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The influence of process parameters and sheet material on the temperature development in the forming zone

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Abstract. Cold metal forming is a fast and economical way of producing a wide range of precise components. Its profitability mainly depends on part quality, process stability, and service intervals of tools. As these factors are all determined by tool wear, detailed process knowledge is indispensable to maximize profitability by minimizing wear. One of the most crucial factors in this context is temperature. During every forming process, a temperature rise occurs between tool and workpiece due to frictional heating and a large part of plastic work dissipating into heat. This phenomenon affects the whole forming process but especially tool wear. Currently, there is little solid information about temperatures occurring during forming operations. Therefore, the temperature was measured based on varying process parameters, sheet materials, and thicknesses in several embossing and blanking examinations. The use of a tool–workpiece thermocouple enabled accurate and instantaneous measurement during the process. The results presented show the strong influence of process and material parameters on temperatures in the forming zone.

Keywords: Temperature / cold forming / tool–workpiece thermocouple

1 Introduction

Cold metal forming and blanking are among the most frequently used mass production processes for sheet metal. To meet increasing requirements concerning part quality, cycle times, and service life, precise process knowledge is essential. During every forming operation, a temperature rise occurs in the workpiece's forming zone. This effect has three causes: first, up to 95% of the plastic work dissipates into heat [1]. Only a small part is stored as dislocations and other lattice defects in the sheet metal [2]. Second, macroscopic friction between contact surfaces, and third, microscopic friction on the atomic level also generates heat [3]. Especially during forming operations with high surface pressures and deformation degrees, such as embossing or blanking, temperatures of several hundred degrees can occur, as shown below. The temperature rise strongly influences the process. Material behavior and tool wear are just two examples [4]. Furthermore, temperature is a decisive factor in the choice of tool coatings and lubricants [5]. Therefore, precise knowledge of the height and profile of the temperature that occurs is indispensable with respect to process parameters.

Several reports have dealt with this topic across various forming and blanking investigations but the determined temperatures differ significantly, even during similar manufacturing processes. Groche et al. calculated maximum temperatures of 36 °C for deep drawing, which is characterized by smaller surface pressures than embossing [6]. Furthermore, when processing aluminum, lower temperatures occur due to the reduced mechanical properties compared to steel. During blanking of steels, authors indicate mostly higher values from 50 °C [7] to 600 °C [8] and even 1000 °C [9]. This discrepancy is mainly due to undefined geometric and temporal resolution of the measurement signal. Demmel was the first to use a tool–workpiece thermocouple during blanking of S355MC. In combination with a punch having undercuts, this method enables an instantaneous measurement of the temperature in situ at the punch edge. They observed a temperature of up to 250 °C for a material thickness of 4 mm and almost 300 °C for 6 mm [10]. The maximum temperature always occurs with the end of clean-cut formation, just before the final separation of the sheet metal. In reference [11], measured temperatures of up to 264 °C for embossing 4 mm carbon steel with a similar tool were observed. They confirmed the significant influence of process parameters on emerging temperatures [12].

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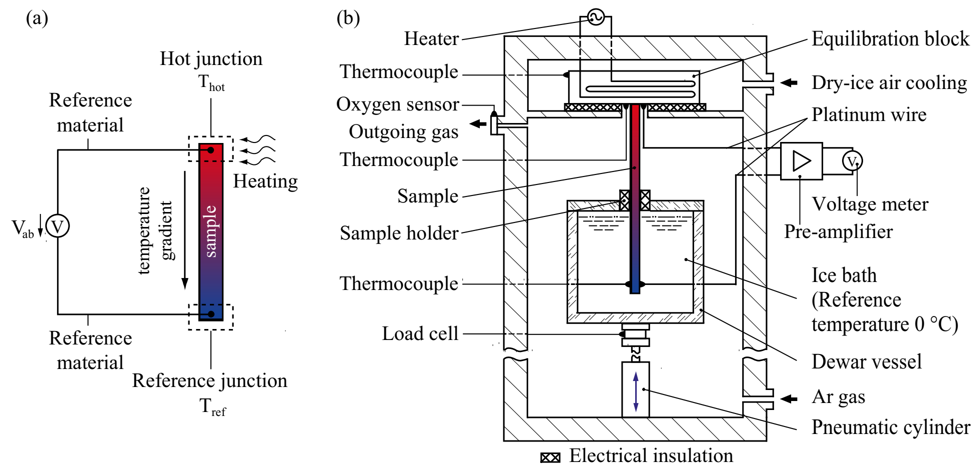


Fig. 1. Schematic diagram of (a) an integral measuring setup for thermocouple calibration and (b) apparatus for measuring relative Seebeck coefficients [13].

