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Numerical Investigations on Stresses and Temperature Development of Tool Dies During Hot Forging

Bernd-Arno Behrens[1, a], Daniel Rosenbusch[1, b], Hendrik Wester[1, c], Janina Siring[1, d*]

[1]Institute of Forming Technology and Forming Machines, Leibniz Universität Hannover, Germany

[a]behrens@ifum.uni-hannover.de; [b]rosenbusch@ifum.uni-hannover.de; [c]wester@ifum.uni-hannover.de; [d]siring@ifum.uni-hannover.de

*corresponding author

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Abstract. Hot-forming tools are subjected to high thermal and mechanical stresses during their application. Therefore, a suitable design of the tool die is important to ensure a long tool life. For this purpose, numerical simulations can be used to calculate the occurring stresses and the temperature development in the tools during the course of a stroke or over several forging cycles. The aim of this research is to investigate the effect of different radii on the resulting stresses in the lower die of the forming tools. Furthermore, the temperature evolution over several cycles is analysed to determine their effect on the temperature. When investigating the stress, it was found that a larger radius leads to a reduction in stresses. In addition, it could be numerically proven that the base temperature of the die levels off after a certain number of cycles. These findings will be used in further research dealing with the service life calculation of dies subjected to thermo-mechanical alternating stresses.

Introduction

For hot-forming tools, martensitic tool steels are often used, which offer the highest possible strength. During hot forming, the tool materials are subjected to high mechanical, thermal, tribological and chemical stresses resulting in a complex load spectrum [1]. By exceeding the local yield stress in the highly loaded areas, plastic deformations occurs, which leads to material fatigue and finally to tool failure due to cracks [2]. For this reason, the finite element method (FEM) is increasingly used to determine the local stress values for the design of tools [3]. Since the tools are subjected to thermo-mechanical alternating stress during their service life, which leads to elastic-plastic failure, models for determining the tool life become more important [4].

Hot-forming tools are subject to high thermo-mechanical stress. This stress occurs cyclically due to the type of use. This cyclic alternating stress leads to failure in the area of the highest stress, which often manifests itself in the form of cyclic cracking [5]. Cyclic cracking results from cyclic thermal hardening and softening, which must be taken into account when planning the tools [6]. Accordingly, models to describe the material behaviour are needed that also represent cyclic cracking. A first approach is in the work of [7], which evaluates failure based on strain and kinematic factors for hot stamping. Another study dealt with crack initiation because of plastic deformation during cold forging [8]. This work provides basic research for a new plasticity model taking into account the cyclic softening of the material during the hot-forging process in order to further improve the numerical model. The final overarching goal for the future is to calculate the service life of the tool.

Optimised numerical tool design can take into account the process variables that occur in the manufacturing process [9] and enable a more efficient design of the tools and step sequences. As a result, an optimisation of the tool configuration is already possible in the construction phase of the forging process through stress-adapted dimensioning with little experimental effort for process design [10]. For this purpose, it is important to determine the occurring temperatures and stresses as well as the effects of design changes [11].

During hot forging, the near-surface areas of the forging dies heat up quickly to peak temperatures of up to 630 °C. In combination with cooling lubricants the die surface can be cooled down to temperatures between 100 °C and 200 °C, resulting in a temperature difference of approximately 400 °C to 500 °C. Most of the thermal energy is introduced into the surface layer of the die by the heated semi-finished product, but the preheating of the forging dies and the friction that occurs during the process also cause a rise in temperature. Typically, the semi-finished product temperatures are up to 1,250 °C in hot forging [12]. A high temperature of the semi-finished product reduces the flow resistance of the material [13]. With a pressure contact time of 50 ms, the heating rate of the die is up to 10,000 K/s, but the temperatures at the surface depend on the process and the geometry. According to [14], temperatures of 400 °C up to 450 °C can be reached during hot die forging, depending on the measuring point in the die. The temperature in the surface increases for a short time (approximately 0.15 s).

Using an FE-based process calculation, the heat transfer from the semi-finished product to the environment and to the tools during the forming process can be calculated locally. Due to high mechanical stresses, it is not possible to measure the temperature in the tool edge layer with the measuring equipment known today. The FEM offers great advantages for the calculated temperature determination of these areas. Within the framework of a research project, various points near the tool surface were measured in experimental tests with the help of thermocouples. The temperatures measured there are used as a comparative value for numerical simulation. If a good agreement between the simulatively and experimentally determined values is achieved at these points, the boundary-layer temperature of the tool can be concluded with the help of the FE model. In addition, the FEM can then also be used to calculate the temperatures or stresses occurring over several cycles [15].

