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Design of a forging process to individually examine thermal, mechanical and tribological stress in the tool surface zone

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Abstract. The surface layer of hot forging tools undergoes local microstructural changes due to high thermo-mechanical and tribological loads. Tools made of hot working steel are usually pre-heated and experience extreme heating and cooling during each forging cycle, affecting their local wear behaviour significantly. Therefore, the analysis of these tool surface layers in die forging and their effect on wear behaviour is of great importance. The microstructural changes in the tool surface layer mainly depend on thermal loads, which are highly influenced by the tool cooling system. A process and a suitable tool system are developed to vary the thermal and mechanical loads on the tool surface layer and fundamentally examine the resulting microstructural changes.

Introduction

Tools in hot forging are exposed to high process related loads and stresses, for which a distinction can be made between thermal, mechanical, tribological and chemical loads. Thermal loads result from thermal expansion due to the increased base tool temperature. Additional thermal loads come from the frequent alternations between the rapid heating of the tool surface area during forming and the rapid cooling due to the relatively cold base material underneath. This is further increased by the cooling of the tools. The mechanical loads result from the forces on the tool during forging. Combined with the relative movement between the tool and the deforming work piece, these lead to tribological stress [1]. All of these loads can cause permanent damage to the tool surface area and ultimately lead to tool failure. The main reason for tool failure is predominantly the wear of the contours [2]. The loss of strength of the material in the tool surface layer is caused by the thermal loads and results in wear. During forging, peak temperatures in the thermally highly stressed tool areas exceed the tempering temperature of the tool material, thus softening the tool surface layer [3].

During forging the heated work piece is placed in the engraving, forged, taken out of the engraving, and subsequently cooled through convection and radiation by spraying the coolant and lubricant into the engraving. The temperature rises to its peak value during contact of the up to 1250 °C hot work piece and the tool with heat being transferred from the first into the latter. Following the forming process, there is a considerable drop of temperature in the engraving surface. The tool starts cooling with the warm work piece still in the die. Due to thermal conduction, the heat flows into the colder base material below the heated zone and thus reduces the contact temperature in the surface. After removing the work piece, the temperature of the engraving surface drops due to radiation and convection. Finally, the cooling lubricant is sprayed into the engraving which cools the tools below base temperature and thus exposes them to additional thermal stress. A considerable amount of heat is extracted from the tool by evaporation of the lubricant. As a result of the spraying process, the temperature in the tool surface area drops below the base tool temperature. Afterwards, the temperature of the engraving surface once again reaches the set base tool temperature and the next work cycle begins (Fig. 1, left) [4]. The base tool temperature can mainly be adjusted by the billet temperature, the amount coolant applied, the overall length of a forging cycles and the tool pre-heating.

