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Nico WAGNER[1*]
Robert TEHEL[1]
Robin KURTH[1]
Steffen IHLENFELDT[1,2]

CHARACTERIZATION OF TOOL CLAMPING CONDITIONS IN FORGING HAMMERS

The present work addresses the topic of die clamping at the forging hammer in the context of the definition of a current requirement profile as well as the evaluation of individual influencing variables on the clamping process. In addition to the presentation of survey results for the requirements profile, the first part focus on the sensible minimization of influencing variables to be investigated and on the verification of a possible evaluation method. Based on this, in the second part exemplary influencing variables on the clamping condition are investigated by means of FEM. Thereby it can be shown by way of example, that the heat flow of the forging process and the friction conditions between the clamping elements have a noteworthy influence on the clamping condition of the dies and that deviations in the clamping force can lead to significant damage.

1. INTRODUCTION

High quality and complex work pieces, established and new high-strength materials, combined with small and medium batch sizes are product technical criteria, which modern forges have to handle. In addition, increasing productivity requirements and increasing international competitive pressure form the boundary conditions make it difficult to consolidate the market position. For a wide range of commercially available, complicated and high-mass forgings, the use of a forging hammer still represents the technologically and economically optimum solution. The special dies of the forging hammers are primarily fixed by wedge clamping systems, whose basic mode of operation has remained unchanged for more than 150 years. These wedge clamping systems have a direct influence on the quality of the work pieces, set-up time, service life and remaining useful lifetime of the dies and clamping devices, and thus on productivity and economic efficiency.

[1] Forming Machines, Fraunhofer Institute for Machine Tools an Forming Technology, Germany
[2] Chair of Machine Tools Development and Adaptive Controls, Dresden University of Technology TUD, Germany
[*] E-mail: nico.wagner@iwu.fraunhofer.de
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Contrary to modern fully automated forging press lines, no automated die change is possible due to the clamping system used on the forging hammer. The adjustment of the wedge clamping system is highly dependent on the expertise of the operator, who sets a clamping force based on experience. During production, this clamping force and especially its distribution is influenced by thermal, dynamic and transient quasi-static load collectives, whose dependencies and influence on the long-term clamping state have not yet been researched.

Based on an analysis of existing clamping devices and forging aggregates on which these clamping systems are used, a general technical requirement profile is derived and further supplemented by a requirement profile for future clamping systems, which is sourced on a survey of forging companies. Out of this picture of requirements, the research question as basis for the further investigations is concretized. Thus, this research contribution is intended to provide a first overview about the subject of die clamping conditions without claiming to be complete. Since no experimental verification is available yet and thus not part of this work, a specified selection of boundary conditions is investigated at this state. For this purpose, the most relevant influencing variables for selected clamping systems are analysed using the finite element method (FEM).

2. MACHINE AND CLAMPING PROCESS

As an energy-bound machine, forging hammers are distinguished from forging presses by maximum forming force combined with low system complexity. Drop forging hammers are mainly used when the product portfolio requires high forming forces, a large working capacity and easy adaptability of the machine parameters to the manufacturing process. [1] Since the 18th century [2], the drop forging hammer has contributed to global economic performance, although its basic operating principle has remained unchanged to this day, improved by pneumatic, hydraulic or electro-mechanic drive systems. In contrast to the drop forging hammer, the necessary die clamping technology and thus the die setup process have hardly evolved during this period, which will be examined in more detail below.

In the context of drop forging at the forging hammer, the tool clamping process influences both the setup process and the production process. Figure 1 shows the process steps from die preparation to the production process including necessary iterative back loops. It should be noted in particular that these back loops are independent of the number of setup processes. The mutual influence of the positioning and clamping of the dies cannot be measured by the forging part quality, but it can be measured by die and machine specific features, which are used as aids by the operator to orient the die. This process can be repeated several times until the operator is satisfied with the die orientation. Building on this back loop, an initial forging is forged and its quality evaluated. If it is not correct, the die alignment process starts over. This cycle can also be repeated several times until the shape of the forging part meets the quality requirements. The third back loop is due to process-related influences that lead to a reduction in the clamping force with which the dies are clamped during production. Depending on the number and intensity of strokes required by the operator to produce one or more forging parts, the clamping system used to clamp the dies in the forging

hammer must be retightened. Whether retightening is required is perceived acoustically by the operator and may have to take place after only a few strokes or after several forged parts. In addition, Fig. 1 shows that a large part of this process depends on the expertise of the operator. This dependency has a direct impact on the tool life, the forging quality, the productivity and thus the profitability of the company. Hence, industrial automation solutions are so far only offered for this process chain in the area of production, but not for the upstream processes. This deficit is due to the lack of basic principles describing the mechanisms of action when clamping the dies, the interaction of the clamping devices with the die forging hammer and the effective clamping state under production conditions.

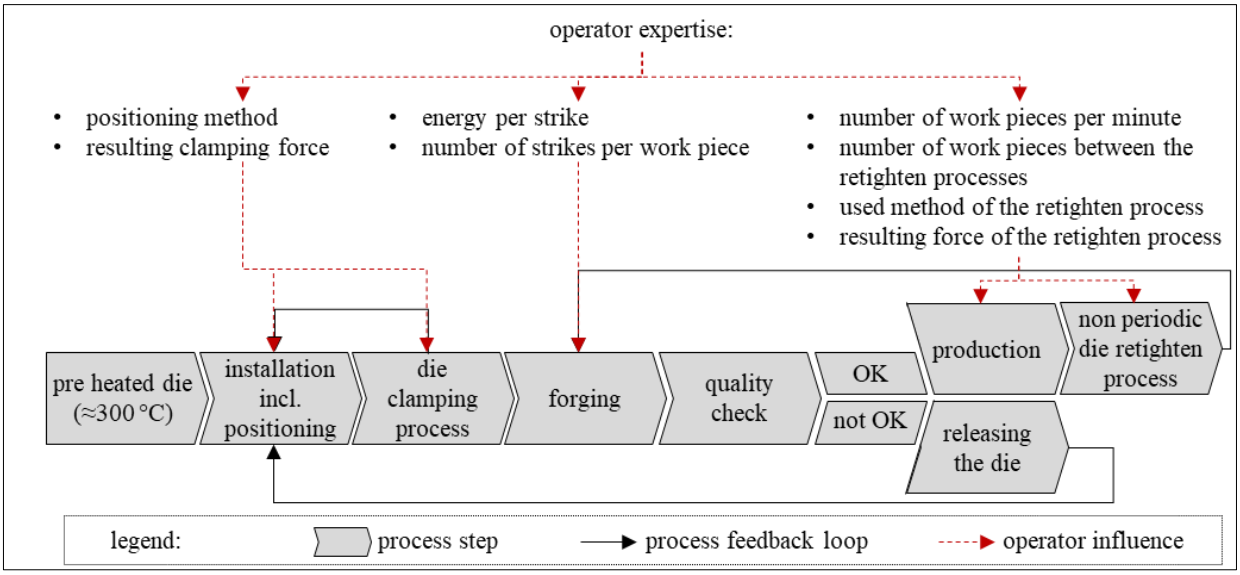


Fig. 1. Division of labour assets over the period of the forging process from the preform to the finished forged piece

