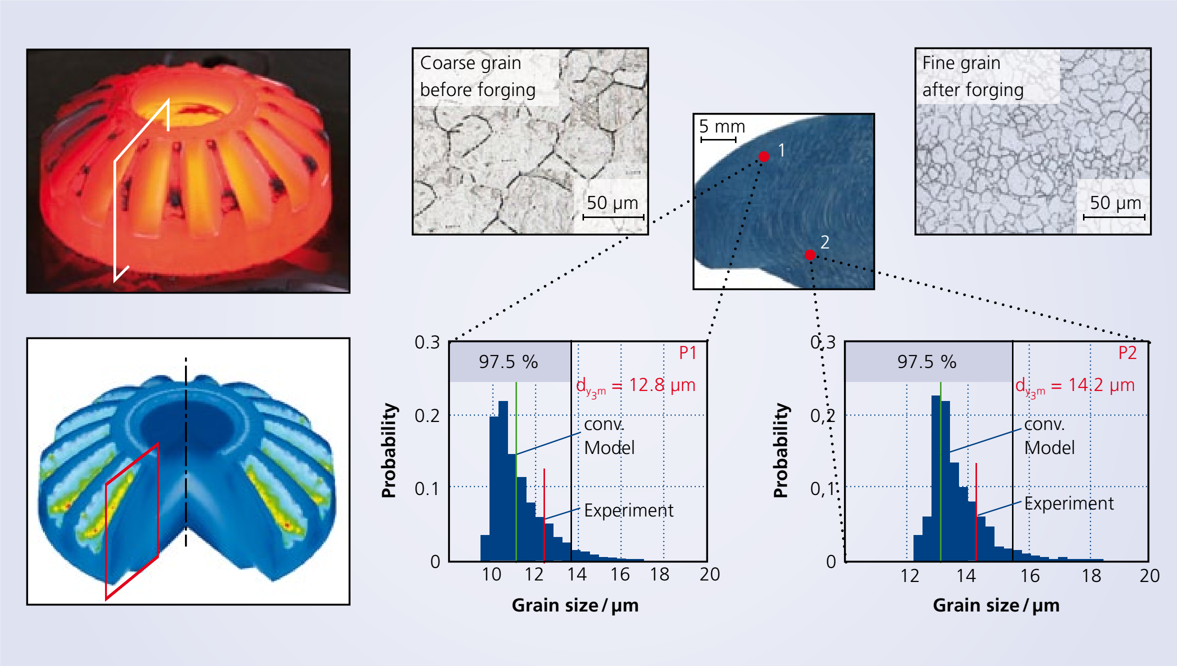


Fig. 5.15: Comparison of simulation with real results of a microstructure analysis

At the same time, the quality of a finite element analysis largely depends on the accuracy of the friction model describing the tribological interactions between the workpiece and the forming tools. Alongside a number of other institutions, the Institut für Produktionstechnik und Umformmaschinen (PtU) of the Technische Universität Darmstadt and the Institut für Umformtechnik und Umformmaschinen (IFUM) at the Leibniz Universität Hannover conduct research aimed at influencing and modeling the friction between workpiece and tool during forging processes.

In order to improve the quality of FEM simulations, the Department of Tribology and Surface Technology of the PtU recently examined a new, optimized modeling of friction in the cold-forming process. To this end, Stahlmann et al. [STAH 1] and Ludwig et al. [LUDW 1] developed a new approach. It describes the changes in the workpiece surface in the course of cold forming and includes field variables with a significant influence on friction behaviour. They found that the friction coefficient depends not only on the normal contact stress but also on the surface enlargement. Furthermore, the model takes the load dependence of the workpiece surface structure into account. A tribometer for cold forming – the compression-sliding plant (Fig. 5.16) – is used to determine the friction coefficient.

As changes of the contact area between the friction partners are taken into account, the results provide information on tribological loads in forming processes. Using these models meant that it was possible to determine the relationship between surface roughness and variables describing the surface state. The methodology proved to be both economical with respect to the computational expense for the simulation as well as promising in terms of predicting the roughness of workpiece surfaces. Furthermore, in future the values for the surface roughness determined by simulation can be used to determine frictional characteristics in relation to surface changes. Better representation of real forging processes can therefore be expected. Further research at PtU aims at transferring the results found so far to industrial practice. In this context, a current shortcoming in the model, integration of the tool surface roughening, will be included in the model description. At the IFUM, B.-A. Behrens et al. [BEHR 1] developed a new model for friction conditions typical of hot forming processes. The friction is influenced mainly by the surface condition, the local stress state and relative sliding velocity. Classic friction mode-

