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

Philipp Tröber[1,*], *Markus* Welm[1], *Hannes Alois* Weiss[1], *Peter* Demmel[2], *Roland* Golle[1], and *Wolfram* Volk[1]

[1]Technical University of Munich, Chair of Metal Forming and Casting, 85748 Garching, Germany
[2]MAN Truck & Bus AG, 80995 Munich, Germany

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 temperature 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 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 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 finally, 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 behaviour [4] and tool wear are just two examples. 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 aluminium, lower temperatures occur due to the low 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 et al. were 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 with a 4 mm thickness and almost 300 °C with 6 mm [10]. The maximum temperature always occurs with the end of clean cut formation, just before the final separation of the sheet metal. Tröber et al. measured temperatures of up to 264 °C for embossing 4 mm carbon steel with a similar tool [11]. They confirmed the significant influence of process parameters on emerging temperatures [12].

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 process.

* Corresponding author: philipp.troeber@utg.de

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 which 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. 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 inelastic 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 the 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]:

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

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 used. 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, 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 showed a maximum measurement deviation of the measured thermovoltage of 1.5 %.

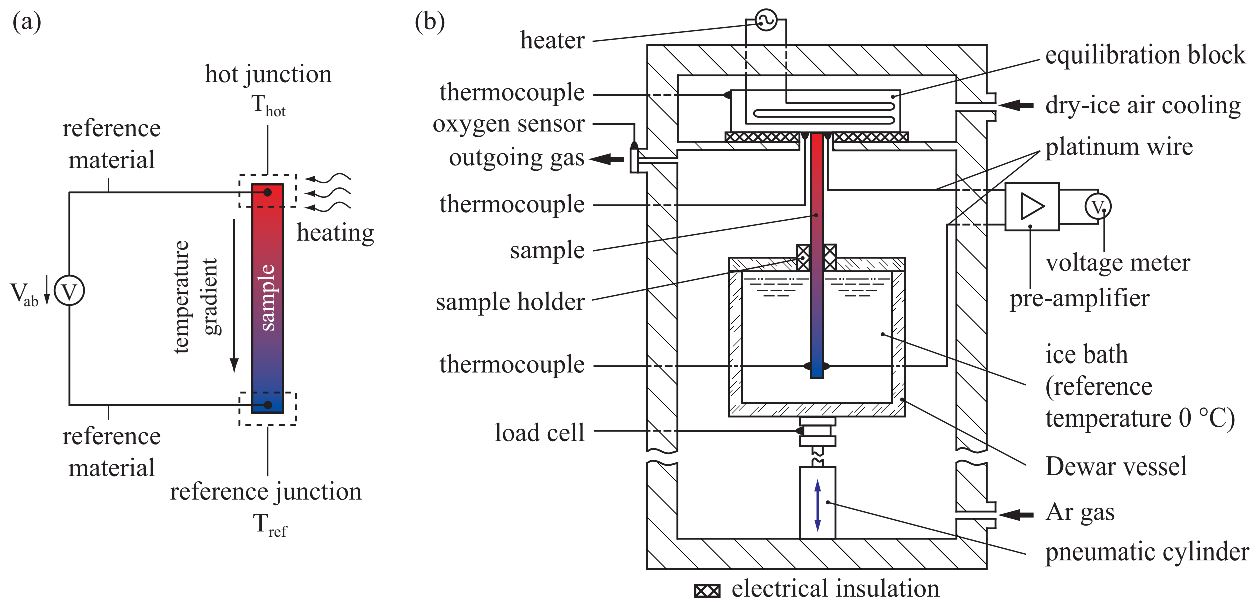


Fig. 1. (a) Schematic diagram of an integral measuring setup for thermocouple calibration and (b) Apparatus for measuring relative Seebeck coefficients [13]

2.3. Tool and press

The experimental tool 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 variation. 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 zirconium oxide applications 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.

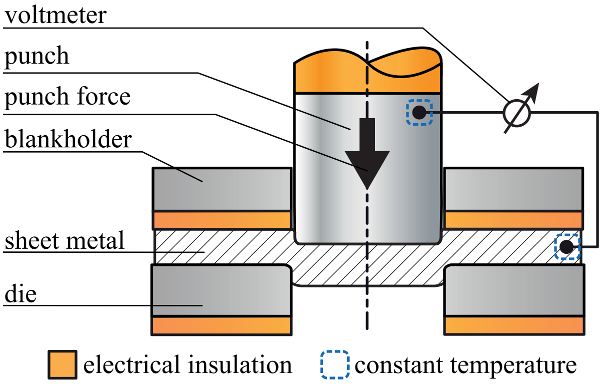


Fig. 2. Schematic drawing of a tool-workpiece-thermocouple for temperature measurement during embossing and blanking operations

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 lubricants were applied during any tests.