The work capacity of drop forging hammers results from the kinetic energy of one or two masses moving towards each other, as shown in Fig. 2. Differences in the work capacity, which can exceed 1400 Kj [3], results from the design and the drive system. Drop forging hammers have the lowest work capacity, because the kinetic energy results only from a drop height and the available mass (Equation (1[1]).The work capacity of top-pressure-forging hammers (Equation (2 [1]) and counterblow-forging hammers (Equation (3 [1]) is largely defined by the pressure in the hydraulic or pneumatic drive system. This energy flow is independent of the drive system of the drop forging hammer but is quantitatively determined by it. It can therefore be assumed that clamping systems designed to meet the tough energy and dynamic restrictions of a counterblow hammer also satisfy those of drop and top-pressure hammers.

$$W_{dfh} = m_{hb} \cdot g \cdot h \tag{1}$$

$$W_{tpfh} = m_{hr} \cdot g \cdot h + A_{pis} \cdot \int p(h)\,\mathrm{d}h \tag{2}$$

$$W_{cbfh} = A_{pis} \cdot \int p(h)\,\mathrm{d}h \tag{3}$$

where: W_{dfh} – work capacity of a drop forging hammer, W_{tpfh} – work capacity of a top pressure forging hammer, W_{cbfh} – work capacity of a counter blow forging hammer, m_{hr} – mass of the upper ram (incl. mass of the upper die), g – gravity constant, h – distance between upper and lower die, A_{pis} – total acting piston area, p – medium pressure (air or oil).

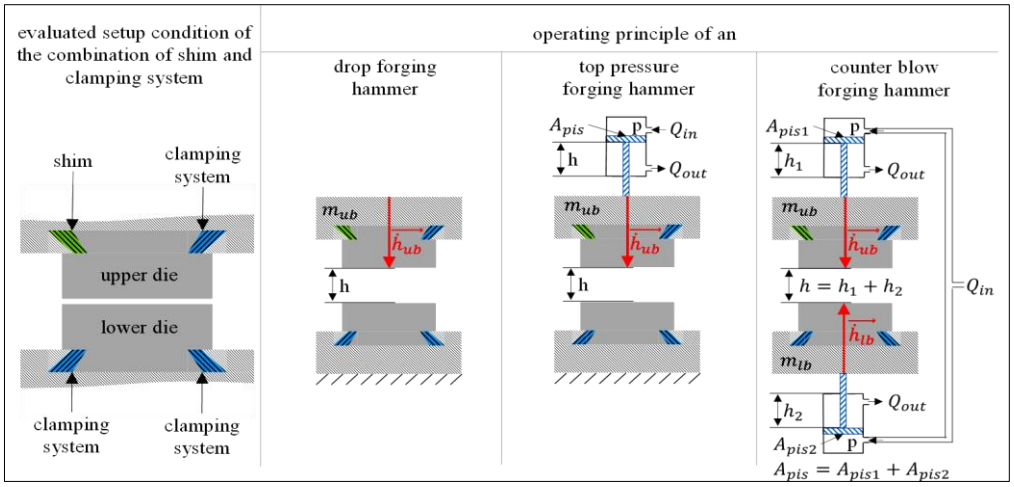


Fig. 2. Construction of a drop forging hammer with selected themed components

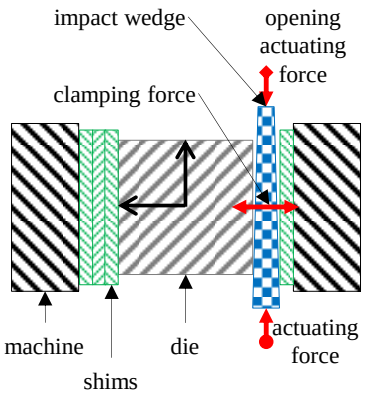
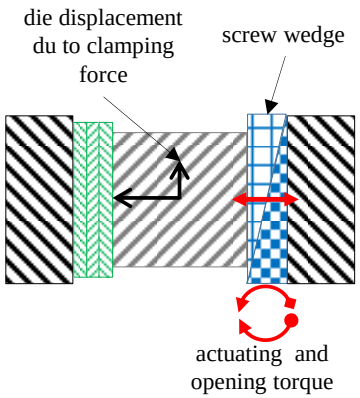
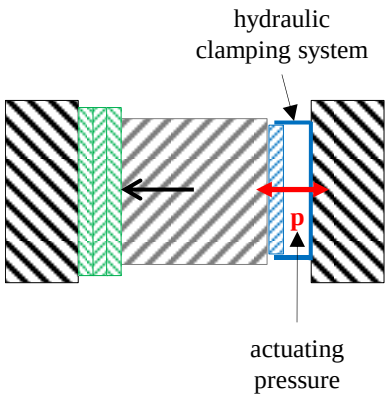
During the forging process, the available work capacity is transformed into forming work, damping energy (material damping) and the kinetic energy of the vibrating machine. The production of a forging always requires several strokes, over which the forming energy decreases and other types of energy increase. This relationship results from the fact that the forging process always ends with one or more bounce strokes to ensure 100% die filling, during which effectively no more forming work is performed and the total available energy must be absorbed by the die forging hammer.

The energy provided by the drop forging hammer is transferred by the drive system to the ram(s) and by the connected die halves into the work piece to be formed. Different clamping systems and methods are used for force-fit fastening of the dies to the ram and the shim, which are compared in Table 1.

The comparison of the various clamping systems could, in addition to the presented separation by functionality, also be depicted historically as a development from the impact wedge system via the screw wedge system to the hydraulic clamping system (cf. periods of origin of patents [4–17]. Both approaches show that regardless of the selected operating principle with its associated advantages regarding production, engineering and environment, various restrictions cannot be eliminated on the basis of these operating principles.

Today, the two systems based on the wedge mechanism are the most established in the industrial environment. This is due to the fact, that leaks in a hydraulic system used in a forging environment result in an increased risk of fire on the one hand, and an increased impact of failure on the other hand, since a failure of the clamping force without further self-locking results in a total failure. For this reason, the wedge mechanism-based systems used in industrial application form the basis for further consideration.

Table 1. Overview of available clamping systems

impacted wedge system	screw wedge system	hydraulic clamping systems
		
Mechanical (by means of a ram) or hydraulically assisted drive of a wedge leads to clamp the dies. Shims are used to correct the misalignment.	By means of a screw, two wedge halves are displaced relatively to each other in the longitudinal direction. The resulting displacement in the width direction causes the wedges to be clamped. I.e. the tensioning force depends on the tightening torque of the screw, located in the force flow.	Various constructions working according to the piston principle clamp the tools depending on a set pressure acting in the piston.
state of the art		
The specification of the wedges is subject to operating standards.	Many different technical solutions patented. The chronology of patents shows the continuous optimization of wedge clamping systems. From the minimization of screw bending ([7]-[9]), to the prevention of wedge half misalignment ([10-11]), to the reduction of screw vibration ([4]-[6]), there are various solutions on the market.	Patented solutions aimed at minimizing system complexity while optimizing sealing systems ([12]-[17]).
advantages		
• high system robustness • simple, low-cost construction • oldest and thus most established system on the market • high availability	• better adjustability of the clamping force • reproducible clamping conditions • higher working safety during set up process	• good adjustability and controllability of the force • clamping force monitoring possible • high degree of work safety during clamping of the dies
disadvantages		
• inhomogeneous clamping conditions • no reproducibility of the clamping condition • high risk potential due to hammering in during setup	• lower system robustness	• dynamic loading of the seals leads to system failure (high hazard potential during operation)

$$F_{clamp} = F_{generate} \cdot \left[\frac{1}{\tan(\arctan(\mu_1))+\tan(\alpha+\arctan(\mu_2))}\right] \text{ [18]} \quad (4)$$

where: F_{clamp} – clamping force, $F_{generate}$ – generating force, μ_1 – friction value wedge and machine, μ_2 – friction value wedge and wedge α – wedge angle.