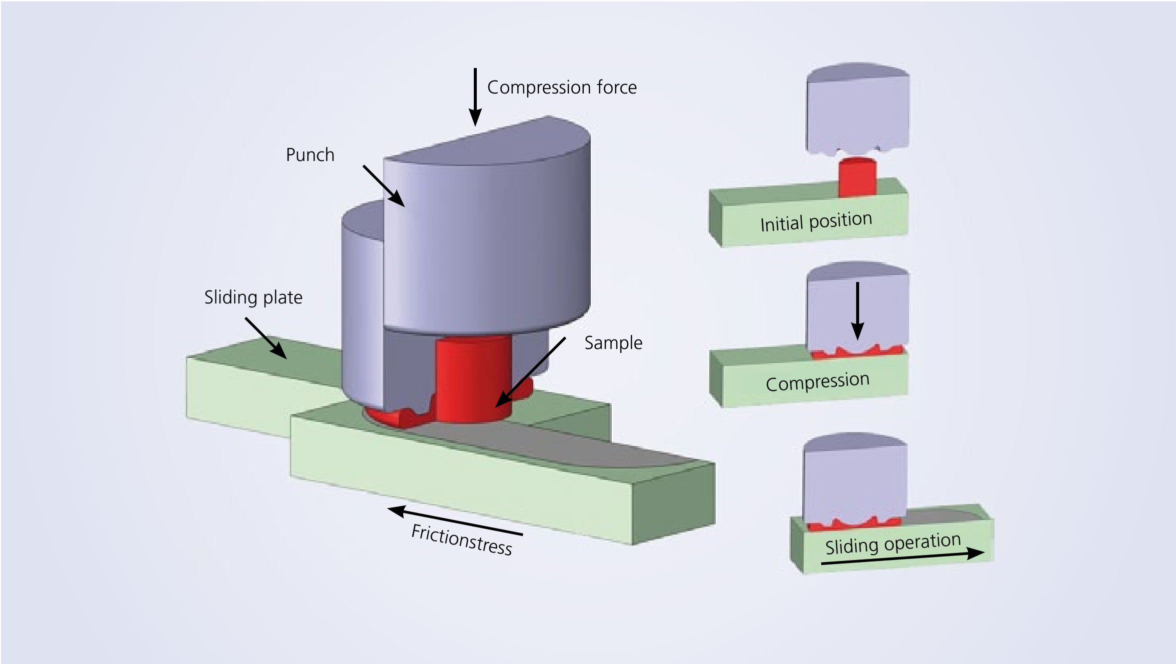


Fig. 5.16: Schematic representation of the compression-sliding system used at the PtU for research into friction ratios between workpiece and tool

ling approaches consider the above factors with insufficient accuracy or even ignore them completely.

In line with existing approaches to friction, the new friction model is able to differentiate between stress states with low or high contact pressures and/or between elastic and plastic deformation. These two stress states are weighted using the ratio of the effective stress according to von Mises and the local yield stress of the workpiece material (σ_{eq}/σ_y), resulting in a combination of the friction figure model according to Coulomb and the friction factor model according to Tresca. A significant enhancement of existing friction approaches is achieved by describing the influence of the sliding speed on the friction shear stress. In the new IFUM model this is performed using an exponential approach that allows for dynamic friction effects occurring during lubricated forging processes.