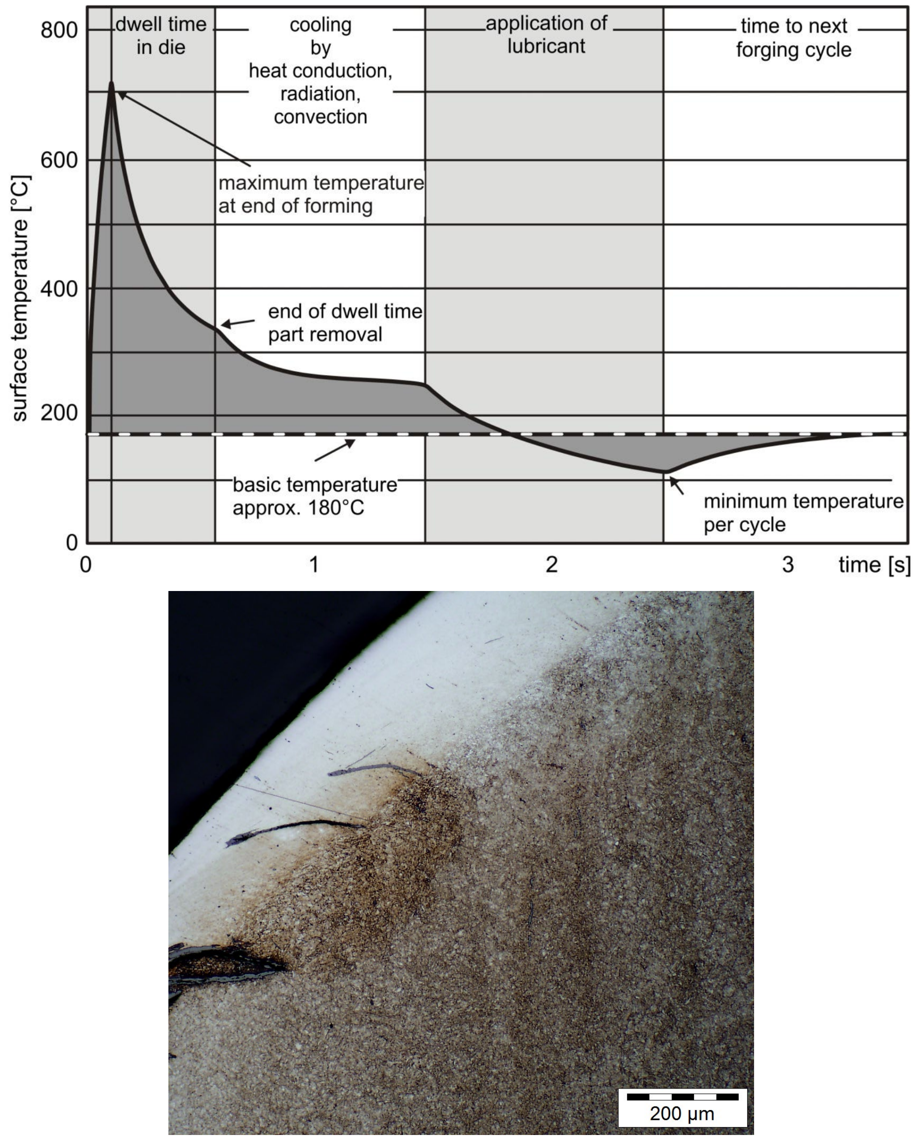


Fig. 1. Tool surface temperature during forging [4] and a tool surface layer with a white, rehardened zone.

The peak temperature in the tool surface area during a forging cycle depends mostly on the temperature of the work piece and the base tool temperature. The great differences between the work piece and base tool temperature lead to a high temperature increase in the tool surface layer during each forging cycle [4]. In metallographic analysis, rehardened tool surface layers often appear as white layers (Fig. 1, right). They form when the tool surface area is exposed to high temperature gradients exceeding the austenite start temperature in combination with cooling above the critical speed [5]. The effects of rehardened zones on the tool wear is controversially discussed in literature. Rehardened zones are often seen as component damage [6]. Some studies compare the rehardening of the tool surface layer as a heat treatment that strengthens the tool surface area [7] and refer to the potential of the special wear resistance when exposed to abrasive stress [8]. Due to engraving areas with convex radii being predominantly at risk of wear, structural changes in these tool edge areas have a decisive influence on the wear behaviour.

Separation of Lubricant and Cooling

To analyse the tool surface layer behaviour under different thermal conditions during forging, the tool cooling needs to be varied. In industrial forging, the lubrication is usually carried by the coolant. When applying a conventional water-graphite suspension to the tool surface area, the heat is dissipated by the evaporation of the water from the thermally sprayed tool areas and the friction conditions on the tool surface are improved by the remaining graphite. Since the cooling lubricant for the spray unit is usually premixed to ensure stable operation, a targeted control of the cooling by specifying a certain amount of water per area and time is not possible.

