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Analysis of tool heating in cold forging using thin-film sensors

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Abstract. Data acquisition and data analysis to gain a better process understanding are one of the most promising trends in manufacturing technology. Especially in cold forging processes, data acquisition close to the deformation zone seems challenging due to the high surface pressure. Thus far, process parameters such as die temperature are mainly measured with state-of-the-art sensors, including standard thermocouples, which are integrated into the tooling system. The application of thin-film sensors has been tested in hot forging processes for local die temperature measurement. However, the process conditions regarding tribology and tool load in cold forging are even more difficult. In this contribution, the use of thin-film sensors, applied on a cold forging punch for cup backward extrusion, is subjected. The aim is to investigate the applicability of such thin-film sensors in cold forging with special emphasis on temperature measurement in cyclic forming processes. The thin-film sensor system and its manufacturing procedure by vacuum coating technology combined with microstructuring are described. With these thin-film sensors the cup backward cold extrusion of steel billets was investigated experimentally. Cyclic tool heating simulations with thermal parameter variations were performed as a reference to experimental results.

Introduction

Cold forging has a long and established history and is still one of the most cost- and energy-efficient technologies to produce metallic components on a large scale for fasteners industry and automotive drive train systems. Besides the high process productivity and the low energy consumption, the parts show increased yield strength as a consequence of strain hardening during cold forming. Scientific process investigations in cold forging technology are usually conducted under stationary conditions, neglecting effects such as cyclic tool heating, which is inevitably a part of industrial processes. Process instabilities can cause scrap and may lead to unplanned downtimes of the whole process. In recent times, process digitization and process monitoring became one of the most promising trends in manufacturing technology to identify such process instabilities [1]. One decisive parameter for both dimension of the forged component and the tribological system of the process is the thermal condition of the tooling system. Especially during

transient ramp-up phase, temperature may increase a lot. To study the influence of tool heating on part dimensions, correct model boundaries are most important for a good prediction.
Fundamental investigations on elastic tool deformation considering both thermal expansion and mechanical compression were presented by Kuzman [2], who found a linear correlation between the normal pressure applied on a punch and its compression under different thermal conditions. The higher the temperature, the more the thermal expansion compensates the elastic compression of the punch due to mechanical loads. Numerical studies on die heating during process ramp-up in cold forging were shown by Qin et al. [3]. Tool heating was investigated with special emphasis on the characterization of ramp-up duration, until the die temperature reaches a steady state. Müller et al. [4] first investigated thoroughly the effect of temperature increase on friction conditions. In sliding friction tests could be shown, that a temperature increase ($\Delta T = 125$ K) during process ramp-up yields in friction coefficient decrease of up to 45 % for several lubricants such as molybdenum disulphide, polymer and soap. Furthermore, adhesion can be one limiting parameter under certain tribological loads and temperatures. Thus, it is important to be aware of the resulting temperature during the forming process close to the deformation zone - or even better, in the interface between tool and workpiece.

For the measurement of process data in the interface between two bodies, the use of thin-film sensors has been studied for different applications in manufacturing engineering [5]. A thin layer of a certain material featuring specific properties is applied on a surface layer, that insulates the sensory layer from the substrate material. Materials such as chromium are used to create thin-film sensors with a specific shape to allow measurement of the electrical resistance during changing external loads. Such sensors have been successfully applied in machining processes for temperature measurement of cutting inserts right on the rake face [6] as well as in grinding processes [7]. Novel application methods for the thin-film layer were studied in [8] and [9]. The application of thin-film thermocouples in surface textures of carbide tools was investigated in [10]. First applications in metal forming technology were shown in [11], where thin-film sensors were applied on hot forging tools to measure the die temperature in the interface between tool and workpiece during deformation. The wear resistance of the sensors, however, was limited.
In this publication, a first application example of thin-film sensors for temperature measurement on a punch surface in cup backward cold extrusion of steel cans is subjected. Especially the high tribological loads regarding normal pressure, sliding velocity, surface expansion and temperature prevailing in cold forging seem challenging for the application of such sensor systems. Wireless data acquisition is tested to gain real-time data during the experiments using an amplifier and data acquisition unit mounted to the press. The results show, that punch temperature profiles could be recorded, using the thin-film sensor system. Cyclic process simulations, considering the forming process itself, the ejection process and transfer time were performed using QForm UK 10.2.2 software. Parameter variations in cyclic simulations showed the main influencing factors during the die heating process within 250 forming cycles.