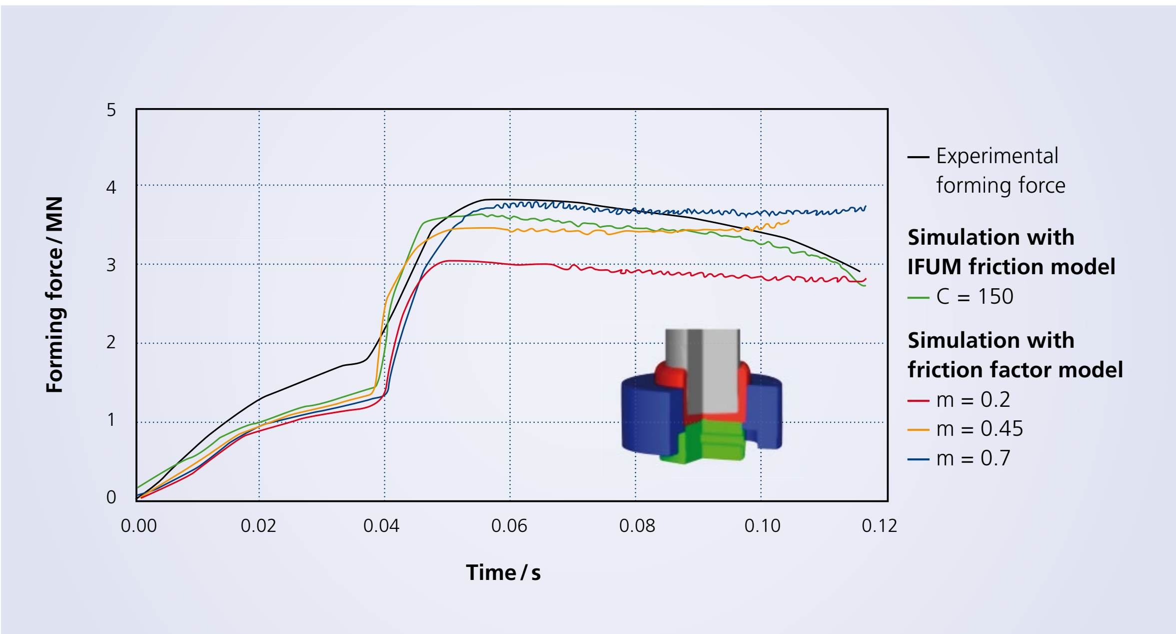


Fig. 5.17: Comparison of force-time curves established by simulation with experimental results

Fig. 5.17 shows a comparison of the numerically versus experimentally determined force-time curves of a forming process. The graph confirms a high correlation of the numerical results between the new friction model and the experimental data.

The use of the new friction model for the numerical representation of industrial-scale forging processes has shown that calculation accuracy can be increased by means of FE-assisted process simulation. This has already been implemented in sector-specific commercial FE systems and validated by comparison with experimental test results.

5.2.6 Coupling of forging simulation with non-linear forging press models

In multi-stage forming processes, measures for adapting individual forming steps (e.g. filling behaviour or the degree of filling) have a major impact on the overall result. At the same time, the influence of such individual actions often cannot be clearly predicted. Fundamental uncertainties arise from the fact that at present interactions between the blanks to be formed and/or their intermediate forming stages, the tool concepts developed for their forming and the selected forging plant have not yet been fully investigated. In this context, the latter plays a key role since every press type usually has its very specific load/displacement characteristic. Furthermore, the respective springback, tilting and offset characteristics are also influenced by the arrangement of the tools on the press table. In practice – especially when matching up forming stages for the production of new parts – this regularly results in increased expenditure and in some cases also in significant delays.

C. Brecher et al. [BREC 1] focus on the analysis and modeling of interactions between the workpiece, the tool and the forming plant, Fig. 5.18. A methodology developed at the Werkzeugmaschinenlabor (WZL) of the RWTH Aachen in recent years supports the virtual optimization of single-stage and multi-stage tools, allowing for the load-displacement behaviour of the production plant and the selected tool system. To achieve this, a new software program is linked to conventional forging simulation systems. The tool analytically depicts the machine- and mold-specific spring and tilt stiffness as well as the translational and rotational allowances of the forming plant and the tool system, using a non-linear approach. Based on the processing force pre-

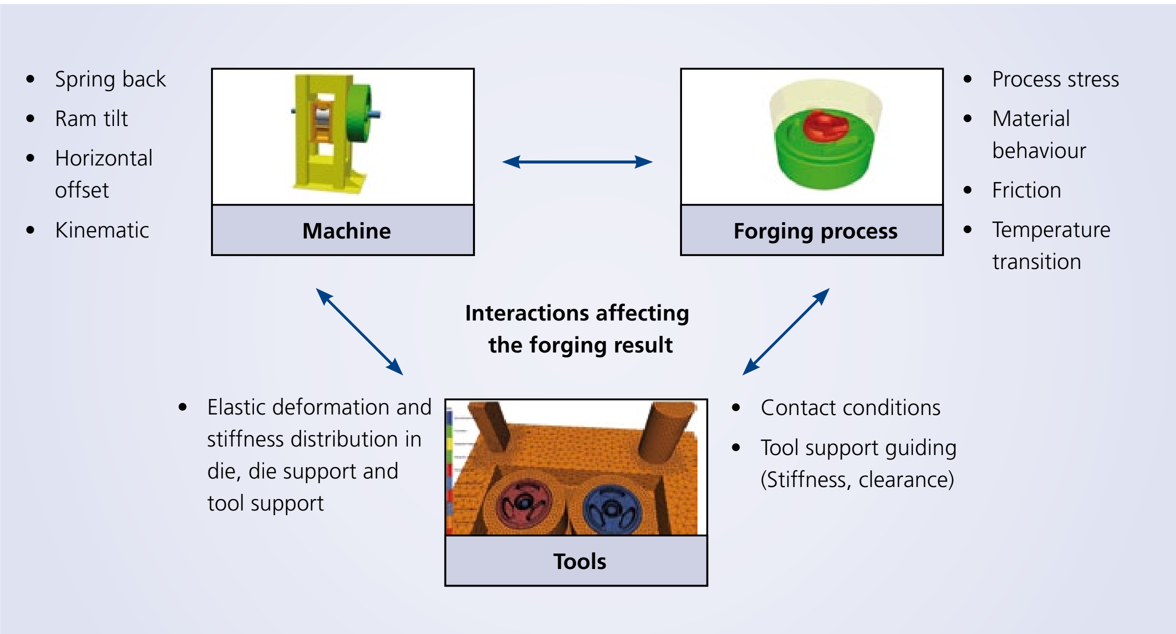


Fig. 5.18: The software developed at the WZL in the context of several research projects takes into account the complex interactions between workpiece, tool and plant and supplies the software used for forming simulation with related corrective values for the part geometry