In order to enable targeted control of the cooling process, the cooling lubrication process has to be separated according to its functions into two independent processes, cooling and lubrication. Therefore, the cooling is carried out by an air-water mixture, which is applied to the tool surface via a spraying system by Gerlieva. The control unit of the supply system can be used to specifically regulate air-water spray parameters such as pressure and duration. The regulation of the spray parameters is to take place in such a way that different base tool temperatures are achieved. Next, the lubrication process is designed. Due to the functional separation of cooling and lubrication, the possibility of conventional lubrication, e.g. by means of a water-graphite suspension, is no longer applicable. For lubrication, the technology of electrostatic powder application is used with powdered boron nitride as the lubricant. Studies have shown that this type of lubricant application can significantly reduce tool wear [9]. Lubrication is applied by a powder coating system by ITW / GEMA Oberflächentechnik. Due to the functional separation of cooling and lubrication, the application is carried out in two stages. Cooling is stage I and lubrication stage II. The lubrication process is controlled by regulating the applied voltage potential, as well as the disperse duration and pressure.

Material Characterization

Steels of different strength are formed to determine the influence of the mechanical load on the tool surface layer. The yield strength of the materials have a direct influence on the mechanical stress on the tool, which in turn influences the transformation behaviour of the material in the tool surface layer. The AFP (Precipitation hardening ferritic-pearlitic) steel 38MnVS6 is selected due to its high-alloy content (Table 1). Because of this, comparatively high flow stresses at high temperatures and thus high mechanical loads on the tools during hot forming when compared to the low alloyed steel C45 are expected. The last mentioned steel is also picked for this study to represent a common forging steel with the option of heat treatment.

Table 1. Chemical composition of the materials under consideration according to the manufacturer's specifications (wt. %).

	C	Si	Mn	P	Cr	Mo	V	N
38MnVS6	0.34 – 0.41	0.15 – 0.80	1.20 – 1.60	0.025	< 0.3	< 0.08	0.08 – 0.2	0.01 – 0.02
C45	0.45	0.25	0.65	-	-	0.020 – 0.035	-	-
X37CrMoV5-1	0.41	0.97	0.32		4.77	1.30	0.46	

For a realistic numerical representation of the mechanical material behaviour of the steels, flow curves of both forging steels are needed at different strain rates and temperatures to calculate the loads on the tool during forging. Flow-curves are recorded through uni-axial cylinder compression tests, which are carried out at constant deformation rates of 0.1, 10 and 50 s^{-1} at process-relevant temperatures of 700°C, 1,000°C and 1,200°C. Tests are performed in the forming simulator

Gleeble 3800 GTC by DSi. The sample temperature is set by using controlled conductive heating controlled by type K thermocouples. To ensure statistical validation, at least three test repetitions are carried out. Based on the force-displacement curves obtained, the effective flow stress k_f is determined as a function of the equivalent plastic strain ϕ, the rate of deformation $\dot{\phi}$ and the forming temperature T. After the experiments, the flow curves are fitted and extrapolated using the Hensel-Spittel 1 model [10] for 38MnVs6 following methods already presented in detail in [11]:

$$k_f = A \cdot \varphi^{m_1} \cdot \dot{\varphi}^{m_2} \cdot \varphi^{-m_3/T} \cdot e^{m_4/\varphi} \tag{1}$$