Experimental Setup and Process Simulation

System description.
For the investigation of the developed thin-film sensors in cold forging technology, a lab-scale cup backward extrusion process, consisting of a mechanical knuckle-joint press and a data acquisition system, was set up (see Fig. 1). The cup backward extrusion punch was chosen for the application of the thin-film sensors. An embedded system was connected to the press for data acquisition and transfer to a processing system via Bluetooth Low Energy (BLE). The thin-film layer system was designed according to the tribological loads applied to the tool surface, such as normal pressure, relative velocity, temperature and surface expansion, which were gained by numerical simulation. Data visualization and analysis was maintained by a data processing unit.

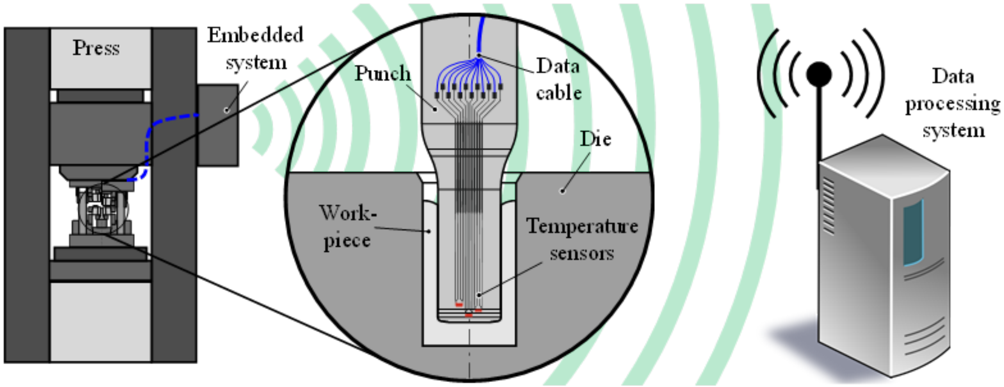


Fig. 1. Procedure for temperature measurement with thin-film sensors and data acquisition.

Thin-film sensor system.

The thin-film sensor system subjected here could be directly applied to the surface of a forging tool and consisted of three different functional layers. These layers were applied to the polished surface of the punch by means of physical vapor deposition (PVD) and plasma-enhanced chemical vapor deposition (PECVD) process. To realize sufficient electrical insulation in the required temperature range between the tool and the sensor structures, an aluminum oxide layer (Al_2O_3) was homogeneously deposited with a thickness of approx. 5 µm. An electrically conductive chromium layer with a thickness of 0.2 µm was chosen for the sensor layer. Due to the positive temperature coefficient (PTC) of chromium, the material was suitable as a temperature sensor, since an increasing temperature led to an increase in electrical resistance. The structuring of the metallic layer was achieved by a combination of photolithography and chemical wet etching. As shown in Fig. 2 a), a final layer of amorphous hydrogenated carbon (SICON®) was applied on top of the structured sensor layer for electrical insulation and wear resistance.

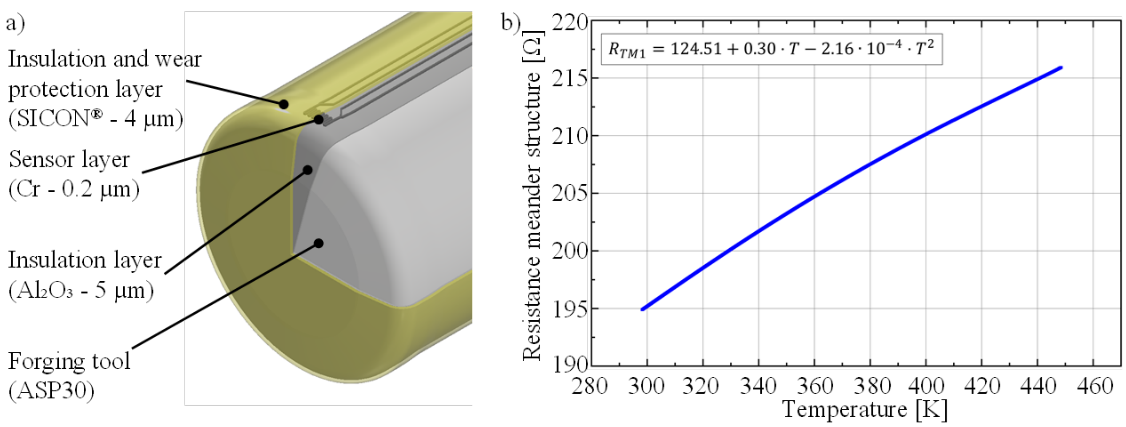


Fig. 2. a) Thin-film sensor on cold forging punch, b) temperature-resistance characterization.