sent in the individual steps, the resulting displacement is calculated and then fed back to the forging simulation system. This in turn updates the tool position so that subsequently the deformation of the workpiece can be determined. The procedure described facilitates increased calculation accuracy in the simulation of forming processes while additional expenses remain at a reasonable level. The new tool thus helps reduce set-up and start-up problems with new tools.

5.2.7 FEM simulation of tool failure in hot forging processes

When steel materials are drop forged, the high process temperatures and forming forces result in huge thermal and mechanical strains on the tools, which significantly affect tool service life. Tool failure by cracking due to thermomechanical cyclical fatigue is the second most common cause of failure after wear and tear. Cracks occur in tool areas that are subjected to cyclical plastic deformation due to alternating mechanical loading. Along with thermocyclical loads, this leads to material damage and ultimately to the initiation of cracks. B.-A. Behrens et al. [BEHR 2] analyzed possible ways of simulating tool failure in forging due to thermomechanical material fatigue. Based on improved FE-based service life predictions, the IGF research project 15640 N examined three industrial forging processes where tool failure due to fatigue cracking occurred.

The forging operations were modeled and analyzed using commercial industry-specific FE-systems, including real process parameters and boundary conditions. The forging stresses and strains induced in the die were calculated using decoupled tool analysis programs. Additional data from controlled-strain thermomechanical fatigue tests on the hot-work steel used were included via the programming interface of the FE system. Quantitative statements on the forging cycles achievable before failure due to cracking were made by correlating the locally determined cyclical strain amplitude in the forging die with the data from the fatigue tests. Fig. 5.19 shows the result of a computer-aided tool life estimate for a forging process in which the lower die is made from the hot-work steel X38CrMoV5-3 (EN 1.2367). The numerically determined local tool life for the lower die is mapped on the left. The actually occurring crack (right) appeared exactly in the area for which the simulation predicted the lowest life expectancy. Based on the calculation results from

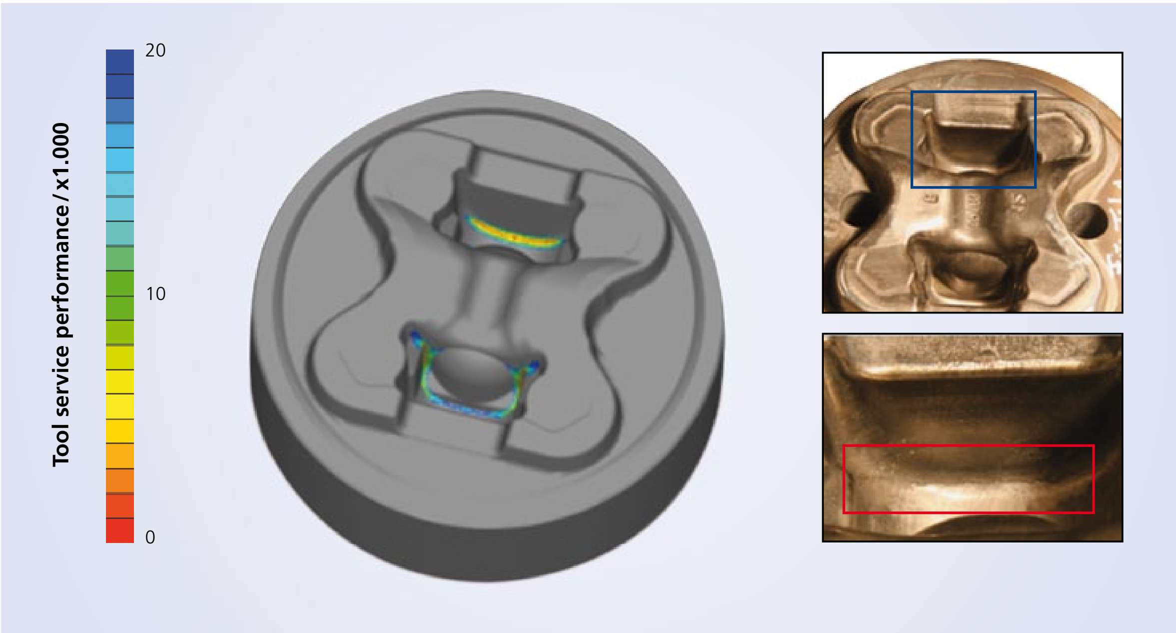


Fig. 5.19: The service life computed using FE-assisted simulation for the lower die of a real forging process (left) compared to a cracked lower die, showing the crack initiation location (right)

the failure simulation, improved and more efficient layouts of tooling concepts and forging stages are possible.