In this research, the process under investigation exhibits high cyclic thermo-mechanical loads, which lead to the formation of cracks in the lower die in the most heavily loaded area. This lies in the lower radius of the inner area of the die. Accordingly, a numerical process investigation is essential to prolong the tool life and to calculate the load progression. The simulation takes into account the thermo-mechanical interactions between the semi-finished product and the dies that are used in hot forming processes. In general, there is the possibility to consider the tool stress within the framework of a thermo-mechanically coupled simulation or in one without coupling [15]. In the thermo-mechanically coupled calculation approach, the tools are considered as deformable components within a process simulation. In this case, the thermal-mechanical tool-material behaviour under normal operating load is already taken into account during the process simulation. In the simulation without coupling, the forming process itself is calculated first and the tools are assumed to be rigid and not thermally conductive. The load on individual tool components is only calculated in a subsequent simulation, but thermal effects are not taken into account. If time and costs have to be saved, the thermo-mechanical interactions are neglected in the simulation, which is why the simulation is carried out without coupling. If an exact representation of the stresses with thermal interaction is to be investigated, the thermo-mechanical coupled simulation should be selected. Since the thermo-mechanical interactions are important in the context of this research, this approach is chosen.

The aim of this work is to identify the influence of different radii on the lower die area by numerical calculations. Such investigations should make it possible to identify the most suitable radius for subsequent application in hot forging for the overall research project. In this way, it is ensured that a compromise between tool life and crack initiation is achieved and that there is no early failure due to crack formation. Another aim of this work is to numerically identify the number of forging cycles until the temperature in steady state is reached in the die. The knowledge gained here with regard to the more precise definition of the boundary conditions can be used for further numerical calculations in order to realise a more precise process simulation with regard to the calculation of tool life.

Numerical Model

Within both investigations (stresses at different radii and temperature evolution over several cycles), the semi-finished product of material 1.7225 according to ISO 683-1 (also referred to as AISI 4140 or 42CrMo4) is used, which has already been characterised and parameterised for simulations within the scope of a previous work [3]. The tool steel 1.2367 according to ISO 4957-2 (also referred to as X38CrMoV5-3) is selected as a typical die material. Flow curves of this material were determined from stress-strain diagrams in previous research such as [4], and in both prepared for usage in the simulations. Complementary material data like yield strength and tensile strength were supplemented by calculations with JMatPro so that a classification of the calculated stresses to the bearable loads can be made. The numerical models were built up within the FE-Software Simufact Forming 16.0 and consist of a lower die with ejector, an upper die and a suitable semi-finished product (Fig. 1). This geometry was chosen here because failure can be induced specifically in the lower radius and is thus suitable for investigating crack initiation by thermo-cyclic loading. The upper die and the ejector are considered as rigid and non-heat-conducting during the simulation, as they are not in the focus of this research. In addition, this simplification has no influence on the temperature and thus the stress development in the lower radius of the lower die. This was checked in advance by simulation and it was found that it has no influence on the lower die considered here. It only has a small influence on the semi-finished product in the upper surface area. This can save resources and the influence can be neglected in this framework. The lower die has been set as deformable with heat conduction. Therefore, the temperature development and the resulting stresses can be calculated within the thermo-mechanical coupled simulation. In addition, this coupled simulation can generate more accurate results regarding stresses arising in the lower die, as the temperature influence is also taken into account. This model of a hot-forming process was used for investigations on the different radii and for the temperature development. For the forming process, a stroke of 29.34 mm is considered which results in a flash thickness of 0.9 mm. A press with a constant speed of 290.57 mm/s was set, resulting in a process time of 0.14 s. This corresponds to the abstracted construction of the press planned for later experimental trials. The friction was approximated with the combined friction model using a friction coefficient μ of 0.15, and a friction factor m of 0.3 based on the information of [16], and the experimental values obtained from previous tests [3]. The initial temperature distribution of the semi-finished product was determined by an additional cooling simulation, which depicts the transfer time of 5 seconds from the heating unit into the press. In the experimental process, the transfer is realised with a robot. The initial temperature after heating is set to 1,250 °C. The basic temperature of the die is 180 °C. A mesh study was carried out to identify the appropriate discretisation of the billet and the lower die for this forming process and the mesh properties determined were used in this research.

Procedure of load analysis with respect to different radii. In this section, the effect of different radii in the bottom die on resulting stresses is investigated. For this purpose, six different variants with a radius of 0.30 mm, 0.50 mm, 0.75 mm, 1.00 mm, 1.50 mm and 2.00 mm were designed (Fig. 1). These studies are used for a more specific design of the die for the selected hot forming process. The loads that occur make it possible to estimate which variant is likely to have a longer tool life compared to the others. Since the overall aim of the research project is not to achieve the longest service life, but rather a suitable one for investigating cyclic crack formation, smaller radii are also taken into account in the comparison.