According to the functional diagram of the two wedge clamping systems shown in Fig. 3, the clamping force can be calculated by Equation (4). Regardless of the source of the generating force, this principle applies to the calculation of the clamping force on both the screw wedge and the impact wedge.

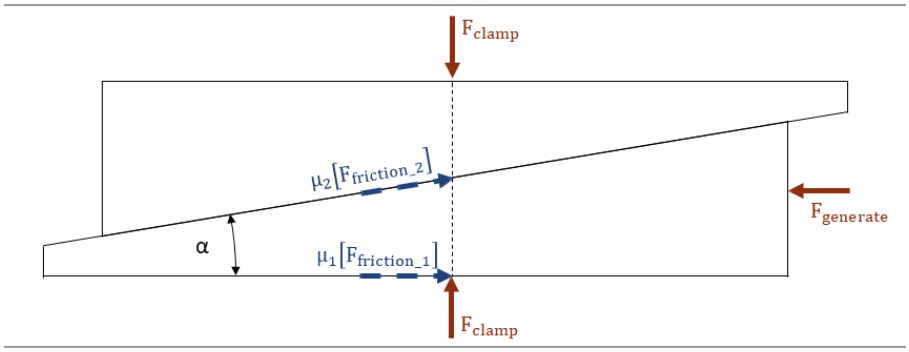


Fig. 3. Forces on the wedge clamping principle

3. REQUIREMENTS AND INFLUENCES ON CLAMPING SYSTEMS FOR FORGING HAMMERS

Technological and process-related constraints are only part of the requirements set to clamping systems. New systems must also meet current and company-specific economic efficiency criteria, generally applicable occupational safety regulations and production-specific operating standards. To qualify this requirement profile, a survey was undertaken in which various companies in the German forging industry took part. For this purpose, the participants of the study were able to evaluate 13 different requirement criteria, in which points from 0 to 10 could be assigned for each criterion. A 0-point rating is equivalent to "unimportant", whereas a 10-point rating is equivalent to the "highest level of importance".

The criteria of the survey address both corporate policy priorities, which are to be understood as an overarching guideline or framework. First-order requirements represent criteria which must be functionally fulfilled by the clamping system. These are underpinned by second-order criteria, in that specific requirements are defined as to how the basic functional principle is to be implemented in order to take advantage of associated effects. Table 2 shows the categorization of the survey criteria.

The individual criteria, their detailed explanation and the average score per criterion are shown in Table 3. For the study, both small and mid-size enterprises (SME) as well as larger companies were taken into account, both on the side of the machine manufacturers as well as on the side of the users, in order to be able to generate a profile of requirements as broad as possible. The distribution of the participating companies is shown in Fig. 4.

Table 2. Categorization of the requirements profile

company political demands	costs	ergonomics	occupational safety		
requirements 1st order	adaptability	life time	positioning quality	reproducibility	setup time
requirements 2nd order	automation capability	clamping force monitoring	intelligence	objectification	process monitoring

The evaluation shows that, in addition to occupational safety, first-order requirements in particular received a high prioritization. These requirements are reflected in the process steps shown in Fig. 1, which are significantly influenced by the expertise of the operator. This leads to the need for clamping systems for die clamping to be able to independently influence the control variables that were previously empirically influenced by the operator.

Table 3. Results of the industry partner survey

requirement criteria	specification	rating	requirement criterion significantly influenced by		
			design	process	electronics
occupational safety	focuses mainly on preventing injuries to personnel that can result from incidents associated with the job they perform in the workplace	10.0	X	X	X
positioning quality	conformity of the die position before clamping and after clamping	9.8	X		
reproducibility	repeatability of die position and clamping forces over several clamping operations	9.8	X		X
lifetime	how many times can it be used before damage occurs	9.2	X	X	
setup time	time period from the insertion of the dies to the start of the forging process	9.0	X	X	X
adaptability	suitability/ adaptability of the system for existing drop forging hammers	8.0	X		X
objectification	increasing the transparency of the mechanisms at work during clamping and sensor technology required for this	7.4			X
automation capability	actuator system operated by the human being	6.0		X	X
intelligence	control structure (independent of human expertise)	6.0			X
ergonomics	optimal mutual adaptation between the person and his working conditions	5.0	X		
costs	monetary expense - procurement & operating costs	5.0	X		X
clamping force monitoring	provision of characteristic values during the clamping process	4.8			X
process monitoring	provision of characteristic values during the forging process	2.8			X

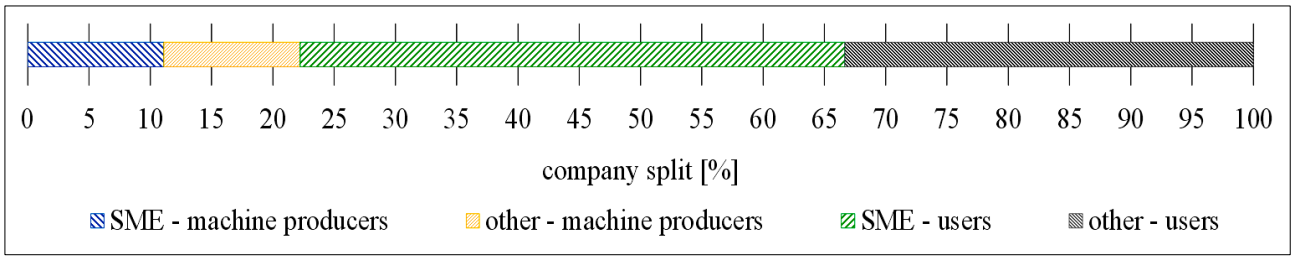


Fig. 4. Distribution of the companies participating in the survey in terms of company size and in the context of the drop forge hammer

On the right-hand side of Table 3, the potential properties of new clamping systems are compared with the influencing variables that significantly determine the properties sought. The “design”-grouping summarizes all geometric adjustments, shapes, tolerances and material properties. The “process”-grouping includes all work organization and action-based procedures, and the “electronics”-grouping includes the power electronics, sensors, actuators and associated software. This shows that the most important properties are all significantly influenced by the design of the fixture, whereas less important properties can be realized by integrating electronic components.

In order to identify relevant control variables which act on the clamping system, the influencing variables and their dependencies are shown qualitatively in Fig. 5. It also systemizes which variables are directly influenced by the operator and which are completely independent of the operator.