5.2.8 Controlling damage in cold forging processes

Due to the complexity of modern materials and the high demands on the finished components, advanced simulation methods for accurately predicting the behaviour of materials in the manufacturing process and the resulting component properties are indispensable. D. Helm [HELM 1] deals with the modeling of the mechanisms that can lead to the formation of internal defects caused by localized transgression of metal plasticity during forging processes. This makes it possible, for instance, to integrate aspects such as quality, cost and process reliability in the development process early on, allowing for material-specific formability limits. For example, if unfavourable processing parameters are used during cold full-forward extruding, massive damage in the workpiece in the form of so-called "chevrons" can occur (Fig. 5.20). Their development can be significantly influenced by a suitable design of the forming process.

The objective of research currently being conducted at the Fraunhofer IWM in Freiburg is to use advanced numerical simulation methods for cold-forming processes firstly to predetermine the development of defects and, based on the results, to identify suitable parameters and/or an optimized tool geometry to avoid the described defect.

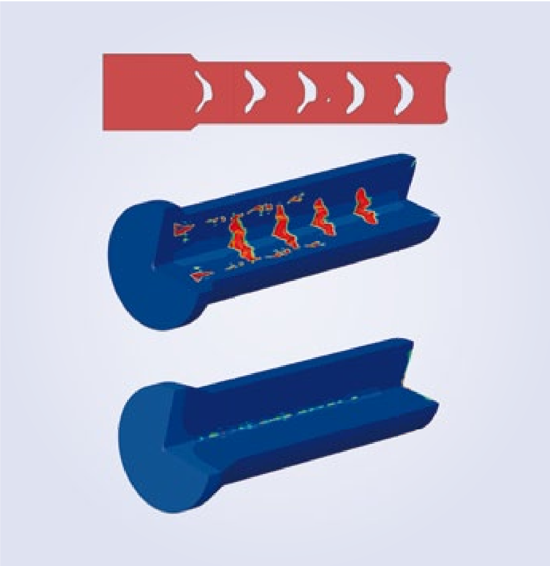


Fig. 5.20: Formation of "chevron cracks": experiment (above) and computed pore density (red = high, blue = low) before (picture at centre) and after optimizing the tool geometry (below) during full-forward extruding

As a starting point, mechanism-based material models are used to analyze and optimize metal forming processes. Based on micromechanics, these model the physical source of the damage resulting from the formation, growth and merger of pores. At Fraunhofer IWM the problem has been addressed using a specially refined model after Gologanu-Leblond, which takes into account the influence of complex deformation paths on pore development and pore shape.

After adjusting the model parameters, it turned out that the initial state of the deformation process to be optimized is described correctly. The periodicity and shape of the "chevrons" predicted by the simulation accord well with the results of practical experiments. Furthermore, the model also correctly depicts two effects known from practice – surface waviness and a drop in the press force profile during formation of the "chevrons". Further simulation studies have shown that by changing the tool geometry at a constant degree of taper, the pore density increases only slightly, thereby effectively avoiding "chevrons". Despite these successes for a relatively simple one-stage forging process, predicting damage evolution in multi-stage cold forging processes with complex deformation paths dependent on the process history is a challenge that requires further research activities.

5.2.9 Development of holistic approaches

Current trends in the forming processes of metallic materials include both the forming of lightweight components and the increase in product diversity. At the same time, there is a desire to improve energy efficiency in production. Likewise, control of the diverse processes, making them shorter and more flexible, as well as integrating them, is taken into account. Moreover, one exciting challenge for forming technology comprises not only predicting product quality, but also controlling development of the microstructure. One of the focal points of research work undertaken at the Institut für Umformtechnik und Leichtbau (IUL) is to develop a method for tackling the different tasks occurring during the development phase of forming processes, [SOYA 1]. This method is based on sophisticated and at the same time efficient numerical models representing the material behaviour and is based on a holistic finite-element approach. The area of investigation extends from analyzing multi-stage sheet forming, forging and sheet forging processes to predicting product features, including the assessment of crash behaviour and service life. The requirements arising from a model or platform change are overcome by making specific use of sophisticated physical material models realistically describing local changes in the state of the material. Typically this involves considering solidification behaviour, the cumulation of defects or changes in textures. This makes it possible to use standardized models for different forming processes. Furthermore, the remaining formability of the material can be estimated, and intended (or unintended) material separations (e.g. cutting, shearing or punching operations) can be modeled, see Fig. 5.21. In addition, the accurate prediction of product characteristics – such as strength or zones with critical defect accumulation – becomes possible, following the product development process. These data are in turn available as input values for predicting crash behaviour and service life. Each characteristic can