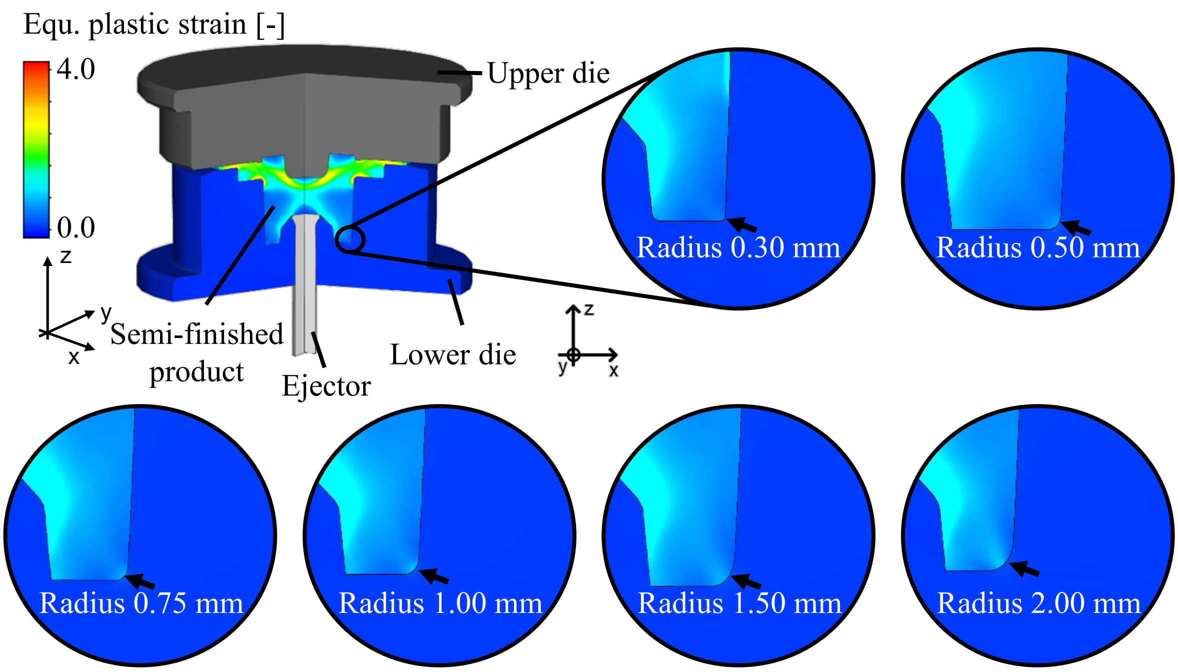

Fig. 1: Overview of the studied variants (equ. = equivalent).

The simulations were evaluated in relation to the equivalent stress and the maximum principal stress. To calculate the loads, a forming process representing the first forging cycle was simulated in each case. For the evaluation of the occurring stresses, the temperature development in the vicinity of the lower radius is also taken into account. In the case of metals, there is a strong temperature dependence of the material parameters, which is why an influence on the occurring stresses can be assumed. Increasing the temperature reduces the mechanical properties and the tools would fail faster under the same load. Accordingly, when comparing the material parameters with the occurring stresses, the consideration of the existing temperatures is of particular importance. By comparing the data, a statement can be made about the probability of crack formation and plastic deformation.

Procedure of the temperature investigation. In the second section, the procedure for investigating the temperature development in the lower die over 30 cycles is presented. A single geometry, the one with the highest stresses in the lower die, was selected and examined as an example.

When setting the boundary conditions for the simulation, the same parameters are selected for the start in the first cycle as were chosen in the previous investigations on the effects of the radius. The semi-finished product has the same initial temperature (1,250 °C) in every calculated cycle. After each calculated cycle, both the thermal and the mechanical load on the bottom die are transferred to the simulation of the next cycle, so that the temperature evolution on the die can be tracked.