The investigation was made on a BSTA 1250-181 built by Bruderer AG (Frasnacht, Switzerland). This high-performance stamping press has a maximum press force of 1250 kN and an infinite variable stroke rate between 60 1/min and 600 1/min.

2.4. Investigated materials

Austenitic stainless steel 1.4301 (X5CrNi18-10) with a thickness of 2.5 mm has been chosen as sheet material. A high tensile strength of up to 720 MPa and good corrosion resistance make this material suitable for many applications.

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

Table 1 shows the chemical composition of CF-H40s and 1.4301 determined by an optical emission spectrometer.

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

1.4301	Si	Mn	Cr	Mo	Ni	Cu	Fe
	0.7	1.3	19.0	0.4	10.8	0.3	balance
CF-H40s	WC						Co
	88.0						balance

3 Results and discussion

In this investigation, the focus is on forming velocity and die clearance. To find out their influence on emerging temperatures in the forming zone, various experiments were done with the aforementioned experimental setup. As the highest temperatures occur during processes with high surface pressures and deformation degrees, embossing was chosen as manufacturing process. As maximum temperatures occur with the end of clean cut formation and thus the maximum embossing depth, a complete sheet metal separation is done. A die clearance of 1 % (0.025 mm), 5 % (0.125 mm) and 10 % (0.25 mm) is chosen for the experiments. The stroke rate is varied between 60 1/min, 150 1/min and 300 1/min which corresponds to an approximate punch impact velocity of 50 mm/s, 140 mm/s and 270 mm/s. Every experiment was repeated at least three times.

3.1. Temperature profile

Figure 3 shows representative curves of the temperature occurring in the forming zone as related to the punch travel. Negative values stand for a punch travel downwards until bottom dead center at 0 mm. In figure 3a, a 1 % die clearance was used. As long as the 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 levelling 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 inelastic 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 of the sheet metal thickness (Tab. 2) and a large contact area between punch and sheet metal, temperature briefly remains at the same level. With the end of plastic deformation, temperature decreases until bottom dead center. During the return stroke, temperature increases again until a maximum of 171 °C at 5.92 mm. With the disconnection of the electric circuit, no more temperature

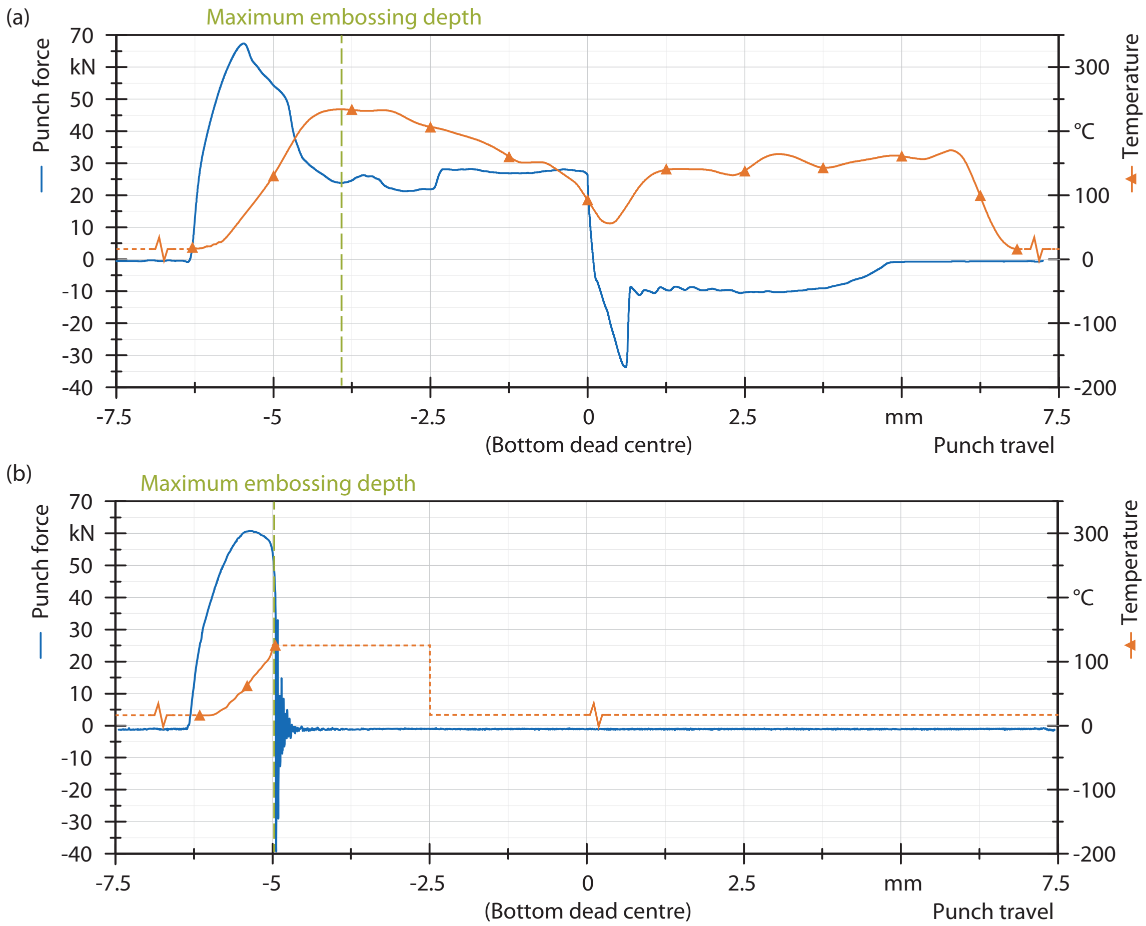
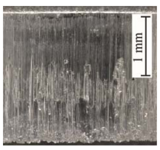
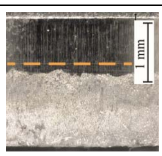