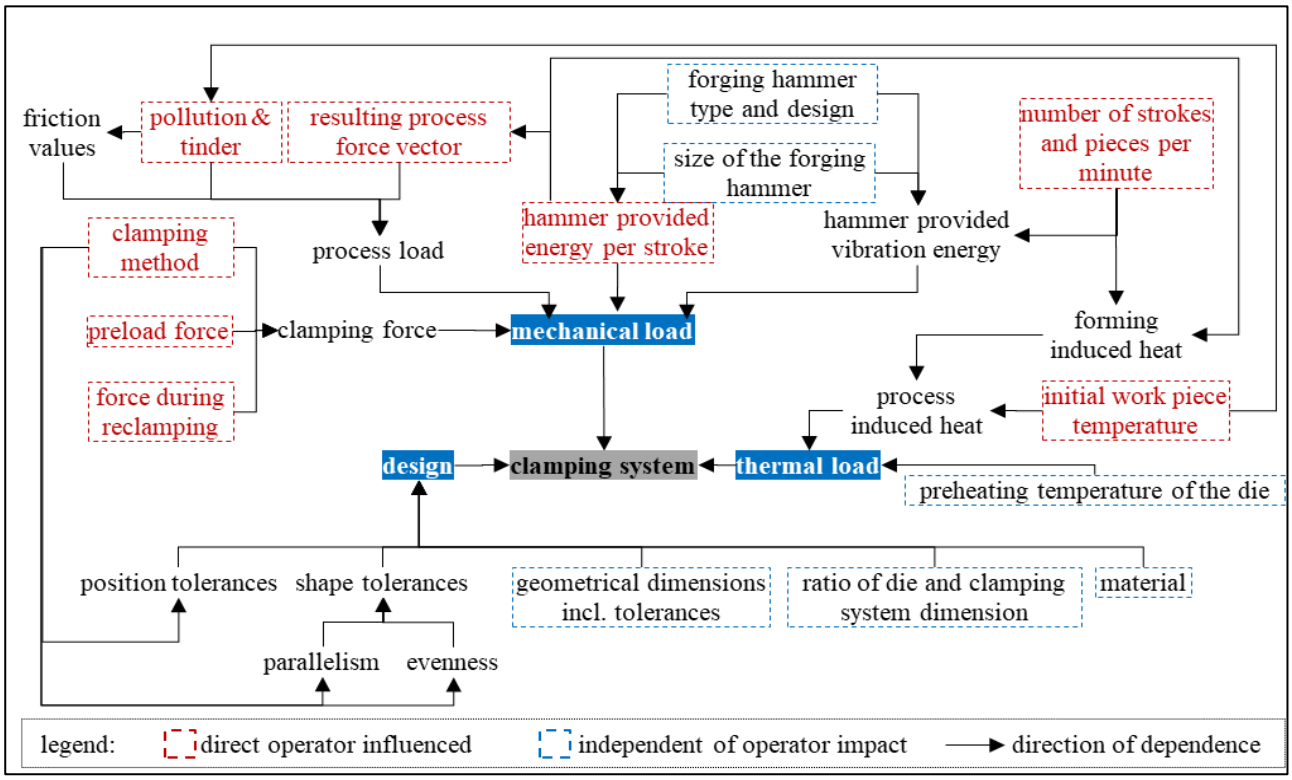


Fig. 5. Influencing variables on the clamping system

Combining the results of the survey and the technical restrictions resulting from the discussed state of the art, the question can be derived from Fig. 5 as to which influencing variables have relevance for the stress state of the dies and to what extent, and which influencing variables can possibly be neglected. Against the background of the increasing automation of plants, these influencing variables are also of significant importance in order to be able to estimate the automation potential and to minimize the influence of the operator. For this purpose, the existing influencing variables are to be consolidated for screening and subsequently investigated by simulation.

The process-induced heat can be simplified as an averaged heat flow when considering the influence of the temperature over a longer period of time. This means that the influence of local heat maxima resulting from the hammer energy provided and the number of strokes per minute are not taken into account. Further, due to the geometric distance from the heat source to the clamping system, the intervening masses and the existing separation layers, it can be assumed that local heat maxima have a subordinate influence on the clamping system compared to the heat flow acting over a longer period of time. The thermal load for the clamping system is therefore still largely dependent on the preheating temperature of the die and the averaged process heat flow.

Assuming that variations in material and structural properties such as stiffness and young's modulus can be neglected for scale and contamination particles, it is permissible to describe these as shape tolerances (flatness) of the geometry. The tribological influence of contamination can also be taken into account by means of friction coefficient variation.

Focussing on the fact that position tolerances are directly influenced by the operator, very large tolerance ranges for all components must be considered to estimate the effect of this variable. Small positional deviations, in which the nominal overlap of the tool contact surfaces is not undercut, can be represented approximately as shape tolerances. A further consideration of these is not intended within the scope of this work.

Under these assumptions, the following influencing variables remain for further considerations:

- averaged process heat flow,
- preheating temperature of the die,
- coefficient of friction,
- process force direction,
- preload force.

4. SIMULATIVE ANALYSIS OF THE TOOL CLAMPING CONDITION IN FORGING HAMMERS

For the evaluation of the influence of the individual factors, it is necessary to define evaluation or comparison criteria against which the sensitivity can be determined. With the focus on the clamping system, comparison criteria should be selected that describe the condition of the clamping system itself or its interaction with surrounding structures. The mechanical and thermal loads acting on the clamping system lead to elastic deformations

and thus to deformation energy which, related to the entire volume of the clamping system, provides information about the work performed on the clamping system.

Due to the geometric boundary conditions and friction ratios, it is to be expected that the normal force per contact surface averaged over the contact surface differs compared to other contact surfaces. Compared to the strain work, this distribution allows a differentiated consideration of the clamping conditions. For the evaluation of local influences such as shape tolerances, or deviations from the idealized centric process load case, further criteria are necessary which allow a discretised analysis of the distribution of the comparison criterion per contact surface. The principal stresses as well as the maximum, the minimum and the mean value of the principal normal stress related to a defined partial area per contact area (as depicted in Fig. 8) are a possibility to show the influence of load cases which deviate from the ideal case.

Due to the multiple influencing parameters, some of which are mutually dependent, the assumptions made to reduce these influencing parameters and the difficult-to-define process boundary conditions resulting from the forging operation and its environment, the simulative investigations carried out serve as a first approximation. For a qualification of the simulation results an experimental verification is necessary, which is discussed in the chapter with perspective character. The simulative results are also needed to estimate the structure of the experimental design.

4.1. MODELLING AND BOUNDARY CONDITIONS

In a first step, the influence of various parameters on the clamping system is to be investigated by simulation using the FEM, before the model as well as the results are to be verified experimentally at a later stage. Against the background of the later verification, the upstream simulative investigations are already oriented to realistic boundary conditions. Figure 6 shows the computer aided design (CAD) model of a 25 kJ counterblow hammer, reduced to the structural elements required for the analysis of the clamping system (lower ram, upper ram, lower die, upper die, clamping system and shims).

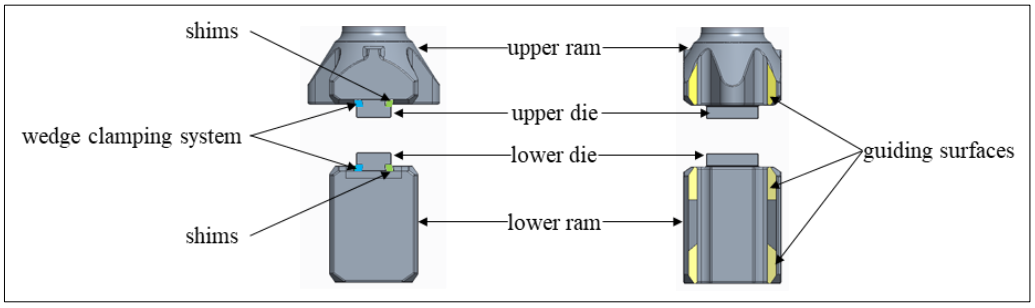


Fig. 6. CAD-Model of the analysed counter blow hammer

The main focus of the analysis is the behaviour of contact areas between the individual components. These are taken into account in the structure of the FE model through a mesh refinement compared with the adjacent surfaces and volumes. All components are meshed

with tetrahedrons, whereas mesh size and mesh function are adapted to the components in order to reduce the number of nodes – see Fig. 7. The mesh adaptations in the upper ram are similar to those in the lower ram from Fig. 7. The insert integrate in the FE model of the rams is only of cosmetic nature and used to qualify the model to make geometric adjustments more easily. The contact between the insert and the ram is modelled as a composite and any numerical uncertainties that may arise have been taken into account by providing an appropriate distance to the contact surfaces to be evaluated. Thus, it behaves structurally as well as thermally like modelled as a single body. All other contacts are modelled as frictional contacts with a defined friction coefficient and the ability to separate by a gap.