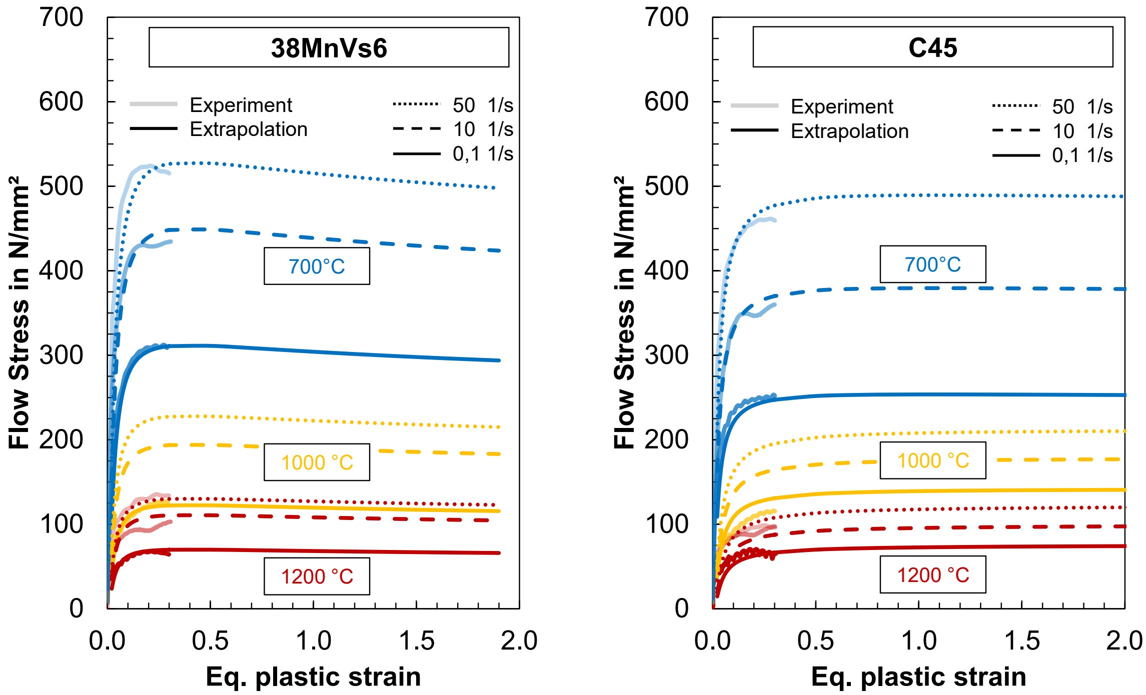
A = 2550, m1 = - 0.0028, m2 = - 0.076, m3 = 0.1 and m4= - 0.03

For C45 the GMT Model [15] was applied:

$$k_f = c_1 e^{c_2 T} \cdot \varphi^{n_1 + T n_2} \cdot e^{\frac{l_1 T + l_2}{\varphi}} \cdot \dot{\varphi}^{m_1 T + m_2} \tag{2}$$

$C_1 = 3600$, $C_2 = - 0.038$, $n_1 = 0.000044$, $n_2 = - 0.05$, $l_1 = - 0.00003$, $l_2 = - 0.0006$, $m_1 = - 0.00009$ and $m_2 = - 0.02$

The resulting flow curves are displayed in Fig. 2. The thicker drawn lines represent the mean experimentally measured flow curve, while the thinner lines represent the corresponding calculated curve from the fitted extrapolation model. As displayed, the flow resistance of 38MnVs6 steel is 10-20% higher, depending on the forming conditions. In the higher temperature range, a more pronounced strengthening of 38MnVs6 as a function of the strain rate is noticeable.



(a) (b)

Fig. 2. Recorded and extrapolated flow curves for the steels 38MnVs6 (a) and C45 (b).

Additionally, in order to be able to assess in the context of a numerical load study whether the tool can withstand the mechanical load during forging, the yield strength of the used tool steel

X37CrMoV5-1 (case hardness: 48+2 HRC) is also determined using uni-axial compression tests carried out with the Gleeble 3800 GTC forming simulatior at temperatures of up to 800°C. The yield strength $R_{p0,2}$ of the tool steel X37CrMoV5-1 is noted in Table 2 for different temperatures and determined according to the method presented in [13]. It becomes clear that a high strength is maintained at a temperature of up to 400°C. Stepping up to a temperature of 800°C, which can be reached in the tool surface layer [4], shows a strong decrease in the tool yield strength. Especially at this temperature, the expected risk of plastic deformation increases based on the measured yield strengths.

Table 2. Recorded yield strength $R_{p0,2}$ of X37CrMoV5-1 at process relevant temperatures.