Especially the wide range of measured temperatures shows a high research demand concerning this topic. For that reason, a tool–workpiece thermocouple was implemented in a new tool and several embossing examinations under varying process parameters were conducted. Investigations of smaller clearances and faster velocities compared to former examinations have enriched knowledge of temperature and improved understanding of the embossing and blanking process.

2 Experimental setup

2.1 Measuring principle

There are several measurement techniques for determining temperatures but the cramped conditions in a forming tool hamper precise temperature measurement. High surface pressures prevent the use of foil or fine wire thermocouples on punch or sheet metal because of insufficient robustness. Another possibility is the integration of thermocouples in small holes in a punch that weakens the tool. Other methods cannot be used because of limited space. In sum, the challenge is to ensure high-quality measurement that is instantaneous and at a defined location without influencing the process.

Thermoelectric phenomena offer the possibility of transforming tools to temperature sensors. Based on different thermoelectric properties of sheet metal and tool, these materials can form a thermocouple. Thermoelectric voltages always arise if two different electrical conductors are put together at one end that has a different temperature than the other ends (Fig. 1). In this case, the thermoelectric voltage is proportional to the temperature gradient along the conductors. The proportional factor is the Seebeck coefficient, which represents thermoelectric material properties [10].

During cold metal forming or blanking, an electrical contact between punch and sheet metal emerges. The dissipation of conducted plastic forming work and friction between sheet metal and punch result in local heating of the contact area. Subsequently, charge carriers in the conductors reach different energy levels. A thermodiffusion starts. The resulting potential difference changes with the temperature difference between the junctions and can be measured with a voltmeter [13]. As the measurement area is identical to that of heat generation, an instantaneous measurement of the temperature occurring during every kind of forming process can be guaranteed.

2.2 Calibration of the thermocouple

To deduce a temperature from the measured voltage, calibration of the thermocouple is necessary. As the thermoelectric material properties can only be determined experimentally [14], a special measurement device was used. Its basis is the integral measuring method, which requires a defined temperature gradient along the sample. Figure 1a illustrates the electric circuit used for calibration. One end of the sample is heated to a defined temperature T_{hot} with a maximum of 600 °C. The other end is kept at the reference temperature T_{ref} of 0 °C in an ice bath. Both ends are attached to a pure platinum wire, which serves as reference material. Depending on the Seebeck coefficients of sample (S_B) and reference material (S_A), a defined thermoelectric voltage according to equation (1) arises [15]:

$$V_{AB}(T,S) = \int_{T_{\text{ref}}}^{T_{\text{hot}}} (S_B(T) - S_A(T))dT$$
$$= (S_B(T) - S_A(T)) * (T_{\text{hot}} - T_{\text{ref}})[V] \ . \quad (1)$$

This voltage lies within the range of a few millivolts for metals. Therefore, the signal is first amplified and then recorded with a precision voltmeter. Figure 1b shows the implementation of the setup. The sample is pushed against a block of pure copper by a pneumatic cylinder. To ensure a well-defined and reproducible electric contact, the adjustable force is observed with a piezoelectric sensor. Another key factor is temperature. As the calibration quality directly depends on temperature measurement accuracy,

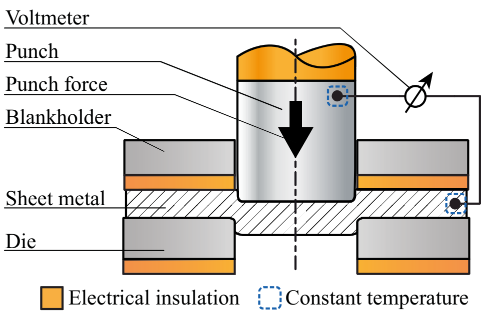


Fig. 2. Schematic drawing of a tool–workpiece thermocouple for temperature measurement during embossing and blanking operations.

Table 1. Chemical composition (elements over 0.1%) of the materials used in weight percent.