component	volumetric element size	shape function	contact surfaces – mesh size [mm]			
			ra	in	we	sh
ram (ra)	50 mm	linear	/	25	/	/
insert (in)	25 mm	squared	25	/	8	8
wedges (we)	18 mm	squared	/	8	/	/
shim (sh)	18 mm	squared	/	8	/	/
die (di)	30 mm	squared	/	15	8	8

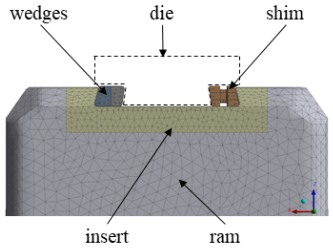


Fig. 7. Boundary conditions in the FEM model

For the evaluation of the described comparison criteria, especially those representing inhomogeneous surface distributions, the software ANSYS offers the possibility to output the nodal results. Due to the large number of nodes, a simplification of the evaluated areas is necessary. For this reason, the nodes on relevant structural surfaces are evaluated and summarized in individual sub-surfaces leading to averaged results for the sub-surfaces. For this purpose, the contact surfaces are divided into 30 sub-surfaces (three over the height and 10 over the length) – see Fig. 8.

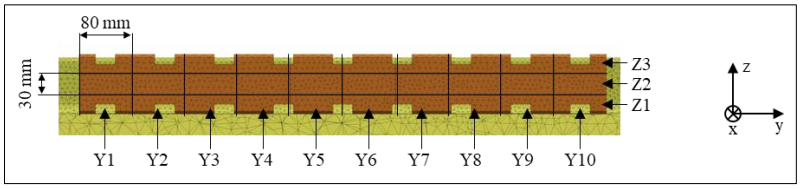


Fig. 8. Division of surface into sub-surfaces

For the simulative investigations concerning the influence of different factors it is necessary to define some boundary conditions. Based on the size of the drop forging hammer, the possible screw wedge variants can be limited. On average, screw wedges for this hammer size are clamped by M30 bolts of strength class 12.9, which apply a bolt pretension force of approx. 440 kN (cf. Fig. 3 – $F_{generate}$). There are no studies on the forces that occur with impact wedges, which is why the 440 kN is taken as given for the further investigations. Furthermore, a standard load case is determined with an acting process force of 5000 kN. The friction conditions in all contacts are described with a friction coefficient of 0.1 if not further detailed. The model underlying all the following FE calculations is a linear-elastic material model, which must be taken into account when interpreting the results.

4.2. STANDARD LOAD CASE CHARACTERIZATION AND SURFACE SEGMENTATION

The simplification due to the segmentation of the contact surfaces used to reduce the number of nodes to be evaluated is an acceptable assumption, as shown in Fig. 9. Qualitatively, the curves of the normal stress in the X-direction from the ANSYS plot are similar to the distribution of the force reaction in the same direction based on the partial surface evaluation. The qualitative comparison of normal stress and force reaction are permissible, according to Equation (5).

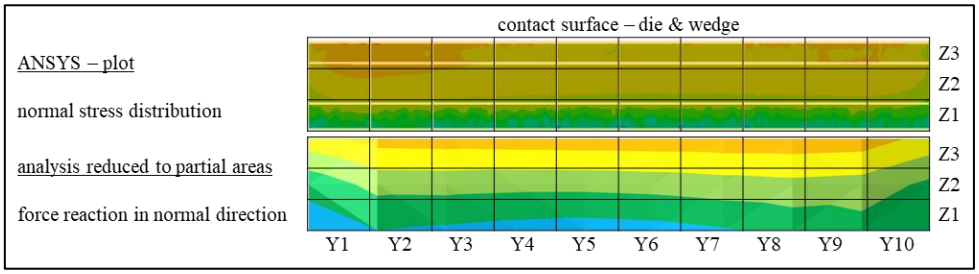


Fig. 9. Comparison of the node-based and partial area-based visualization for the standard load case

$$\sigma_n = \lim_{A \to 0} \frac{F_n}{A} \tag{5}$$

where: σ_n – normal stress, F_n – perpendicular force acting on surface, A – surface.

Figure 10 shows the normal stress distribution in the *X*-direction (orthogonal to the contact surface) for the five contact surfaces under standard load case. All contact surfaces are characterized by a homogeneous stress distribution over the length of the wedge (*Y*-direction), with a decrease over the height (positive *Z*-direction) of the contact surface (lower ram).

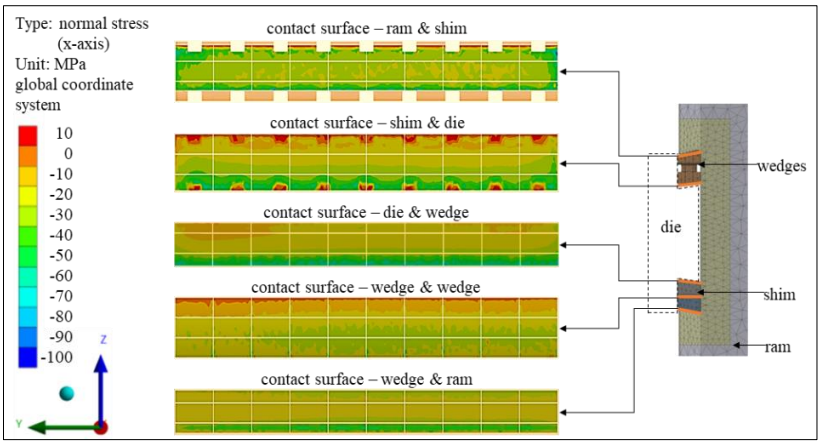


Fig. 10. Formation of the normal stress distribution per contact area at normal load case

This means that the highest normal stresses in the *X*-direction and thus the highest clamping forces respectively contact pressure occur in the area of the clamping elements or shims facing the ram. The somewhat higher stresses at the shim result from the interrupted geometry, which reduces the effective contact area.

4.3. INFLUENCE OF VARIATION OF THE LOAD CASE

In addition to the defined normal load case, Fig. 5 shows that deviations can occur due to the operator, which manifest themselves in eccentric and non-coaxial load applications as shown in Fig. 11. In order to verify the suitability of the partial area-based analysis, the normal force distribution for these possible deviations is compared to the normal load case (standard load case) in Fig. 12. The eccentric load case is defined by the application of the process force of 5000 kN to half the die face. For the non-vertical force application, the process force of 5000 kN acts on the entire die engraving at an angle beta of –5°.