When investigating the temperature development, the cooling effect of the cooling lubricant was abstracted by two different variants, without implementing an active cooling process in the abstraction. This means that the otherwise active cooling by means of cooling lubricant is transferred within the simulation into a cooling process without actively influencing the tool cooling. On the one hand, cooling with a small abstracted cooling effect and, on the other hand, with a high abstracted cooling effect between the strokes are simulated. From this, a conclusion can be drawn about the influence of the cooling effect on the temperature development. To compare the results, four measuring points (MP1 to MP4) were defined based on the first cycle to determine the resulting temperature in the lower die (Fig. 2). The measuring points are oriented in such a way that they represent both the temperature in the lower radius (MP1 to MP3) and the one further inside the die (MP4). The distance of MP4 from the surface is 5.00 mm. A total of 30 cycles with the abstracted cooling were examined and the temperatures before and after cooling were analysed. 30 cycles were chosen because a constant temperature range has already been established at this point. The measurement time before cooling means that the temperature was determined at the end of the forming process. Afterwards, the temperature after the abstracted cooling was evaluated so that the influence of the cooling could be analysed.

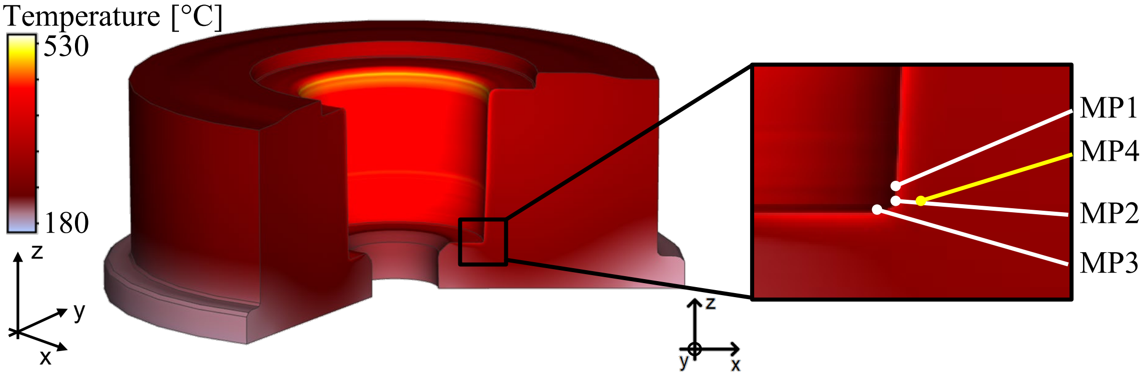

Fig. 2: Temperature distribution after the 30th cycle before cooling at 100 % stroke (left) and positioning of the measuring points within the lower die (right).

Key Findings

In order to be able to make a statement about the influence of the radius on the stresses, the data from the stress calculations are dealt with first. For this reason, the results of 100 % stroke are shown. Moreover, the most advantageous variant is selected and then the temperature evolution in this lower die over the 30 cycles is presented.

Development of stresses in the lower die. The lower die experiences a thermo-mechanical load, which is why the choice of the correct radius is of particular importance. Since a suitable service life of the lower die is desired for the investigation of cyclic crack detection, the stresses should not be too low. In order to be able to put the results of the stresses into the right context, the temperature development in the lower die must first be considered (Fig. 3). Here, the area of the radius is considered in particular. The results show that in the lower area there is no significant temperature difference between the radii. For all radii, the temperature is about 350 °C with a radius of 0.3 mm and 400 °C with a radius of 2.0 mm. Due to an increase in temperature with increasing diameter, it can be assumed that there is a higher heat input due to a larger contact area in the radius.