1.4301 (2.5 mm)	Si 0.7	Mn 1.3	Cr 19.0	Mo 0.4	Ni 10.8	Cu 0.3	Fe Balance
1.4301 (4 mm)	Si 0.4	Mn 1.7	Cr 18.5	Mo 0.3	Ni 8	Cu 0.4	Fe Balance
CF-H40s				WC 88.0			Co Balance
S355MC		C 0.1			Mn 0.45		Fe Balance

two high-precision thermocouples are placed directly at both junctions. They are small to minimize time delay due to heating. An argon atmosphere prevents measurement errors because of chemical effects at the sample surface and platinum wires. Characterizing both standardized type K thermocouple legs shows a maximum measurement deviation of the measured thermovoltage of 1.5%.

2.3 Tool and press

Figure 2 illustrates the experimental tool that has a four-pillar structure providing high stiffness and the application of smallest cutting clearances down to 25 μm. Due to its modular design, the tool is very variable and suitable for parameter variations. A configurable blankholder force allows analysis of different materials. The punch and sheet metal are electrically insulated from the remaining tool to prevent interfering signals. This is done with application of zirconium oxide on the die, blankholder, and punch (Fig. 2).

The whole tool consists of four stations where both forming and blanking operations can be implemented. A fifth station can be used for cutting sheet metal strips. This enables instantaneous and simultaneous temperature measurement during continuous stroke experiments. The forming forces are measured by piezoelectric load cells in every station and the punch travel by a contact-free eddy current sensor.

For the investigations in this paper, a circular punch with a diameter of 15 mm and a punch edge radius of 50 μm was used. The immersion depth was 4 mm. No lubricant was applied during any test.

The investigation was made on a high-performance stamping press having a maximum press force of 1250 kN and an infinite variable stroke rate between 60 and 600 L/min.

2.4 Investigated materials

To gather information, not only about the influence of process parameters, but also of sheet material and thickness, the following sheet metals were chosen. The austenitic stainless steel 1.4301 (X5CrNi18-10) has a thickness of both 2.5 and 4 mm. A high tensile strength of up to 720 MPa and good corrosion resistance make this material suitable for many applications.

The hot-rolled fine-grained steel S355MC with a thickness of 4 mm is a representative steel for cold forming and blanking operations. Its tensile strength of 491 MPa is about 32% lower compared to 1.4301.

The punch is made of CF-H40s, a powder metallurgical cemented carbide. Its fine grain structure and high homogeneity provides constant thermoelectric properties across the whole punch and thus a high-quality temperature measurement. Its hardness of 1400 HV10 allows use for forming and blanking processes.

Table 1 shows the chemical composition of CF-H40s, S355MC, and 1.4301 in both thicknesses determined by an optical emission spectrometer.

3 Results and discussion

Besides the process parameters forming velocity and die clearance, sheet materials and thicknesses were varied in this investigation to evaluate the respective influence on the emerging temperatures in the forming zone during embossing. As the maximum temperatures occur with the end of clean-cut formation and thus the maximum embossing depth, a complete sheet metal separation is done. This relieves the load on the punch and prevents punch failure. Every experiment was repeated at least three times.

3.1 Temperature profile

The results of the accomplished embossing examinations showed similar characteristic features, which depend primarily on the cutting surface or rather the maximum embossing depth. For that reason, the shown temperature profiles were only for the sheet material 1.4301 with a thickness of 2.5 mm. A die clearance of 1% (0.025 mm), 5% (0.125 mm), and 10% (0.25 mm) as well as a stroke rate of 60, 150, and 300 L/min, which corresponds to an approximate punch impact velocity of 50, 140, and 270 mm/s, was chosen. Figure 3 shows the representative curves of the temperature occurring in the forming zone as related to the punch travel. Negative values stand for a punch travel downward until bottom dead center at 0 mm. In Figure 3a, a 1% die clearance was used. As long as the