The temperature sensors were conceived in a meandric design that enables a high spatial resolution of the measurement while keeping the sensor resistance in an optimal range for the measurement system. Due to the low resistance of the conductor paths, 4-wire sensing was used, enabling resistance measurements without an influence of the leads. To determine the characteristic curve for each sensor, the thermoresistive behavior was analyzed. For that purpose, the punch was heated up to 180°C in a furnace and cooled down to ambient temperature. A Pt100 reference sensor was positioned on the surface close to the sensor structure. As shown in Fig. 2 b), the dependence between resistance and temperature is approximately linear. To achieve higher accuracy, the measured values were fitted with a quadratic function.

Data acquisition system.

An embedded data acquisition unit was developed to collect the temperature data directly within the press in close distance to the sensory punch to suppress noise. The system is depicted in Fig. 3 a) featuring the sensory punch itself (1), the acquisition unit (2) and the data processing system (3).

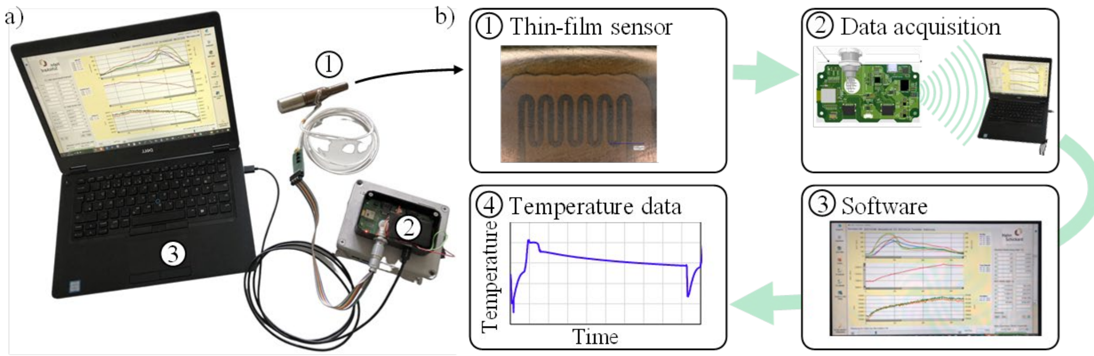


Fig. 3. a) Embedded data acquisition unit and b) process flow for temperature measurement.

The data acquisition process is shown in Fig. 3 b). A variation of the measured physical quantity, here punch temperature, led to a variation of the electrical resistance of the meandric thin-film sensor structure, which was measured by the data acquisition unit. This was achieved by sourcing a known current through the sensor and measuring the voltage drop across the sensor. To compensate the voltage drop over the wires, the sensor was connected with four wires. The known current in the range of 2 mA was flowing through two of them. The 4-point measurement method was used for the punch temperature sensor, as the sensor resistance was in the range of about 230 **Ω**. The main board included the power management unit, the USB- and BLE-interface for data exchange and the direct interface to the thin-film sensor via the analog frontend. To guarantee a good radio transmission, a polymer case surrounded the main board. Texas Instruments ADS131 analog to digital converter (ADC) was used within the embedded system. In the first stage, the embedded system sent raw digital data to a graphical user interface (GUI) running on a personal computer. The data was processed outside the embedded system. The digital value was transformed to the sensor resistance using the following Eq. 1.

$$R_{Sensor} = \frac{ADC_{value}}{ADC_{max}} \frac{U_{ref}}{I_{Sensor}} \tag{1}$$

where U_{ref} is the reference voltage of the ADC, I_{Sensor} is the known current trough the sensor, ADC_{value} is the measured ADC-Value of the ADC and ADC_{max} is the maximal ADC value of the ADC. Then, using the calibration curve of the sensor in Fig. 2 b), the resistance was transformed into the temperature signal.

Investigation of Tool Heating

Experimental investigations.