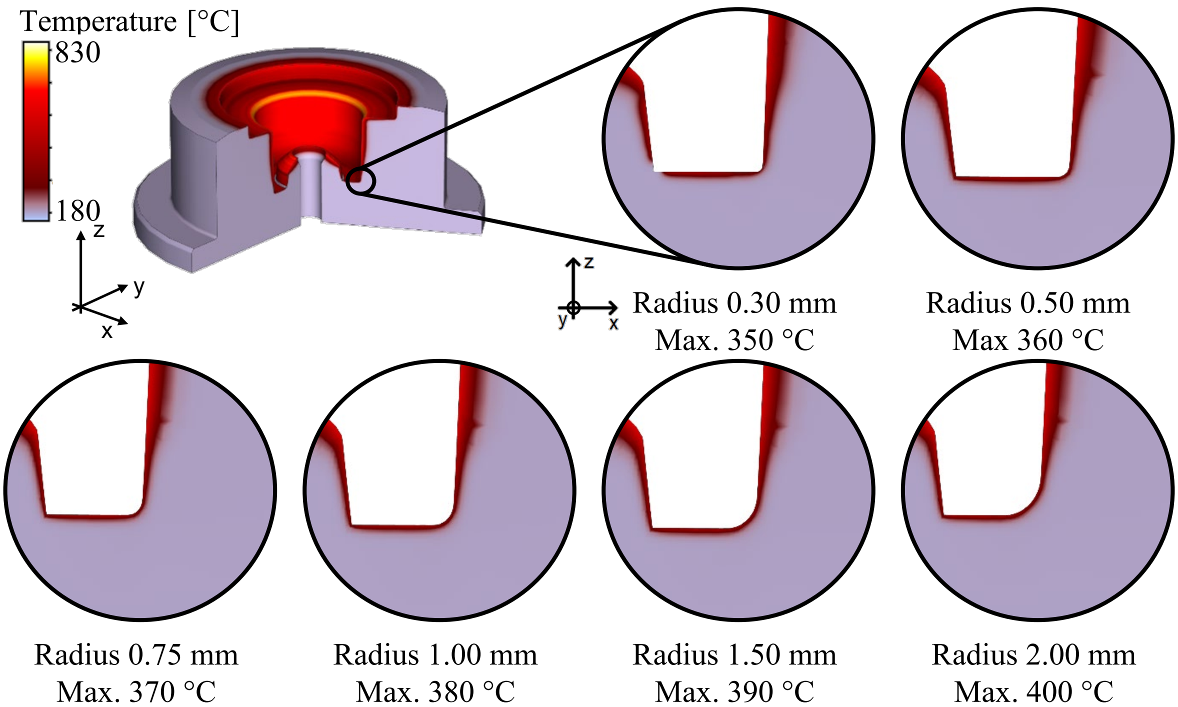

Fig. 3: Overview of the temperature development in the lower radius for the different dies.

In Fig. 4, it can be seen that the maximum values are limited to the area of the radius. Thus, the maximum is between 560 MPa to 650 MPa depending on the radius size. Furthermore, it can be seen that the smallest radius selected, 0.3 mm, has the highest value regarding the equivalent stress of 650 MPa. As the radius increases, the equivalent stress decreases to 560 MPa at a radius of 2.00 mm. It can also be seen that the area of the maximum value is smaller with a smaller radius. As the radius increases, this area becomes larger because the load is also applied over a larger area. In addition, the notch effect also decreases as the radius increases.

At 400 °C, the yield strength for tool steel 1.2367 is 1,100 MPa and the tensile strength is 1,300 MPa (calculated with JMatPro). If lower temperatures occur in the region under consideration, this has no negative influence on the service life of the die in the radius. The yield strength at 400 °C can be compared with the equivalent stress in the range at the different radii. It is noticeable that the equivalent stress is below the yield strength. Accordingly, it can be assumed that no plastic deformation will occur in the area under consideration within the first cycle.