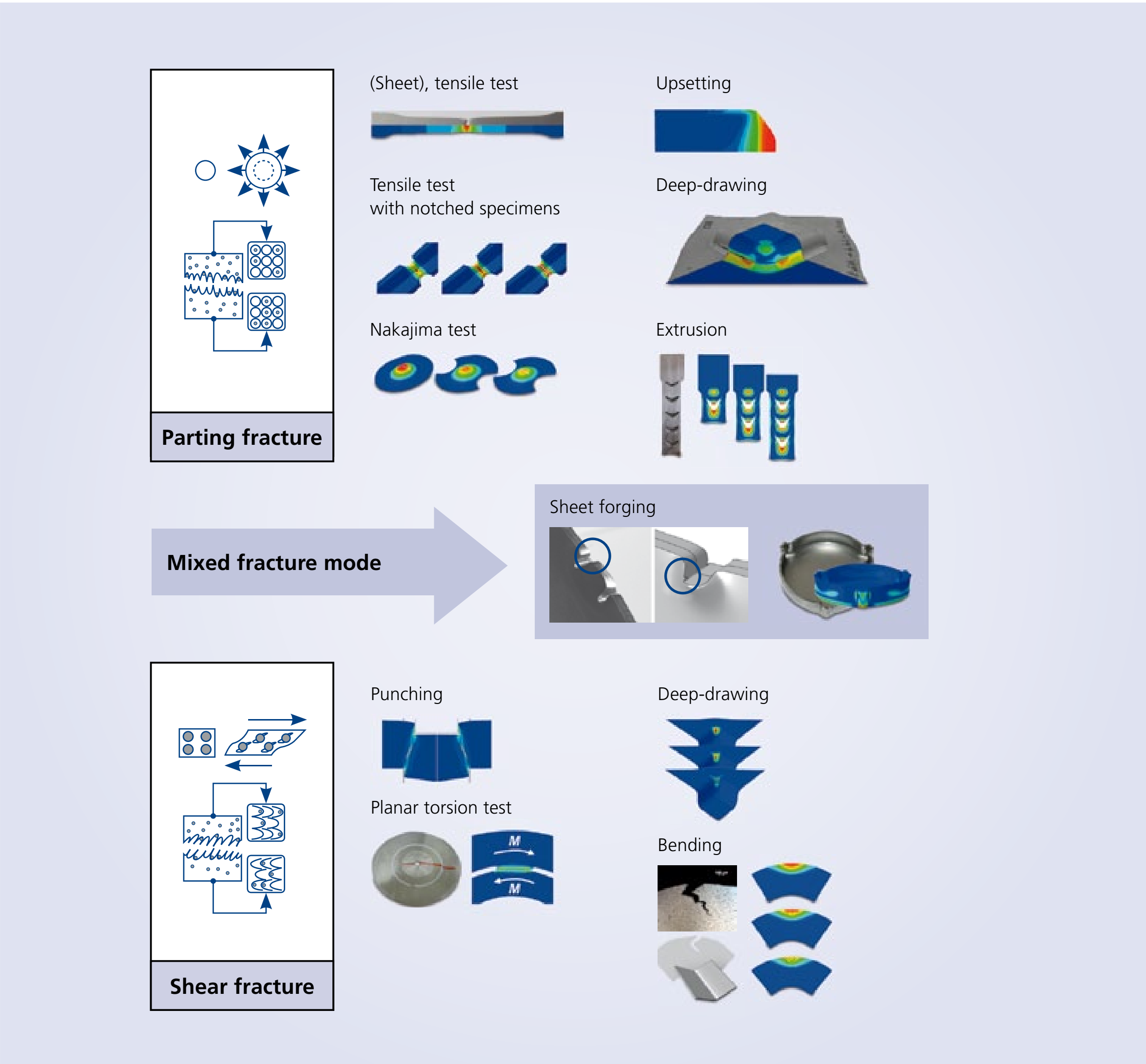


Fig. 5.21: Research performed at the IUL to simulate defect evolution during different sheet forming, forging and sheet forging processes using a holistic model approach

be specifically set if it has initially been defined as a target value for the design process. In order to verify this holistic approach, the IUF conducts experimental studies. The respective material properties are characterized on this basis. This is done in order to optimize existing manufacturing processes or to develop new processes. In the course of this work, the development of previously unavailable or only vaguely defined interfaces between the simulation of multi-stage forming processes, the prediction of product features and the product service life is continuously advanced.