Cyclic tool heating was investigated experimentally based on an automated cold forging process. For the experiments, steel billets from DIN C15 (AISI 1015) were prepared by cropping and upsetting ($d = 22.2$ mm, $l = 22.1$ mm). A usual lubrication system, consisting of a phosphate conversion layer with soap lubricant (5 g/m^2) was applied to the billets. The cyclic cold forging experiments were performed on a mechanical knuckle joint press MAY MKN2-600/14 ($F_{max} = 6{,}000$ kN), equipped with a gripper automation system featuring 6.5 strokes per minute, see Fig. 4 a. Process subjected here was cup backward extrusion. The billet and a cross section of the cold extruded cup are shown in Fig. 4 b).

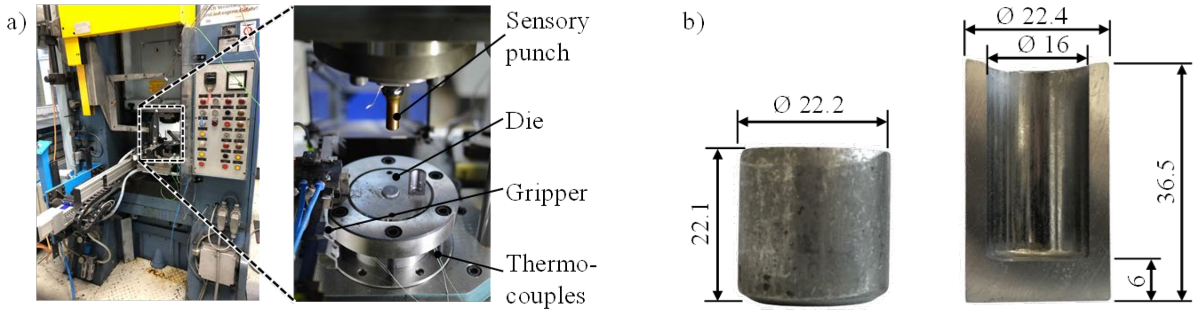
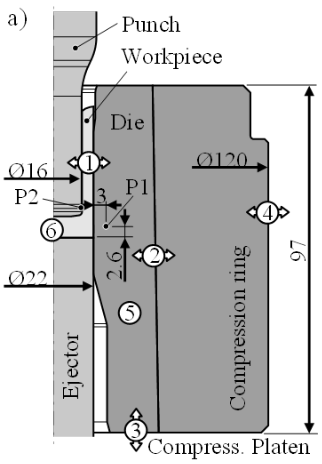


Fig. 4. Experimental setup for temperature measurement in punch and die during cyclic cold forging a) press and tool set, b) workpiece.

The average strain for this process was $\varepsilon_A = (d_a^2\text{-}d_i^2)/d_a^2 = 0.48$. During the experiments, process data such as ram stroke and punch load were recorded. As a central part of the investigation, thermal conditions of both die and punch were measured. For the application of thermocouples inside the forming die, a deep hole ($d = 0.9$ mm, $l/d = 50$) was manufactured by electrical discharge machining. The position and depth of the hole were chosen in such a way, that its ground was close to the inside die surface and close to the deformation zone during cup backward extrusion. The punch temperature acquisition was performed using the thin-film sensor and equipment described in 2.3 according to Fig. 2. The cyclic forging experiment was started at ambient temperature (28°C). A maximum of up to 250 cycles in one batch was performed with an average cycle time of 9.25 s.

Numerical investigations.

Punch diameter $d = 16$ mm was used to simulate the forming process of cups with an outer diameter $D = 22.4$ mm. Initial billet height was $h_0 = 22.1$ mm and final bottom height $h_1 = 6$ mm (see Fig. 4 b). Finite element code QForm UK 10.2.2 was used to create an axisymmetric process model with a plastic workpiece and rigid tools. Initial workpiece temperature was set to $T = 28$ °C and mixed friction model with a friction factor $m = 0.12$ and a friction coefficient $\mu = 0.05$ was used for contact definition between workpiece and tools. Decisive for the tool heating simulation were the heat transfer coefficients applied to the interface between the objects (see Fig. 5), such as heat transfer between workpiece and tools (including punch, ejector and die), heat transfer between die and compression ring / compression plates as well as heat transfer between die and environment, considering heat convection. Regarding the material properties, literature values for conductivity and heat capacity of M2 tool steel and AISI 1015 workpiece material were used. A full factorial design of experiments was set up for parameter identification according to the upper and lower limits depicted in Fig. 5. All parameter combinations were performed for 250 forming cycles. For analysis of the most suitable parameter combination, the temperature profiles of simulation variants and experiment were compared. The maximum temperature T_{max}, minimum temperature T_{min} and mean temperature $T_{mean} = (T_{max}+T_{min})/2$ were calculated for each cycle as shown in Fig. 5 b). For the simulated 250 forming cycles, an average value of the deviations in minimum, maximum and mean temperature between experiment and simulations was calculated for identification of the most suitable parameter set within the last third of the subjected number of strokes.