As shown in Fig. 12, the part-surface based evaluation allows a differentiated analysis for deviations from the standard load case. Corresponding to the displacement under the eccentric force, the normal force distribution in the contact area between the wedge and the die also shift in the negative *Y*-direction, which can be derived by comparing the highest normal force of up to 90 kN per sub-surface (left, *Y*1) with forces of around 40 kN (right, *Y*9) at the opposite end of the contact area. Similarly, the application of a non-vertical force leads to a significant increase in the force reaction in the contact area, whereby the distribution over the contact area width is similar to the distribution under centric vertical force application. The increase in the normal force in the contact surface between die and wedge for different angles is shown in Fig. 13 and illustrates, that a small change in angle leads to a significant change in the normal force. With increasing angle, the increase in normal force becomes smaller.

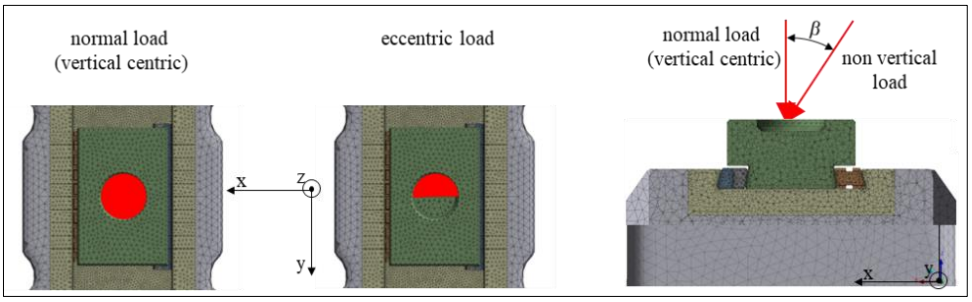


Fig. 11. Variation of load cases

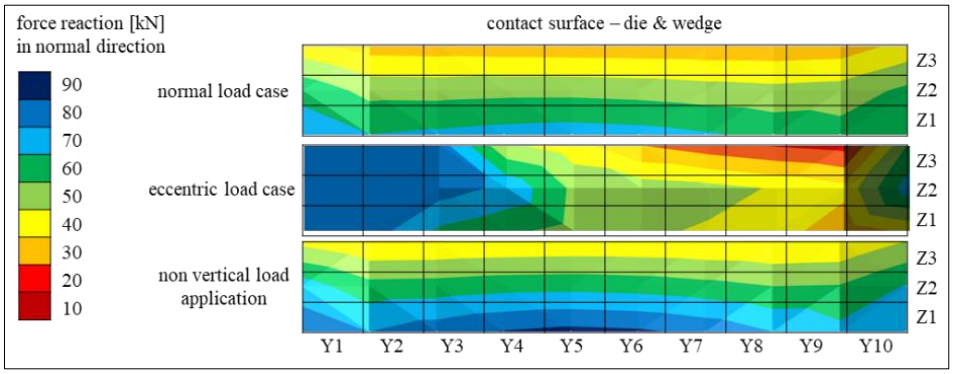


Fig. 12. Comparison of the standard load case with eccentric and non-vertical load application based on the partial area analysis of the normal force

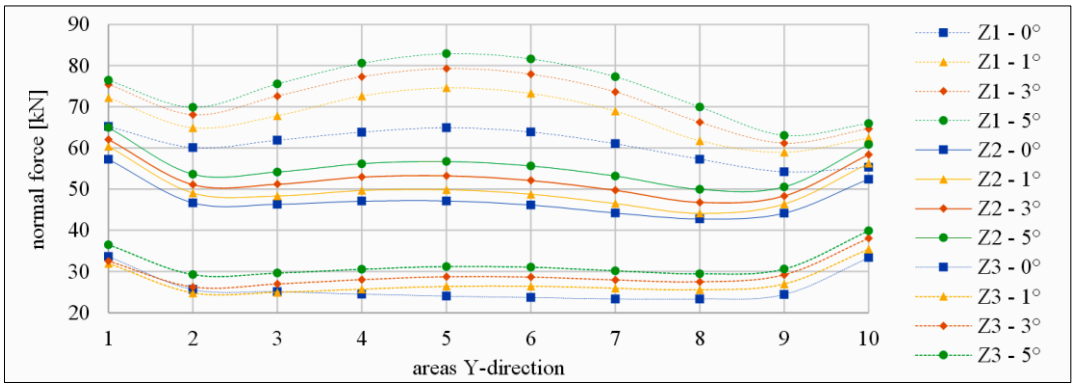


Fig. 13. Comparison of the normal force distribution in the surface between die and wedge for varying angles of the applied force

Figure 14 shows the normal force averaged over the entire respective contact surface for all contacts being in the clamping plane under the influence of the process force during the normal load case. This shows that the forces in the contact surfaces of the shims decrease slightly over an increasing process force, whereas the force in the contact surfaces of the wedges increase at the same time. The reason for this distribution still needs to be investigated more in detail.

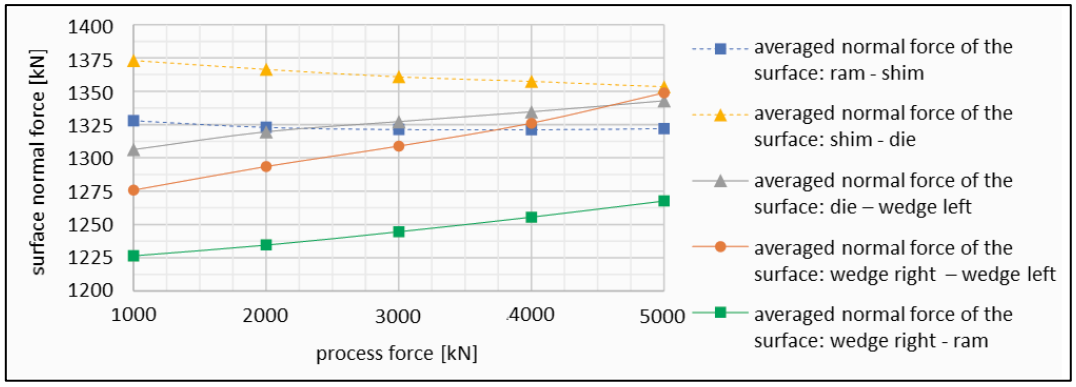


Fig. 14. Comparison of normal forces for different contact surfaces under the standard load case

4.4. INFLUENCE OF THE THERMAL LOAD ON THE CLAMPING FORCE

Thermal-transient calculations were carried out to estimate the influence of temperature on the clamping force. For this purpose, a die preheated to 150°C, 225°C and 300°C with a preload force of 440 kN was clamped in the forging hammer and a continuous heat flow was mapped as an abstraction of the process heat flow immediately after the clamping of the die. To estimate the influence of the process heat flow, the power was varied in the simulation in steps of 3 kW, 7 kW and 11 kW, acting on the entire engraving. The simulation took into account an ambient temperature of 22°C, a thermal conductivity value at all solid-solid contact areas of 5000 W/(m²·K) and a heat transfer coefficient of 12.5 W/(m²·K) for all surfaces in contact with the room air. Radiation was also considered in combination to convection and conduction as an ideal black body.

For the practical interpretation of the simulation results, it is assumed that the tools are aligned in the machine for a period of 600 s after reaching the preheating temperature and then clamped. During this time, the tool can already transfer part of its thermal energy to the surrounding structures, which reduces the temperature difference between the contacting bodies. The thermal expansions approaches each other and thus the clamping force loss due to the thermal expansion reaches a practical level.

Figure 15 shows the averaged surfaces temperatures for different preheating temperatures of the molds in combination with different process heat flows. This clearly shows, that irrespective of the preheating temperature of the dies, after about 2 hours the average die temperature is defined to a large extent by the process heat flow, whereas the preheating temperature is the dominant factor for the first hour.