Economic Aspects

In the course of a survey conducted among member companies of the Industrieverband Massivumformung e. V. (IMU, German Forging Association), H. Ade and J. Heizmann [UMFR 1] went into the question as to what benefit the companies in the sector attribute to the programs they use to simulate forging processes. For this purpose, a questionnaire on monetarily and non-monetarily assessable aspects of the software application was developed. This survey provided an overview of the application of forming simulation software within the German forging sector. Furthermore, participants were offered the prospect that this feedback would make a valuable contribution to assessing the benefits of forging simulation software in the companies.

In total, almost 140 companies were contacted and sent a questionnaire, and around one fifth of them provided return information. The following topics were addressed in the survey:

- Introduction of the software, (reasons and criteria for selecting the software),
- Software application (forging and tool engineering applications),
- Application period, budget and hardware & software used,
- Economies experienced through FEM application (parameters such as time, costs, etc.),
- Production, process development and costs (processes, materials, cost distribution),
- Trends, (expectations of companies using simulation, as well as customer expectations).

Results of the business survey:

The distribution of yearly turnover of companies responding reflected the typical state of the industry: accounting for around 56 %, smaller companies with an annual turnover below Euro 100 million dominated, 30 % were in the range between Euro 100 and Euro 200 million in annual sales and only 15 % belonged in the top group with more than Euro 250 million in annual sales.

The results obtained can thus be considered representative of the sector.

The verdict of the practitioners was particularly positive with respect to the fulfillment of expectations regarding the benefits of the software used, with the reduction in process development time in the

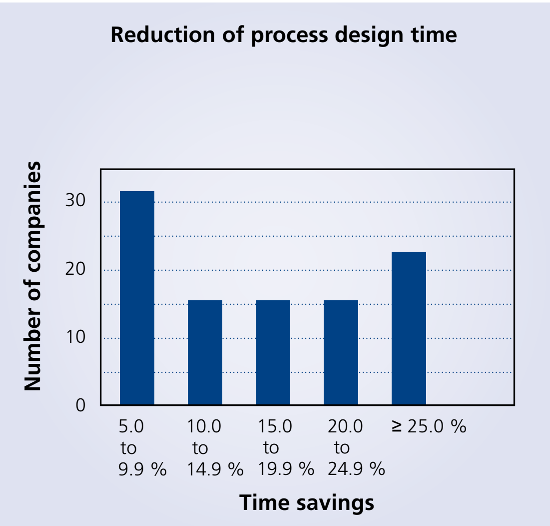


Fig. 6.1: The vast majority of companies participating in the survey expected to experience a reduction in process development time by using simulation software

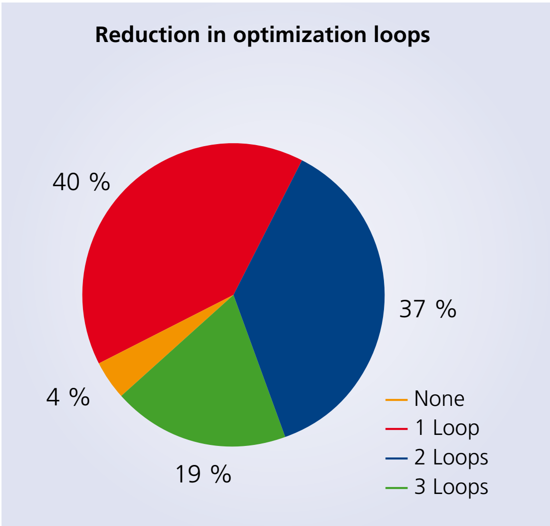


Fig. 6.2: Nearly all the companies participating in the survey were able to save at least one optimization loop through using simulation software

foreground, Fig. 6.1. In this regard, almost all responding companies expected a significant benefit. With respect to this point no negative statements at all were given while a full 75 % completely agreed, with almost 70 % putting the benefits in the double-digit range. Nearly as high, at 52 %, the assessment was that process development costs are reduced by more than Euro 10,000 per component. Other important reasons for introduction were to improve the company's innovative edge, reduce press downtimes, improve staff training and reduce tooling costs. With respect to the benefit of the programs used, the positive assessment of the reduction in the number of development loops for new components clearly stood out, Fig. 6.2.

Further advantages of using the software were seen with respect to raw material weight savings (Fig. 6.3) and tool costs.

When simulation software is used, the main focus is on obtaining a better filling, reducing wrinkle formation and raw material input as well predicting force and/or energy requirements. There is also considerable interest in analyzing the fibre flow pattern and crack development. On the other hand, computations of residual stress and component distortion, as well as analyses relating to hardness and microstructure, are performed less frequently. Tool calculations have mainly focused on the aspects of reducing wear and tear as well as on failure analysis – especially as in forging tool costs usually account for a significant percentage of total component cost (Fig. 6.4).