Heat transfer $\left[\frac{W}{m^2 \cdot K}\right]$	Basic value	Lower limit	Upper limit
① Tools ↔ Workpiece	15.000	5.000	30.000
② Die ↔ Compress.ring	6.000	3.000	10.000
③ Die ↔ Platen	500	200	1.000
④ Die ↔ Environment	30	30	30

Material properties	Conductivity	H. capacity
⑤ Die (M2)	$24 \frac{W}{m \cdot K}$	$420 \frac{J}{kg \cdot K}$
⑥ Workpiece (AISI 1015)	$55 \frac{W}{m \cdot K}$	$492 \frac{J}{kg \cdot K}$

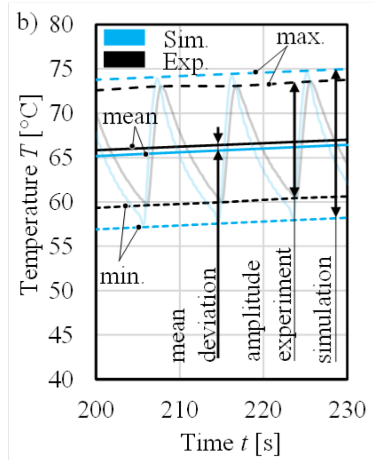


Fig. 5. a) Simulation model for cyclic tool heating, b) analysis of heating curves.

Flow stress data for C15 steel was gained from compression tests at the Institute for Metal Forming Technology at the University of Stuttgart. The characterization tests were conducted on a thermomechanical testing system Gleeble 3800 C in a temperature range of 20°C ≤ T ≤ 200°C with strain rates of 0.1 $s^{-1} \leq \dot{\varphi} \leq 10\ s^{-1}$. Die and punch temperature were analyzed in the same area as measured by the thermocouples and the temperature meander, respectively (see Fig. 5 a). Using the cyclic heating simulation module in QForm UK 10.2.2, the whole process chain, consisting of forming operation, return stroke, ejection and transfer time, was modeled to gain representative results for thermal analysis. Mean cycle time in experiments was 9.25 s with a deviation of ± 0.6 %.

Results and Discussion

Experimental results.

The experimental investigations showed, that the embedded system and the wireless communication with the data processing system allowed to record the process data with a sampling rate of 60 Hz. For the punch temperature measurement, a maximum of 22 forming cycles were performed and for the die temperature measurement, 250 cycles were investigated. First surface scratches of the punch coating layer were detected in the area of the punch land after 22 cycles. The sensory structure considered here was not damaged, as it was located in the relief area of the punch. The experimental results for die heating (thermocouple at point P1, see Fig. 5 a) and punch heating (meander structure at point P2) are depicted in Fig. 6 for the second forming cycle of a continuous experiment. During forming process (1→2) with a duration of 1 s, heat was transferred to the tools and resulted in a die temperature increase. Due to the elastic compression of the punch, the measured resistance and thus the calculated temperature decreased in the first 0.2 s of the forming process. Possible reason for that behavior is a temporarily short-circuit between the sensory chromium layer and the punch substrate or the workpiece due to insufficient insulation under combined thermal and mechanical loads. As the heat transfer to the punch increased and the punch load decreased towards the end of the forming process, the calculated punch temperature significantly increased and reached its maximum. Elastic deformation of the workpiece as a consequence of residual stresses led to frictional heat and frictional forces during retraction of punch (2→3). This is why die temperature increased further, where the calculated punch temperature decreased due to the resulting axial and radial loads. During ejection process (3→4) and transfer time, both die and punch temperature decreased due to heat transfer to the surrounding objects and heat convection to the environment. For further analysis of the experimental punch heating profile, the areas with a significant influence of mechanical loads on the measured resistance and temperature profile respectively, were neglected. Assuming, that the thin-film sensor measured the temperature without force influence only right after retraction of punch (2→3), a simplified linear segment between (A) and (B), as depicted in Fig. 6 a), was inserted. Due to the neglected thermal influence between (2→3), the temperature at point B was assumed as a lower bound estimation of the maximum cycle temperature.