Fig. 3. One representative temperature profile and punch force over the punch travel for a die clearance of (a) 1 % and (b) 10 % blanked with a punch stroke rate of 300 1/min

is measurable. A die clearance of 5 % showed almost the same temperature curve as 1 % because the achieved cutting surface and thus, the embossing depth is equivalent to the sheet thickness, as can be seen in table 2.

Figure 3b shows the representative temperature curve for 10 % die clearance, which is used for very small embossing 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 due to the release of elastic energy. Due to undefined contact conditions, no temperature can be measured until the end of the progress.

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	

3.2. Maximum temperatures as a function of chosen process parameters

Figure 4 illustrates the maximum temperatures as a function of the stroke rate for all die clearances investigated. As already mentioned, the temperature trend of 1 % and 5 % are very similar. Regarding the maximum temperatures, minor differences are ascertainable. For 60 1/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 1/min the difference amounts about 7 %. At the fastest stroke rate (300 1/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 the influence of process parameters. 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 1/min. The maximum temperature of 126 °C (SD = 1 °C) could be measured at 300 1/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 is, the less time exists 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 inelastic 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, inelastic work dissipates in a smaller area which results in higher temperatures.

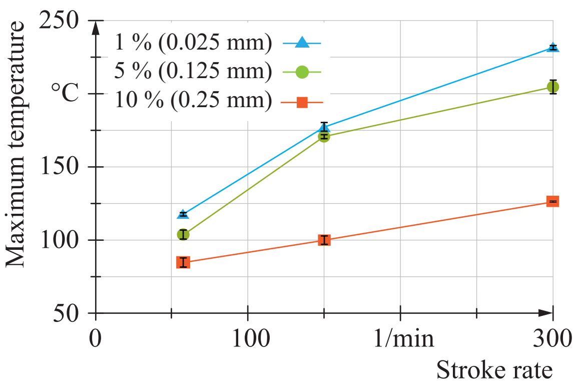


Fig. 4. Maximum temperatures occurring during embossing with clearances of 1 %, 5 % and 10 % over stroke rate

4 Conclusion and outlook

In this paper, a method was presented for measuring temperatures occurring in the forming zone during embossing based on thermoelectricity. The temperature trend shows a characteristic curve that is almost independent of the chosen process parameters. 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. The peak value of these temperatures strongly depends on both punch velocity and die clearance.

In the case of punch velocity, no changes in the maximum embossing depth could be observed. In contrast, the occurring temperature at the highest stroke rate and therefore punch velocity 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.

The die clearance also shows a significant influence on the peak temperatures. With a stroke rate of 300 1/min, temperature increases by 83 % when embossing with the smallest die clearance. This increase appears for two reasons. First, the maximum embossing depth decreases at larger die clearances, which means that less plastic work is conducted. Consequently, less work dissipates into heat. Secondly, the forming zone grows at bigger clearances and the dissipation is distributed over a larger volume.

Using the smallest die clearance of 1 % and the highest stroke rate of 300 1/min, a temperature of 230 °C was measured. Due to the geometry of the punch, this temperature is a mean value over the whole contact area of punch and sheet metal. Therefore, local temperatures can be even higher, which confirms the significance of the temperature in the forming zone. Besides wear behavior and part quality, the functionality of lubricants can especially be affected, which proves the necessity of temperature consideration during forming operations.

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