	20 °C	**200 °C**	**400 °C**	**800 °C**
X37CrMoV5-1	1888 MPa	1703 MPa	1512 MPa	409 MPa

Tool Design

A rotationally symmetrical tool system, which experiences high thermal loads in the surface area during forging, is selected for easy adjustment of the thermal loads. The dies are to be made of hot working tool steel X37CrMoV5-1 (case hardened to 48+2 HRC). The geometry of the upper die has engravings, where locally different loads occur during forging (Fig. 3, left). In previous research results, it was shown that these tools display the essential structural changes and the associated wear due to abrasion and plastic deformation, which mainly occurs on the convex tool radius. Besides high surface pressures, a high thermal load is to be expected at these points due to the relatively long time of contact and the deep penetration of the tool into the work piece. To characterize the cooling behaviour, the tool temperature during forging is analysed. The temperature development of the near-surface edge areas is recorded by using thermocouples (TC) inserted into the tool. The recording takes place continuously over the entire forging process during the heating and cooling phases. Encapsulated Type K thermocouple with a 1.5 mm diameter are selected for which 1.6 mm diameter holes are integrated into the tools. The TC wiring is to exit the tools to the sides (Fig. 3, right). Thermal paste is used to increase the heat transfer and decrease reaction time between the tool and the TC.

Numerical Investigation of the Die Load

In order to enable a realistic prediction of the die load, an FE model of the forging process is set up using the FE application *simufact.forming 16*. Due to the complex tool geometry with six channels for the TC, a complete 3D model is necessary to theoretically derive a sink load in each channel (Fig. 3, right).

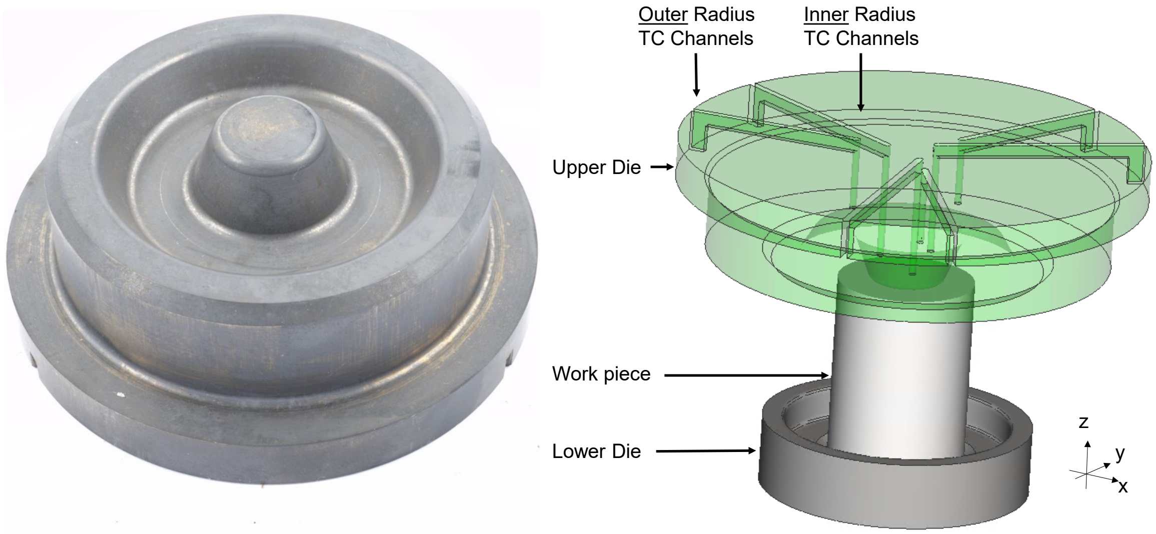


Fig. 3. Upper forging die (left) and CAD-view of the 3D-FE calculation model showing the Initial design of the upper die with channels for thermocouples (right).