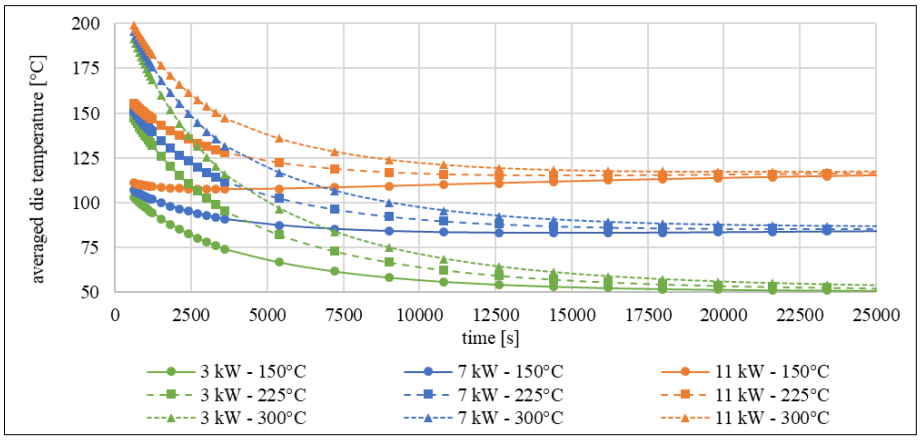


Fig. 15. Averaged die temperature over time for different preheating situation and different process heat flows

Figure 16 shows the normal force for the contact surface between die and wedge under the influence of different process heat flows and die preheating temperatures plotted against time.

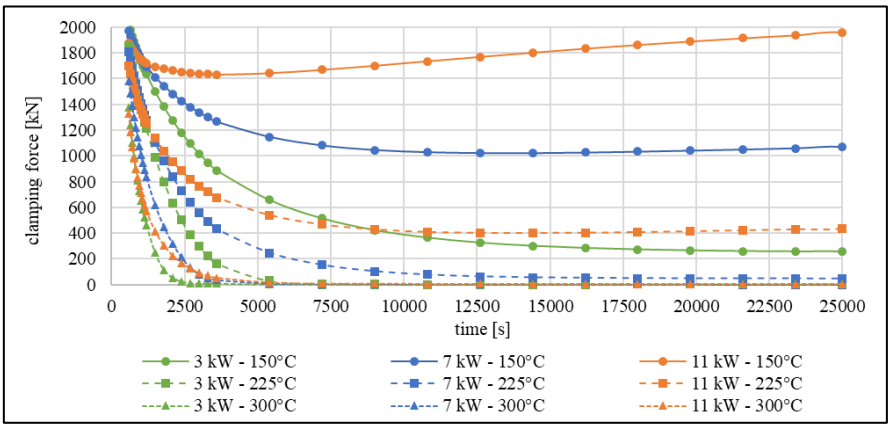


Fig. 16. Influence of the die temperature on the clamping force

In general and nearly independent of preheating temperature or process heat it can be seen, that the normal forces reach a quasi-static state after approx. 2 hour as the average die

temperature reaches it steady state. With increasing preheating temperature it can be seen, that the speed of the normal force decrease increases and the remaining normal forces converge towards 0 kN. Low preheating temperatures lead to higher quasi-static normal force distributions.

This behavior arises from the varying temperature difference between preheated die and ambient temperature, the resulting heat flow of the convection, leading to the associated cooling d$T(t)$ of the dies and finally their reduction in volume ΔV as well in width ΔL decrease. This relationship is described in Equation 6. The different process heat flows have a significant influence on the quantitative level of the quasi-static normal stress state and, as in the example of the 150°C preheated die with an applied process heat flow of 11 kW, can even lead to a quasi-static state above the applied preload force.

$$\Delta L(t) = \alpha \cdot L \cdot \Delta T(t) \tag{6}$$

where: ΔL – change in length, α – material specific coefficient of thermal expansion, L – initial length, dT – temperature difference, t – time

This effect is amplified by an increasing setup time of the dies, which was assumed to be 600 seconds for these simulations. This means that the preheating temperature in combination with the process heat flow have a significant influence on the stress state of the dies and thus also on the reclamping cycle, which is controlled by the operator.

4.5. INFLUENCE OF FRICTION

The influence of friction is essential for the stressing of the dies, since the dies are mainly held in the ram by frictional contacts. For this purpose, different friction coefficients respectively friction value pairings were assumed according to Equation 5 and the resulting clamping force, by a generating force of 440 kN, was calculated. The coefficient of friction µ1 characterizes conditions between the wedge and the die or between the wedge and the ram, whereas $\mu 2$ affects the friction conditions acting between the two halves of the wedge. Fig. 17 shows the various possible combinations of friction coefficients over the wedge angle.

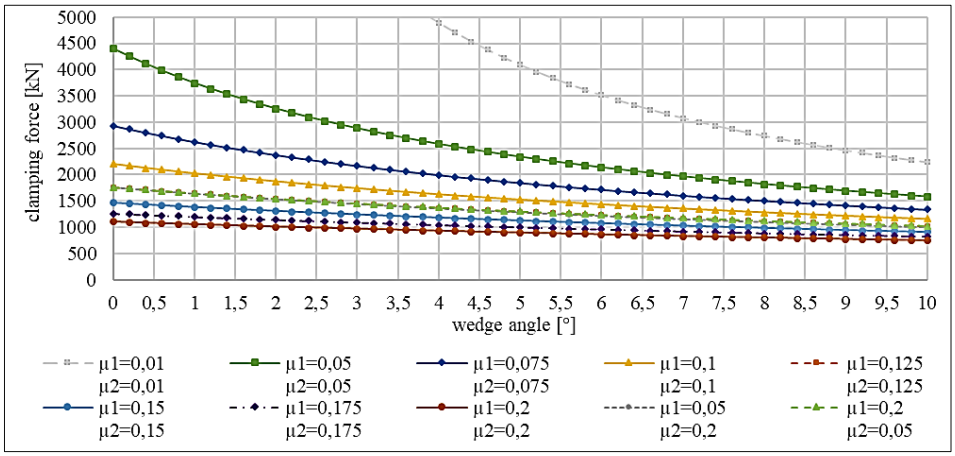


Fig. 17. Clamping force for different clamping conditions

This clearly shows that friction at small wedge angles has a significant influence on the clamping force and must therefore be taken into account in more detailed considerations. For this purpose, it is necessary to define the exact friction conditions, since the differences in clamping force can be very high. In addition, Fig. 17 shows that for combinations of friction values, the nominally larger friction value has the more dominant influence on the clamping force, irrespective of the acting contact area. This means that for further investigations, it is particularly important to determine exactly the coefficients of friction of the rougher surface structures. Mechanically finely machined surfaces in combination with coarsely machined surfaces have a subordinate significance for the clamping force.

4.6. PRELOAD FORCE ON THE CLAMPING SYSTEM

During the setting or retightening of the dies, the clamping forces are adjusted to varying degrees at the discretion of the operator, depending on the clamping system selected. In the case of screw wedge systems, the screws are ideally tightened in a torque-controlled manner; in the case of impact wedges, the clamping force is achieved by hammering the wedges in again or further. The forces that occur in this process lead to material stresses in the die and the ram. These stresses must be below the fatigue strength limit of the material to ensure continuous operation of the systems. On average, this is around 990 MPa for hot work tool steels.