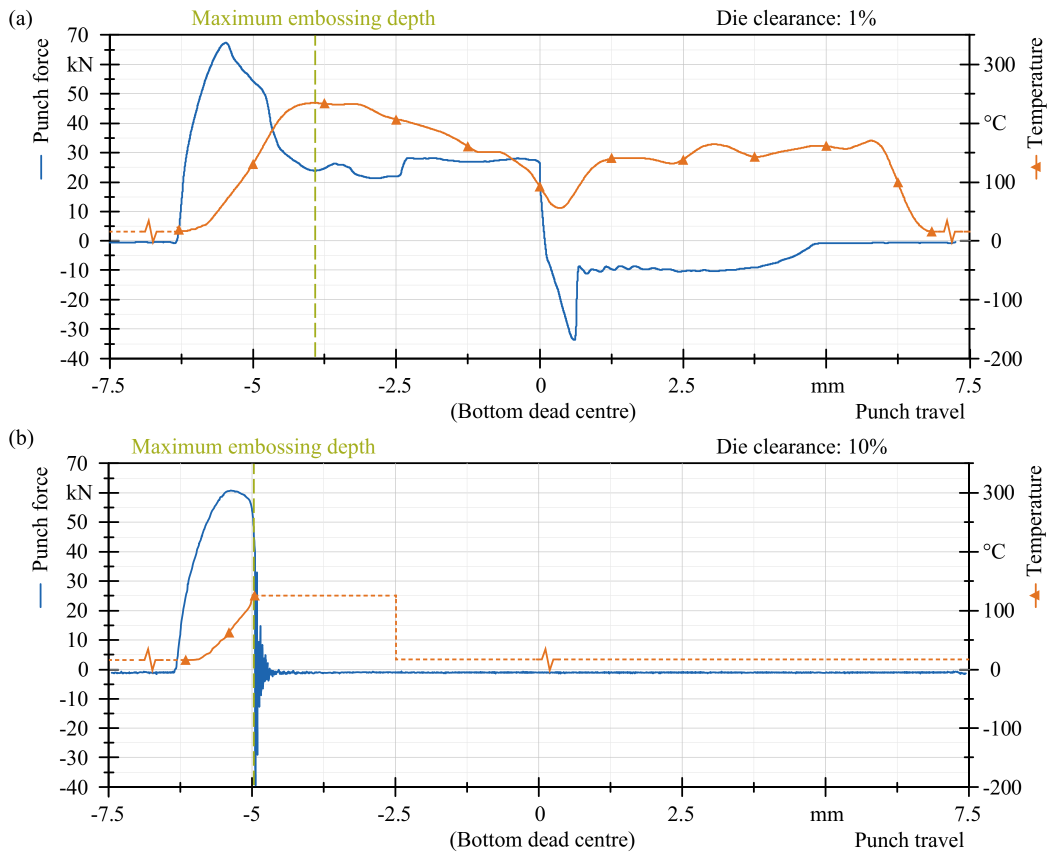
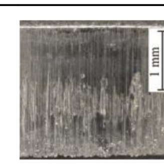
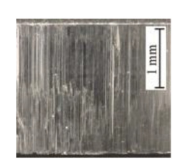
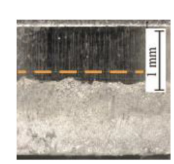


Fig. 3. One representative temperature profile and punch force over the punch travel for a die clearance of (a) 1% and (b) 10% blanked with a punch stroke rate of 300 L/min.

contact between sheet metal and punch remains, slight adjustments in process parameters only lead to changed slopes and higher or lower maximum temperatures. With the contact of punch and sheet metal at −6.34 mm, a thermoelectric voltage emerges and a temperature of 22 °C occurs, which corresponds to room temperature. During elastic deformation at the beginning, a leveling of roughness asperities takes place, which results in a slight temperature rise until −5.90 mm. With the plastic deformation of the sheet metal, the temperature increases faster due to dissipating plastic work. The maximum temperature of 230 °C is reached shortly before the complete separation of the sheet metal at the maximum embossing depth at −3.93 mm. Due to the high embossing depth compared to the sheet metal thickness (Tab. 2) and a large contact area between punch and sheet metal, the temperature briefly remains at the same level. With the end of plastic deformation, the temperature decreases until bottom dead center. The rise to a plateau of the punch force at −2.5 mm is due to the cylindric geometry of the die where the slug from the previous stroke is still clamped. During the return stroke, temperature increases again until a maximum of 171 °C at 5.92 mm. With the disconnection of the electric circuit and thus the loss of contact between punch and sheet metal, no more temperature is measurable. A die clearance of 5% showed almost the same temperature curve as 1% because the achieved cutting surface and the embossing depth is equivalent to the sheet

Table 2. Cutting surfaces and corresponding maximum embossing depth for 1%, 5%, and 10% die clearance.