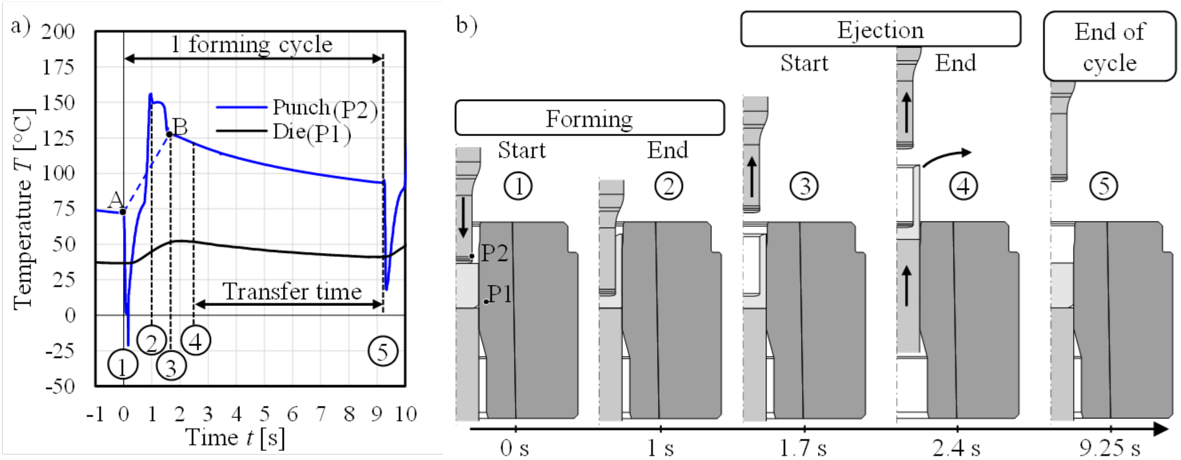


Fig. 6. a) Experimental tool heating profiles for one cycle; b) referring cold forging process.

The temperature profile for one forming cycle in Fig. 6 a) was extracted from a cyclic forming experiment depicted in Fig. 7. The diagram shows both punch and die heating during the first 22 forming cycles of the cold forging process. The punch temperature profile was simplified as described above by neglecting the influence of elastic punch deformation. Minimum, maximum and mean values of die and punch temperature profile were calculated as described in Fig. 5 b). Comparing the profiles after 22 strokes, the mean value of punch temperature is around 2.6 times higher than die temperature. The measurement position of punch temperature was close to the deformation zone, where frictional heat was generated.

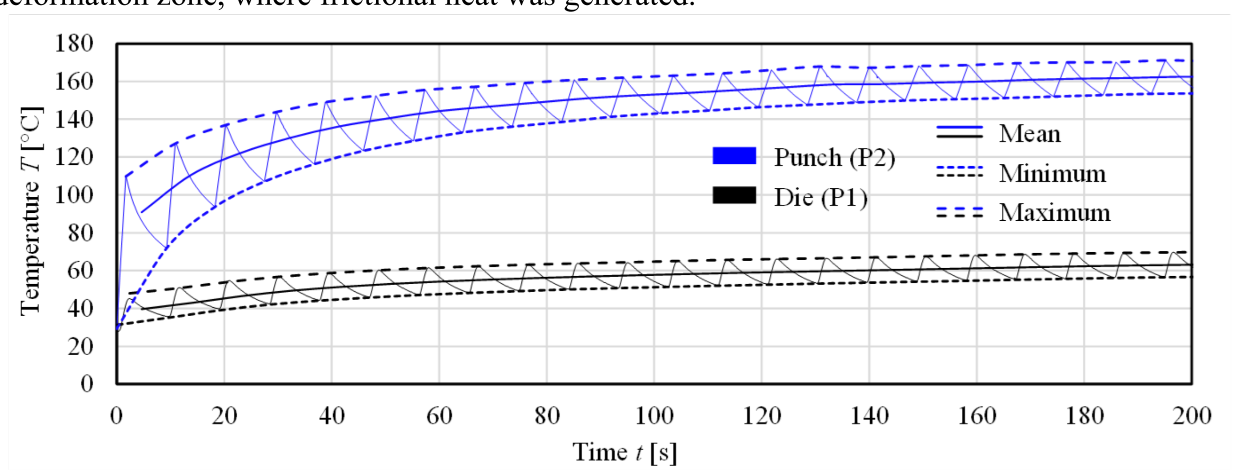


Fig. 7. Comparison of experimental punch and die heating profiles during 22 forming cycles.