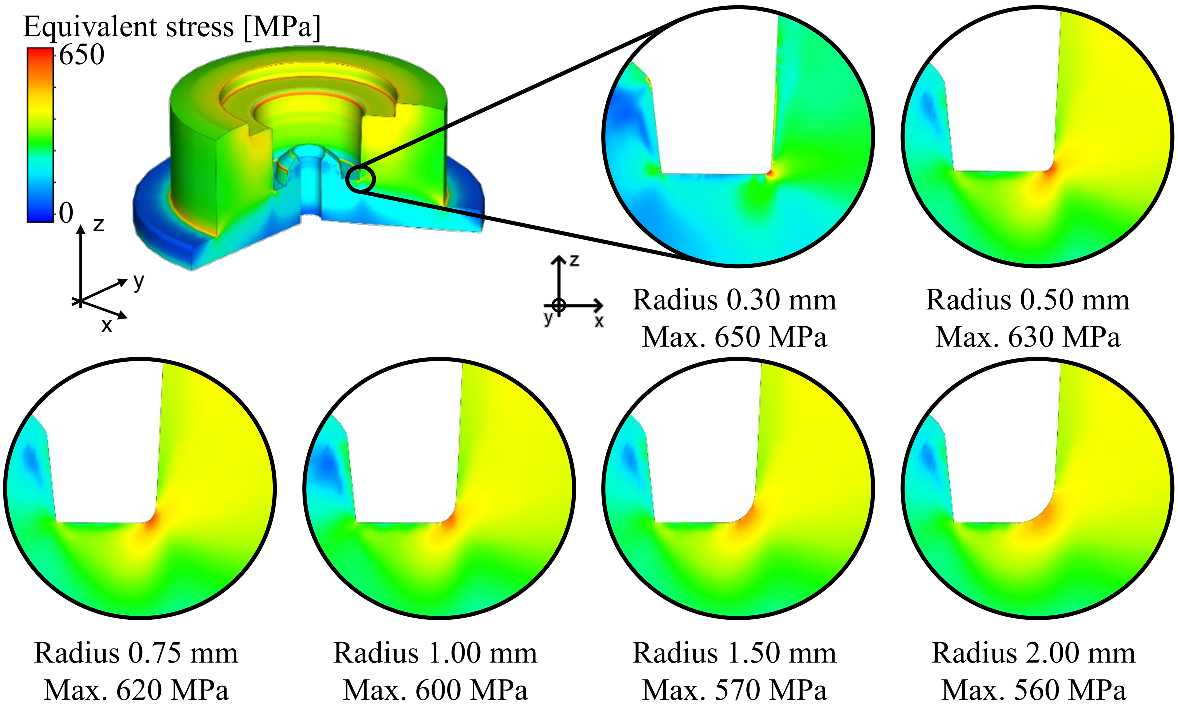

Fig. 4: Overview of the equivalent stress with the maximum values in the lower radius for the different dies.

Comparing the positive maximum principal stress at the different radii, a decrease of the maximum value from 480 MPa at a radius of 0.30 mm to 350 MPa at a radius of 2.00 mm can be seen (Fig. 5). All dies have the same orientation in the stress profile. In addition, a downward and slightly lateral orientation can be seen in all of them. The area of the maximum values increases as the radius increases. In addition, the positive maximum value for all variants is in the lower radius, which was to be expected due to the shape of the die. The focus is mainly on the positive maximum principal stresses, as these represent the tensile load in the die. If the tensile load is too high, cracks can develop, which then lead to failure. In the area of the lower radius, the strongest force acts outwards, creating the tensile load. The selected tool material 1.2367 has a tensile strength of 1,300 MPa at 400 °C (calculated with JMatPro). In comparison with the occurring positive maximum principal stress, it can be seen that the tensile strength is above the calculated stress. This means that there will be no failure due to cracking within the cycle under consideration.

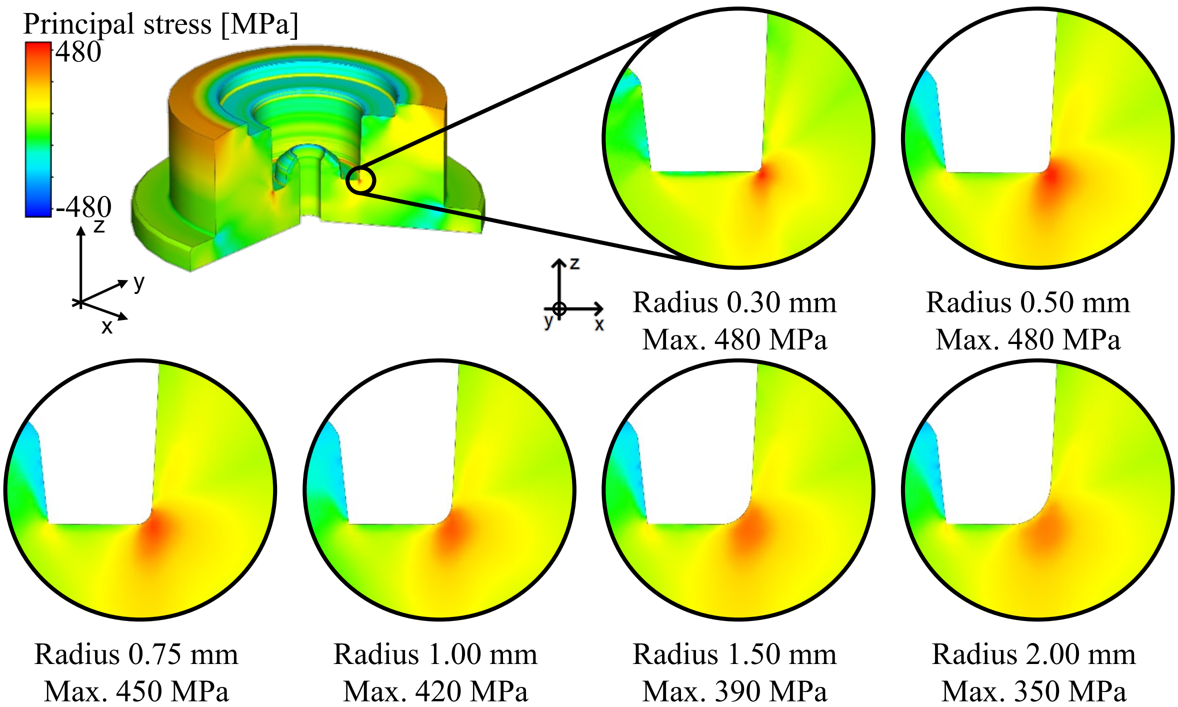

Fig. 5: Overview of the principal stress with the maximum values for the different dies.