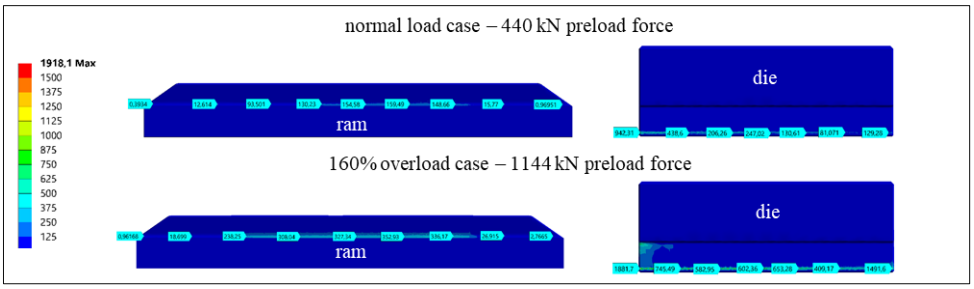


Fig. 18. Stress distribution for 0% and 160% overload preclamping force at the ram and die

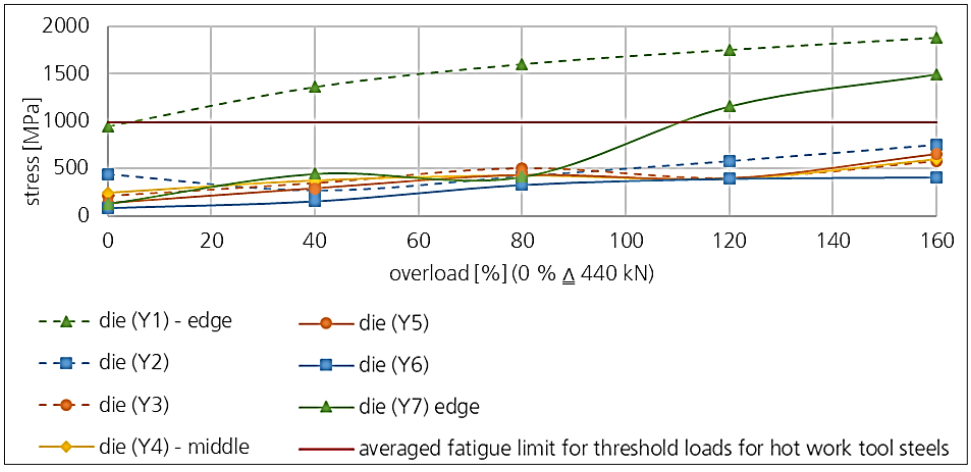


Fig. 19. Stress distribution at the die for different samples

The applied loads were increased from 440 kN (0% overload) preload to 40%, 80%, 120% and 160% overload and the critical contours at the die and the ram were evaluated by means of random sampling. The relatively high overloads were chosen to account for the high uncertainties of force application in impact wedge systems.

Figure 18 shows on the one hand the critical areas, which are located at the edges and corners of the tools, and on the other hand the chosen distribution of the samples. Under the assumed simulation conditions, the load for the die is significantly larger than for the ram. This is due to the fact, that the largest stresses occur in the edge areas of the contours and the die has smaller dimensions than the bear, which means that the die is enclosed over its entire length. Figure 19 shows the equivalent stresses at the die for the different load levels and samples. For the critical edge areas, this shows that these are stressed beyond the permissible fatigue limit even at low exceedances of the preload forces.

4.7. OUTLOOK FOR EXPERIMENTAL VERIFICATION

On the basis of the simulative investigations, a measuring system has already been developed which can measure the distribution of the occurring strains over the length of the forging die as well as the temperature distribution over its length – see Fig. 20. Strain gauges on the upper and lower side of the measuring die are designed as half bridges to compensate for the temperature-induced strain and to be able to determine differences in the various contact surfaces. Following static and dynamic calibration tests, investigations are planned in the forging store, where the measuring system is applied to record data over a longer period of time under production conditions. This relates to both die set-up as well as the forging process.

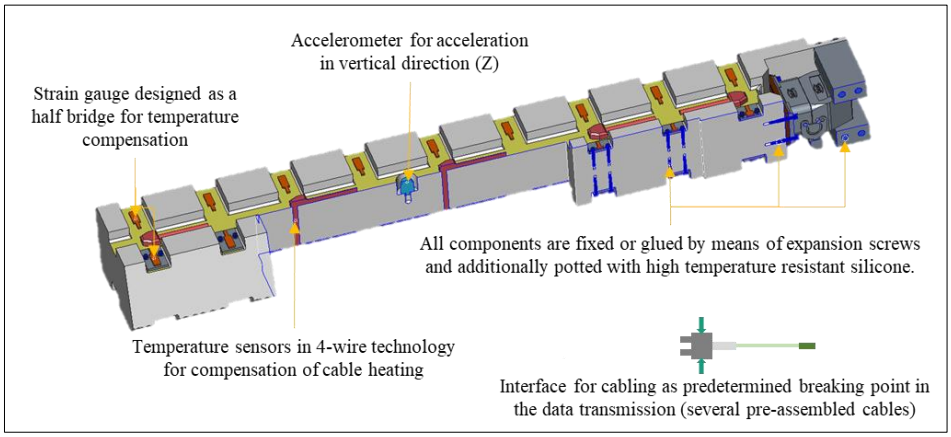


Fig. 20. Principle of the measuring device developed on the basis of the simulative investigations

5. CONCLUSION

The present work addresses the subject of die clamping on the forging hammer. Based on the description of the forging process, starting from the preheating of the dies up to the series forging process, the individual process steps are presented with regard to their

influence on the clamping process. Forging hammer-specific restrictions, boundary conditions of different clamping systems and process-specific influencing variables are taken into account. Based on this, it was possible to work out that the forging quality, the tool life and the productivity depend significantly on the expertise of the worker.

Against this background, a generally applicable requirements profile for die clamping systems was drawn up, taking into account both technical and economic interests. The economic interests were determined by means of a survey among industrial companies, which identified work safety, positioning quality, reproducibility of the clamping conditions, set-up time and service life of the clamping system as the most important factors. An analysis of all existing requirements showed that they are partly interdependent and can be consolidated and simplified under some assumptions.

This consolidated requirements profile forms the basis for the subsequent simulative investigations, for which a realistic FE model of a 25 kJ counterblow hammer was created. To simplify the evaluation of the large number of necessary calculations, the partial area analysis used was first successfully verified with regard to its informative value for centric, eccentric and non-vertical loads. In a second step, the influence of non-vertical loads as well as of different vertical loads on the clamping surfaces was investigated. The influence of the preheating temperature on the clamping condition and the influence of different process heat flows were also investigated. It was shown, that the process heat has a significant influence on the clamping force curve depending on the preheating temperature of the die. At high process heat flows, these can even lead to an increase in the clamping force and thus to damage to the clamping equipment. Depending on the local distribution, even slightly higher pretensioning forces can lead to a non-durable load on the clamping devices or dies, as was also determined during the investigations. It was also demonstrated that the influence of friction has a significant effect on the clamping force, especially on wedge constructions with such small wedge angles as those used in the clamping systems investigated, which is why coefficients of friction must be specified and considered in correlation with other influencing variables for further investigations.

The planned measuring device was also presented for verification of the findings obtained so far and further qualification of the boundary conditions. The results will be presented in a follow-up paper when the experiments are finished.

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