For this purpose, the upper die is modelled fully thermo-mechanically coupled, while the lower die is set as an analytically rigid body. To reliably assess the tool stability, the most extreme parameter set is mapped in the process model, at which the highest thermo-mechanical load is expected. These are at a base tool temperature of 400°C, a work piece temperature of 1200°C, a friction factor of m = 0.6 and the material data set of the steel 38MnVs6. With these parameters, the stationary state during series forging is represented in the FE simulation. For a later evaluation of the temperature-time history, the return stroke and the subsequent cooling phase are taken into account in addition to the actual forming step. The influence of the spray cooling is taken into account by applying corresponding heat transfer coefficients, which were previously determined experimentally in [11].

To evaluate the numerical results regarding the thermo-mechanical loading, a sectional plane of the tool with the TC channels closest to the surface is shown in this study. In the following illustrations, the TC channels are also highlighted with a black or white outline for better visibility.

Fig. 4 shows the calculated temperature distribution at the end of the forming process before the removal of the part and spray cooling for the mentioned parameter set. This shows that a peak temperature of approximately 900 °C is reached in the mandrel radius of the die engraving. Based on this, a re-hardening of the tool surface layer can be expected after cooling. Furthermore, the heat-affected zone does not reach the tips of the channels during the forming process, which can be seen as advantageous for the structural die stability. However, this circumstance prevents the measurement from being able to resolve the direct surface heating caused by the work piece contact.

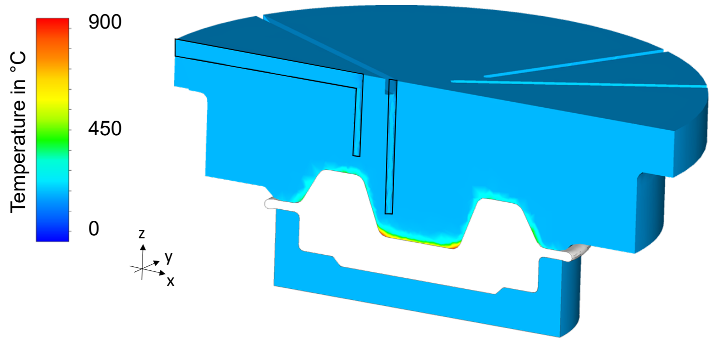


Fig. 4. Temperature distribution in the upper die at the end of forming.

For the evaluation of a possible crack risk, the common main normal stress hypothesis according to Rankine is applied, which can be used as a first assessment criterion for brittle fracture materials, such as the hardened tool steel used here [14]. In order to make crack-critical areas directly visible, only the 1st principal stress (tensile stresses) exceeding the experimentally determined yield strength at 400 °C is visualised in Fig. 5.

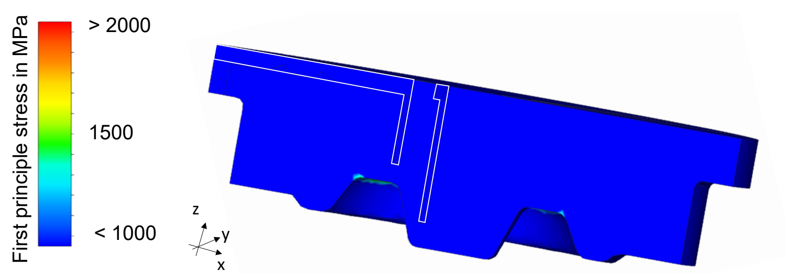


Fig. 5. First principle stress distribution on the upper die limited to the critical value range.

This allows for a clear assessment, that the areas around the TC channels are not under significant tensile load and thus uncritical with regard to a possible risk of cracking. Only in the area of the inner radii of the engraving slight cracking can be expected, which is also known from previous studies with this die geometry [7].

For the estimation of plastic deformation, the yield criterion according to von Mises is applied to compare the flow stress in the die with the experimentally determined values for the yield strength. It must be taken into account that the die load increases exponentially towards the end of the forming process. Thus, the von Mises comparative stress at three different stages of the forming stroke, characterised by the respective burr thickness subsequently measurable on the component, is shown in the following Fig. 6.