While the die temperature amplitude showed a decrease of about 20 % within 22 strokes, the amplitude decrease in punch temperature was about 70 %. Starting from an initial temperature of 28°C, the punch temperature showed a significant increase within the first strokes and a significant decrease during transfer time, where heat convection to the environment was predominant. As the temperature was measured with the thin-film sensor on the punch surface, such effects were even more visible.

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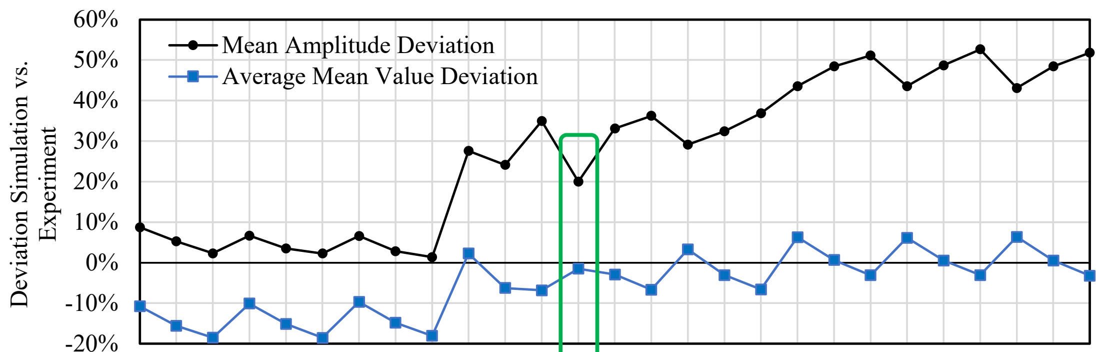
Simulation results.

The fitting between full-factorial numerical parameter variations and experiments was analyzed by means of the die heating profile. For each forming cycle, the difference in mean value and amplitude between simulation and experiment was calculated according to Fig. 5 b). For an overall comparison of the parameter variations, the average of both mean value difference and amplitude difference within the last third of the subjected 250 strokes (no. 166-250) was quantified. Fig. 8 shows the magnitudes of both parameters as relative values, referred to the experimental result, for all 27 parameter sets. The sampling of each parameter set, consisting of heat transfer coefficient between workpiece and tools (parameter 1), between die and compression ring (parameter 2) and between die and compression platen (parameter 3) according to Fig. 5 is given below the diagram. The results show, that parameters 1 and 3 were the most decisive for both mean value and amplitude deviation. An increase of the heat transfer coefficient between tool and workpiece decreased the mean value deviation, but in the same way led to a higher amplitude deviation. An increasing heat transfer between die and compression platens (parameter 3) yielded in decreasing mean values of the heating profiles. The thermal field within the die showed after 50 strokes temperatures in the interface between die and compression ring of about 60°C and in the lower area of the die, close to the compression plate, around 40°C. It can be assumed, that both parameters 2 and 3 showed low effect due to the limited die heating prevailing within 50 forming cycles. With increasing number of strokes, the thermal field propagates in the die, which is why the heat transfer between die and adjacent objects becomes more important as shown in Fig. 8.



Set #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Param. 1	5.000									15.000									30.000								
Param. 2	3.000			6.000			10.000			3.000			6.000			10.000			3.000			6.000			10.000		
Param. 3 $\left[\frac{W}{m \cdot K}\right]$	200	500	1.000	200	500	1.000	200	500	1.000	200	500	1.000	200	500	1.000	200	500	1.000	200	500	1.000	200	500	1.000	200	500	1.000

Fig. 8. Deviation of cyclic die heating profiles between simulation and experiment as mean values for stroke no. 166-250 for a full factorial parameter study with 27 parameter sets.

For best fit between simulation and experimental results within the subjected strokes no. 166-250, the mean value deviation was the most important factor for the correct prediction of the heating profile. Parameter set no. 13, as highlighted in Fig. 8, was the most suitable for describing the experimental heating profile with a little mean value deviation (-1.5 %) in combination with an amplitude deviation of 20 %. The numerical die heating result for parameter set no. 13 is shown in Fig. 9 in comparison with the experimental results.