If all results are summarised, the expected tendency in the stresses can be clearly seen. Despite the stress peak in the area of the lower radius, the material characteristic values of yield strength (1,100 MPa) and tensile strength (1,300 MPa) are not exceeded in comparison with the equivalent stress (max. 650 MPa) and the maximum principal stress (max. 480 MPa). This means that no plastic deformation and no crack will occur in the considered cycle based on the given material properties.

It is possible to use the distribution of the stress type (tension-compression) to recognise how the load acts on the radius. By compressing the semi-finished product, a force acts radially outwards on the upward-extending wall of the bottom die. This creates an expanding force on the lower radius and a tensile force on the radius. This mode of action does not depend on the selected radius and leads to a cyclical tensile alternating stress. This type of load creates cyclic cracks in the die, which are the target of this research.

Temperature development over the number of cycles. The temperature development in the lower die was simulated with two different abstracted cooling scenarios for the lower die with a radius of 0.3 mm. When comparing the results, it is noticeable that the tendency is the same for both variants. The temperature at four measuring points at the end of the forming path and at the end of the cooling is considered. The tool temperature after cooling with a short cooling effect reaches a constant temperature range after approximately 16 cycles (Fig. 6, top). Over the cycles there is first a high rise up to 250 °C before it settles down to a base temperature of 230 °C after cooling. The temperature at 100 % stroke behaves similarly, even though greater fluctuations in the results can be seen. The only difference lies in the height of the temperature (about 350 °C).