These different stroke lengths in respect to the burr thickness are chosen starting from the stroke at which a complete filling (burr thickness = 2.4 mm, Fig. 6, a) is achieved. Fig. 6, c) clearly shows that a critical condition is reached, when a burr thickness of 1.6 mm is formed, as the equivalent stress in the centre of the die exceeds the experimentally determined yield point at 400°C. In relation to the TC channels, an unwanted deformation of the channel walls would most likely occur at this stage of forming as well. Reducing the forming stroke length results in a reduction of the burr thickness to 2.0 mm (Fig. 6, b), with the burr being less strongly formed radially. By reducing the forming stroke, the loads on the tool decrease, as less material has to be displaced into the decreasing burr gap. At this stroke setting the von Mises stress does not exceed the given yield strength so there is a significantly reduced risk of deformation. Keeping in mind that the chosen

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process parameters for this stability estimation represent the most extreme case, for further forging experiments, this forming stroke length will be used for experimental forging tests.

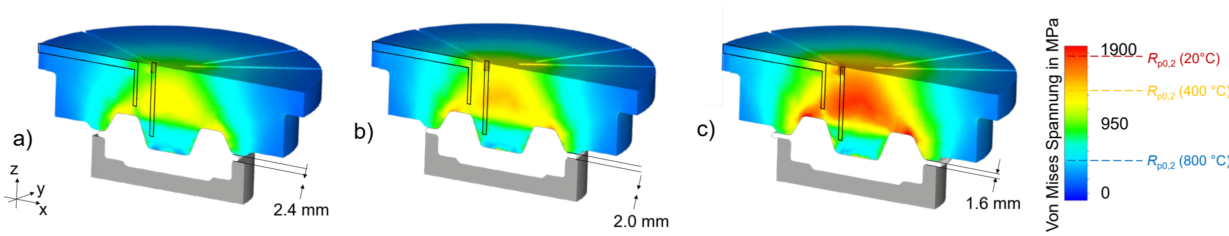

Fig. 6. Distribution of von Mises stress in the die at different stroke lengths.

Regarding the general die design, however, it became clear that the outer radius TC channel tips are located directly in a mechanical loaded area. This implies that the heath thermocouples used in the process are also subjected to mechanical stress. Since these cannot be represented and analysed within the framework of the FE analysis, it can be concluded from the results shown that damage to the measuring tip might not be completely ruled out. There is therefore a risk that no valid data can be recorded in the process without any recognisable signs of damage being visible from the outside resulting in invalid data. Furthermore, the simulation shows that the position of the TC channels is not close enough to the surface zone to record its heating phase. With this application, the temperature measurement can however be used to reliably validate the base tool temperature in the mandrel area. With regard to these two findings, it is concluded that the outer TC channels offer no added value and can therefore be assessed as an unnecessary risk. These channels are therefore removed in the following design update and the demonstration tools are manufactured accordingly (Fig. 7).

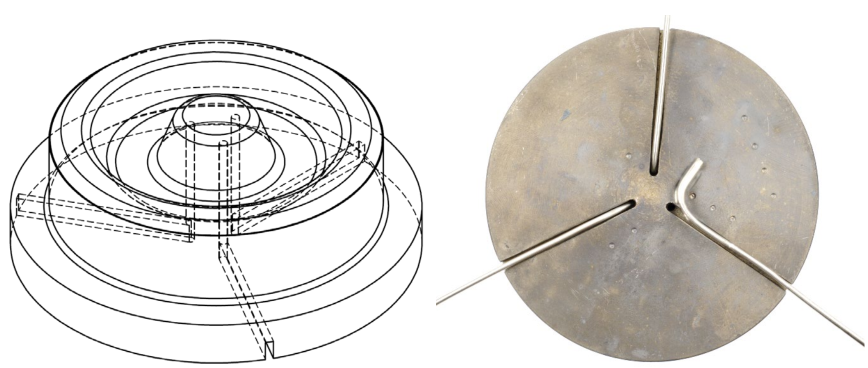

Fig. 7. Updated die Design for thermally loaded tool with channels for three mantled thermocouples.