Looking to the future, the vast majority of participants expect their customers to insist on even shorter development times, while development costs will increase. This is very similar to expectations with respect to the number of variants to be presented in development projects: here 93 % expect an increase. A full 100 % of the companies surveyed expect that the importance of simulation will continue to rise. Accordingly high approval ratings are thus found with respect to readiness to expand the use of such simulation tools in the future, both in terms of the width, but even more of the depth of application within the company.

In evaluating these results it should be noted that not only technical improvements, but also economic advantages, such as shorter development times and reduced manufacturing costs, will ultimately also benefit the purchasers of forged components. After all, in our functioning market economy, competition automatically ensures that benefits of any kind do not remain solely with the manufacturer: they are usually passed on to his customers in the form of discounts or product enhancements.

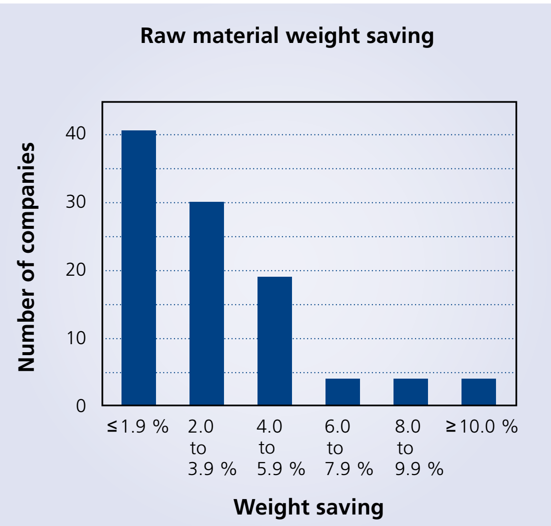


Fig. 6.3: The majority of simulation software users were able to achieve significant weight reductions of the rough forgings, resulting in a marked increase in resource efficiency

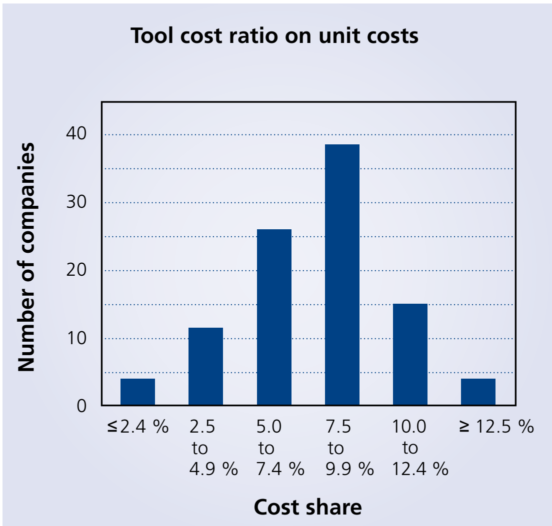


Fig. 6.4: Wear and tear on the tools and the related costs have a significant impact on unit costs

Outlook

Over the years, the use of simulation software for designing and optimizing forging processes has evolved into an encouraging success story. In this connection, both forging companies and their customers have constantly achieved improvements. This applies both to technical advances with respect to the usefulness of the products as well as to performance improvements in the processes. The nature of these successes is every bit as varied as the products that are manufactured by forging. A particular focus will be on issues such as lightweight construction, resource efficiency and cost savings. Ultimately, these benefits will be shared by all stakeholders in the value chain – by the forger just as well as by his customers and – in the end – by the consumer enjoying either extra product performance for the same money or the same product performance at reduced prices.

Simulation also plays an sifnificant role in the field of resource conservation by further improving alloying concepts. Not only are many alloying elements expensive, but accessing them is becoming increasingly difficult. The use of simulation tools is becoming ever more important in the development of new, powerful yet resource-efficient alloy concepts. Using numerical models to describe the interactions of various alloying additions with the crystal lattice of iron makes it possible to develop new steels and processes that fulfill high mechanical requirements while at the same time taking account of the security of supply. Thanks to this achievement, the forger can react faster to supply and price changes by adjusting his alloy concept.

Another factor – albeit only indirectly attributable to the use of simulation – is the marked gain in development skills. Through this additional know-how, the forger can generate additional benefits for his customers in the course of product development partnerships. Thanks to the use of simulation software, not only can design products be optimally adapted to service requirements with a high quality and low reject rates, but development and production processes can be designed faster and more efficiently. This development expertise is also a key factor for success in international competition with suppliers from low-wage countries. Simulation thus also helps safeguard jobs at home.

This trend is set to continue in the coming years in line with improvements in the simulation models, in conjunction with further enhancements of computer performance. All providers of simulation software have a full pipeline of prospective improvements and new features that should gradually become available on the market over the next few years. In addition, many universities and other research institutions are engaged in scientific research the results of which will sooner or later find their place in industrial practice.

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