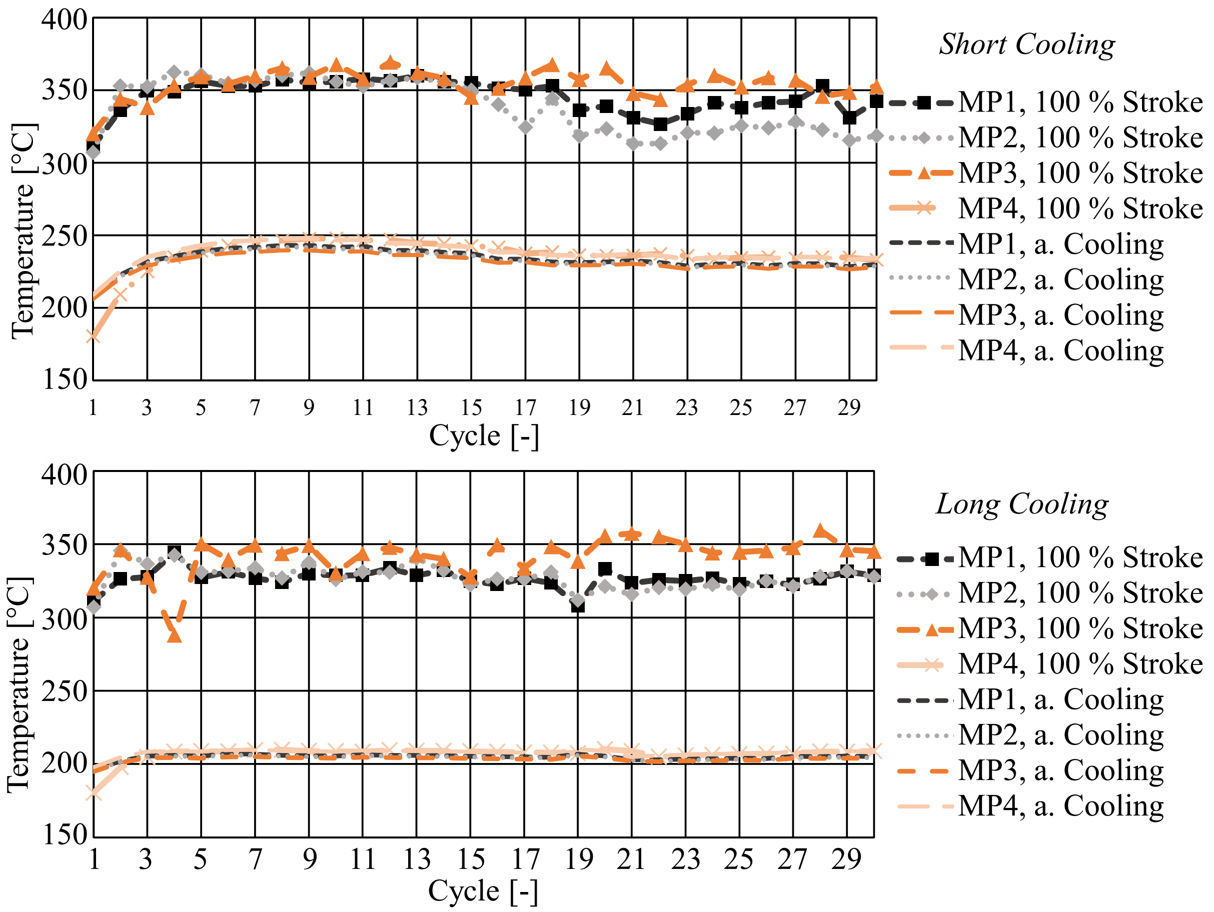

Fig. 6: Temperature development over the cycles with short cooling (top) and with long cooling (bottom).

In the simulations for the higher cooling effect (Fig. 6, bottom), the temperature in the die could be reduced further to about 210 °C. The temperature settles at an earlier point, namely after about five to eight cycles. As with the other cooling effect, the temperature inside the lower die (MP4) hardly changes before and after cooling.

The comparison of the temperature development shows a high dependency between base temperature and cooling effect. Accordingly, it is important in the further course of the project which intensity of cooling lubrication is chosen. If a cooling lubrication is chosen that lowers the temperature too much, the thermal load is also reduced. This is disadvantageous for a service life model that is based on cyclical thermomechanical stresses, as is planned in the rest of the research project. Furthermore, it can be seen that the highest temperature differences are in the surface area of the lower die. The difference between base and peak temperatures is approximately the same for both cooling effects considered. Accordingly, a cooling lubrication should be used that does not strongly reduce the base temperature. This allows higher peak temperatures to be reached within the process, which leads to a higher thermal load in the die.

Conclusion and Outlook

Based on the investigations of the stresses and the temperatures in the lower die with different radii, the following can be stated. It is important to consider the selected geometric shape in relation to the influence of temperature development. In addition, an influence can be seen in the stresses that arise at different radii. It has been shown that a larger radius leads to lower stresses in the lower die, which is also already known from the literature.

The geometry chosen here is suitable for investigating crack initiation due to thermo-cyclic loading, since failure can be specifically induced in the lower radius. By targeting the crack initiation, subsequent investigation and installation of measuring equipment during the experimental test, for example, to record the temperature development in the lower die, is facilitated. The chosen simplifications related to the reduction of the simulation time by using non-heat conducting components saved resources. It was possible to prove in advance that this simplification has only a minimal influence on the semi-finished product and not on the lower die investigated here. Overall, it can be concluded that the starting temperature or the selected radius has a greater influence on the resulting stresses. In addition, this investigation has identified a highly stressed die that will withstand the first cycle. This will be validated in further researches.

The results from the stress calculations and the temperature development are used for the design of a suitable lower die for the experimental forging tests to follow. Although failure due to crack initiation of the lower die is aimed for, this is not to take place in the first cycle. Instead, a service life of 500 to 1,000 parts should be available, which allows a good analysis of the crack initiation. The mechanism of time- and temperature-dependent crack growth is to be used as a basis for the accurate prediction of the service life. A further basis for this is to be an extended time- and temperature-dependent plasticity model for the tool steel used here, with an overall mechanism-based approach describing the softening.

By simulating the temperature development via the number of cycles, it can be stated that this process does not need many cycles for the temperature to run in a steady state. For later simulations or experiments, this means the following: In the experiments, the temperature in the die can be recorded within the first 30 to 50 cycles in order to determine the basic temperature in the die. This depends on the starting temperature of the die and the cooling strategy used. Furthermore, process parameters such as semi-finished product temperature, process time and geometry are important. By determining the temperature in the first 30 to 50 cycles, the simulation can be more accurately specified based on measurements from experiments. Further calculations can then be carried out with the basic temperature that is then set, so that the calculated loads correspond to the steady state in serial forging tests. Furthermore, the base temperature in the die can be further reduced by a greater cooling effect during cooling lubrication. This should be avoided in the context of this research question, as a too strong reduction of the peak temperature reduces the thermal load. Since the thermal load on the die is important for the upcoming experimental tests and for setting up the targeted service life model, this must be taken into account.

Based on these results, the variant with the smallest radius can be recommended as the preferred die. This ensures that failure does not occur within the first load cycle. Nevertheless, the thermal and mechanical load is in a range that suggests a failure due to cyclic loading. Accordingly, the next step is to fabricate the dies and validate the simulations through experimental forging tests. At the same time, a service life model is built together with a plasticity model that describes the cyclic softening of the tool material and, based on this, calculates the crack initiation.

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