A tool equipped with TC is then stressed in forging tests. The tool is pre-heated to 200°C. Cylindrical work pieces made of steel C45 are used with a diameter of 30 mm and a height of 40 mm. The billets are heated to 1200°C and forged with a forging cycle time of 8 s. Between each forging cycle, boron nitride powder is applied for lubrication and water is sprayed for cooling. Fig. 8 shows the comparison of the measured temperature curve with the numerically determined one during a forging cycle for a tool base temperature of 200°C. Here a characteristic deviation is recognizable, as the temperatures in the simulation are evaluated directly on the bottom of the channel wall, while in reality there is an additional heat transition from the channel wall to the mantle thermocouple. This reduces the measurement dynamics that can be achieved in reality and consequently shifts the measured temperature curve to lower and time-delayed values. In practice, this deviation has no relevant influence on the validity of the die stress simulation carried out. In fact, the example of an excerpt from the recorded temperature-time curve shows that it was possible to achieve highly reproducible process execution.

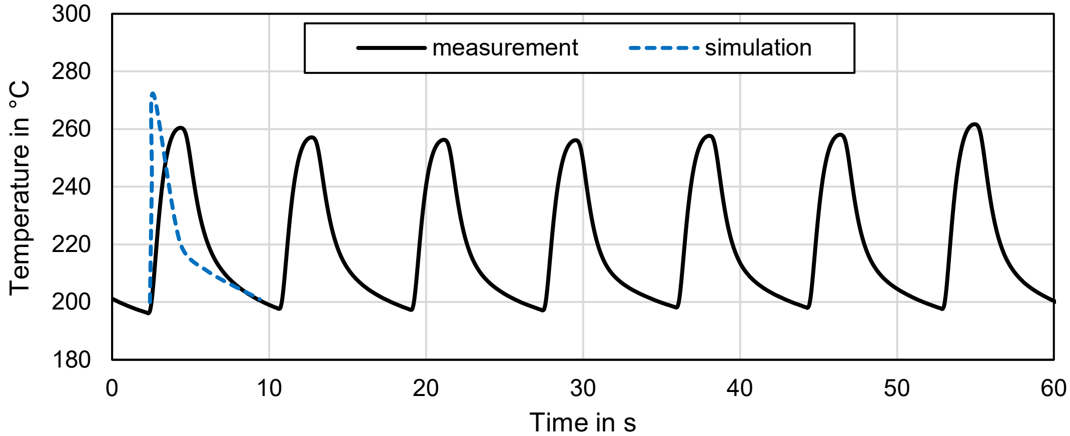

Fig. 8. Temperature measurement at the tool mandrel.

Summary

The main objective was to develop a process to investigate microstructural changes in the surface zones of hot forging dies under varying cooling conditions, as well as varying tribological and mechanical loads. A primarily thermally loaded tool system was investigated and equipped with multiple internal TC at predetermined positions for better regulation of the tool temperature. To ensure structural stability of the tool system, the thermo-mechanical loads on the die were calculated using a FE-model. The mechanical stresses on the dies will be altered by varying the forging steels of different flow resistance. The necessary material data regarding the mechanical behaviour was obtained by uniaxial compression tests using the forming simulator Gleeble 3800 GTC. To investigate the influence of thermal and tribological loading on the microstructure in the surface zone, cooling and lubrication strategies were developed, achieving different stationary die temperatures. Here, the separation of lubrication and cooling functions replaced the conventional lubrication with a water-graphite suspension by using boron nitride powder for lubrication and a water-air-combination for cooling. With these methods, temperature measurements at a short distance from the surface can be carried out and monitored during forging. During forging tests it was shown that for a base temperature of 200°C the peak temperature values after each forging cycle are consistently ranging around 260°C. Taking into account the aforementioned dynamic losses of the thermocouple measurement, this corresponds to an actual measured value of approximately 270°C at the selected measuring point.

Acknowledgements

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