The simulation profile showed due to the little mean value difference a good agreement with the tendency of the experimental die heating profile, thus the amplitude difference was about 22 %. Parameter set no. 13 was used to track also the punch temperature profile as a reference to the experimental results for 22 forming cycles. The maximum value of the experimental punch heating profile was well represented by the cyclic simulation result, whereas the amplitude was overestimated by two times in simulations. The large deviation in punch heating amplitude may arise from the assumptions described in Fig. 6 a). According to this, higher maximum temperature values of each stroke should appear considering the complex interaction between elastic and thermal deformation of the punch. Furthermore, the punch was modelled as a monolithic body, which does not include the thermal properties of the thin-film layer system on the punch surface.

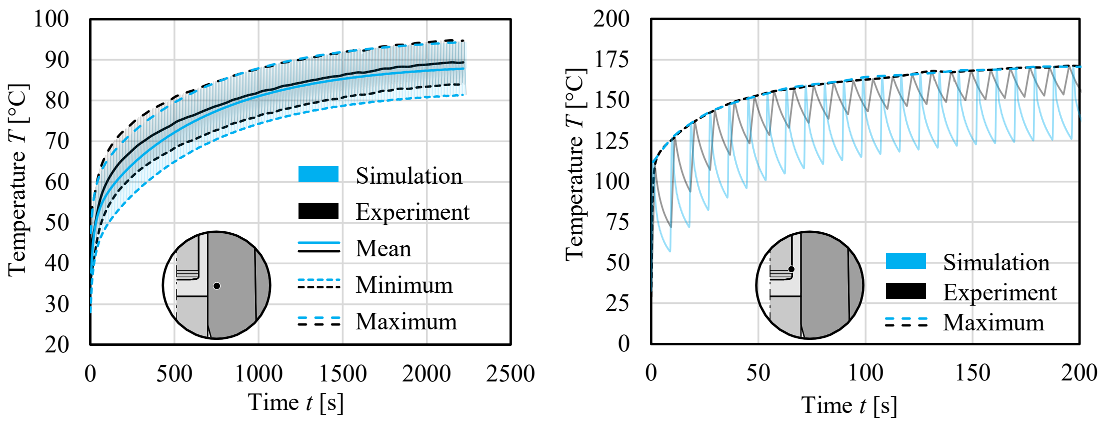


Fig. 9. Comparison of cyclic tool heating in simulation and experiment: a) die, b) punch.

Summary

In this contribution, the application of a thin-film sensor system on a cup backward extrusion punch in cold forging of C15 steel for temperature measurement close to the deformation zone was subjected. Punch heating during cold forging process was analyzed in experiments using the novel sensory structure in combination with the developed data acquisition unit featuring wireless data transfer. For calibration of simulation model, die temperature close to the deformation zone was measured with thermocouples inside the die. Numerical parameter variations were performed to gain suitable heat transfer coefficients for die heating and to use this data for punch heating simulation. The investigations showed, that the application of the thin-film sensor for temperature measurement on a cold forging punch close to the deformation zone is possible considering the prevailing tribological loads during 22 cyclic experiments. The developed embedded system allowed resistance measurement of the applied thin-film meander structure and wireless data transfer via Bluetooth Low Energy, where the actual punch temperature values were calculated based on calibration curves. The thin-film sensors for temperature measurement on the punch surface were due to the physics of the measuring principle force sensitive. A simplified punch temperature profile could be gained by neglecting the area of the process, where the punch was under mechanical load and thus yielded in a lower-bound estimation of the maximum temperature during deformation. The cup backward extrusion process could be modelled using the cyclic tool heating module in QForm UK 10.2.2 considering the whole process chain over a duration of 250 strokes. Parameter variations showed, that the heat transfer coefficients to adjacent objects, such as compression platens underneath the die, become more important for a correct prediction of the heating profile with increasing number of forming cycles. The analysis of mean amplitude deviation and average mean value deviation between measured and simulated die heating profile is a suitable method to find a best-fit parameter set. Using the most suitable parameter set of the die heating investigation also for the punch heating investigation yielded in an underestimation of the measured punch temperature profile, where maximum values were in good agreement.

In future investigations, the calibration of force influence on the measured resistance signal of the thin-film sensor should be considered for a precise estimation of the maximum temperatures during forming process. Furthermore, for both die and punch, more temperature measurement points should be investigated to make proof of the identified heat transfer parameters.

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