Die clearance	Maximum embossing depth (MED)	Cutting surface
1%	MED is equal to sheet metal thickness	
5%	MED is equal to sheet metal thicknes	
10%	MED reached at the dashed line	

thickness. Cutting surfaces and corresponding maximum embossing depths are illustrated in Table 2.

Figure 3b shows the representative temperature curve for 10% die clearance, used for very small embossing

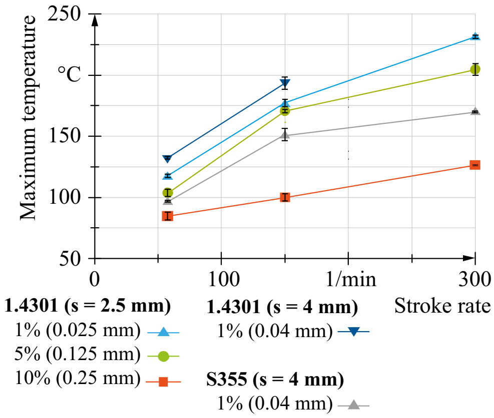


Fig. 4. Maximum temperatures occurring during embossing with clearances of 1%, 5%, and 10% for different materials over stroke rate.

depths. The temperature trend at the beginning shows a comparable increase to smaller die clearances. Its maximum of 126 °C is reached at −5 mm right before the complete separation of the sheet metal. Contrary to smaller die clearances, the maximum embossing depth is not equivalent to the sheet metal thickness. The sudden rupture and the loss of contact results in strong vibrations caused by the release of elastic energy. Due to undefined contact conditions, no temperature can be measured until the end of the progress.

3.2 Influences on the maximum temperature in the forming zone

3.2.1 Die clearance and stroke rate

Figure 4 illustrates the maximum temperatures as a function of the stroke rate for all die clearances and materials investigated. Therein the results of 1.4301 with a thickness of 2.5 mm reflects the influence of process parameters. The temperature trends of 1% and 5% are very similar. Regarding the maximum temperatures, minor differences are ascertainable. For 60 L/min, 1% die clearance reaches 119 °C (SD = 2 °C), which is 14% higher than 5% (104 °C (SD = 6 °C)). In case of 150 L/min, the difference is 7%. At the fastest stroke rate (300 L/min), the smallest die clearance results in a temperature of 230 °C (SD = 3 °C), which corresponds to a 11% increase compared to 5% clearance (208 °C (SD = 6 °C)). This shows that a good choice allows similar embossing depths with a simultaneous reduction of the occurring temperatures, which for example, can positively affect tool wear. A 10% die clearance results in a significantly lower temperature of 84 °C (SD = 6 °C), increasing to 101 °C (SD = 1 °C) in the case of 150 L/min. The maximum temperature measured of 126 °C (SD = 1 °C) occurs at 300 L/min.

There are two different effects explaining the development of the maximum temperatures occurring during embossing. On the one hand, punch velocity has a great influence on the thermal conduction. The faster the forming velocity, the lesser the time for heat equalization. This results in higher temperatures in the forming zone. Varying die clearances have different consequences. First of all, smaller clearances enable higher deformation degrees of the sheet metal for which more plastic work must be conducted. This is in accordance with increasing blanking work for decreasing clearances [16]. As a result, more work dissipates into heat and higher temperatures occur. This effect is strengthened by the changing size of the forming zone. A higher clearance entails a larger forming zone in the sheet metal. Consequently, plastic work dissipates in a smaller area, which results in higher temperatures.

3.2.2 Sheet metal thickness

The sheet metal thickness has a significant influence on the maximum temperature in the forming zone. Earlier investigations were examined in the field of blanking with different thicknesses but the same die clearance. Therefore, the relative die clearance that is related to the sheet thickness is different. The sole influence of the sheet thickness embossed with the same relative die clearance has not been investigated yet. Figure 4 illustrates the maximum temperatures of 1.4301 with 2.5 and 4 mm thickness, both embossed with a relative die clearance of 1%. At a stroke rate of 60 L/min, a thickness of 2.5 mm leads to a maximum temperature of 119 °C (SD = 2 °C), while 4 mm results in 136 °C (SD = 6 °C). This corresponds to a relative increase of about 20%. In case of a stroke rate of 150 L/min, 4 mm thickness leads to a 10% higher maximum temperature of 196 °C (SD = 15 °C). Noticeable is the high standard deviation of 15 °C. The chosen process parameters and the thick material in combination with the lack of lubricant leads to high tool loads and harsh conditions for the tool. Consequently, the formation of small breaks at the punch edge indicate the process limit. Therefore, a temperature measurement at the highest stroke rate was not possible. However, compared to the increase of 60% in sheet metal thickness, the temperature rise is very small. In principle, this discrepancy is mainly related to the size of the forming zone. As the die clearance is adapted to the sheet metal, the forming zone increases with the sheet metal thickness by about 125%. Therefore, the dissipating work is distributed over a larger material volume resulting in a lower average temperature.

3.2.3 Tensile strength of the workpiece material

As the occurring temperature is related to the dissipation of forming work and thus the amount of work conducted, the mechanical sheet metal properties belong to the most determining factors on temperature. Besides sheet metal thickness and embossing geometry, the amount of forming work is determined by the tensile strength of the material. In order to evaluate its influence, two alloys, S355MC and 1.4301, both with 4 mm thickness, were investigated. While S355MC has a tensile strength of 491 MPa, 1.4301 has 720 MPa. Figure 4 illustrates the measured temperatures when embossing with a relative die clearance of 1% for at least two stroke rates. As mentioned earlier, a measurement of temperature for 1.4301 at the highest stroke rate was not possible. Considering the lowest stroke rate, the maximum temperature increases with the tensile strength from 96 °C (SD = 4 °C) to 136 °C (SD = 6 °C). As expected, this relative increase of 42% is equivalent to the difference in tensile strength of the materials. In case of 150 L/min, temperature increases by only 30%. The process limits prevent a temperature measurement at the highest stroke rate for 1.4301. In case of S355MC, a temperature of 165 °C (SD = 10 °C) occurs, which is even lower than the measured temperature of 1.4301 with a thickness of 2.5 mm and a relative die clearance of 5%.

4 Conclusion and outlook

This paper presents an instantaneous thermoelectricity-based method for measuring temperatures occurring in the forming zone during embossing. The temperature trend shows a characteristic curve that is determined by the cutting surface. Only slope and maximum temperatures change during all experiments. Due to the dissipation of plastic work, the temperature rises steadily until the maximum embossing depth where the temperature reaches its maximum.

Besides the slope of temperature, several tool- and workpiece-related factors have been investigated. Regarding punch velocity, no changes in the maximum embossing depth and thus in the cutting surface could be observed. But the maximum temperature increases strongly with it. At the highest stroke rate, punch velocity temperature increases by 95% compared to the lowest one. As the maximum embossing depth does not change; higher temperatures emerge because less time is available for temperature equalization in the sheet metal. Die clearance also influences peak temperatures significantly. With a stroke rate of 300 L/min, temperature increases by 83% from the smallest to the biggest die clearance. This happens for two reasons: First, the maximum embossing depth decreases at larger die clearances, which means that less plastic work is conducted and consequently less work dissipates into heat. Second, the forming zone grows with the clearance and the dissipation is distributed over a larger volume.

This phenomena affects also the maximum temperatures in case of different material thicknesses. Therefore, an increase in material thickness of 60% lead to a only 20% higher temperature when the same relative die clearance of 1% was used. While the conducted work increases by 156%, the forming zone grows by 125%. One of the most important factors is the tensile strength of the workpiece material. Provided that all process parameters are equal, the increase in tensile strength can be directly transferred to the maximum temperature. Therefore, an increase of 45% in tensile strength leads to a 41% higher maximum temperature.

In principle, the spread of the maximum temperatures shows that many factors influence temperature. Maximum temperatures of over 230 °C may affect material properties, especially considering that the measured temperatures are a mean value over the whole contact area between the punch and the sheet metal. Therefore, local temperatures can be much higher, which confirms the significance of the temperature in the forming zone with regard to wear behavior, part quality, and the functionality of lubricants.

Additional investigations are currently being conducted with regard to other materials like aluminum alloys. Furthermore, the measurement principle will be transferred to other cold forming processes.

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