Temperature measurement during blanking with enhanced speeds

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Abstract. Shear cutting is one of the most important manufacturing processes due to its high productivity and process stability. The advantages of shear cutting also obtain in high-speed cutting and cutting with enhanced speed. In addition, further advantages such as high dimensional accuracy and a predominant fracture zone accompany it. At the same time, according to literature, high cutting speeds lead to increased temperatures in the shear zone, which can entail tool damage and wear in the short or long term. Knowledge of the temperatures is therefore indispensable for forward planning and economical production processes. Therefore, measurement of temperature in the shear zone has already been approached by a wide variety of methods. In this paper, the temperatures are determined by recording the thermoelectric voltages occurring during shear cutting with enhanced speed up to 270 mm/s and converting these voltages into temperature values using knowledge of the Seebeck coefficients of the punch and sheet material.

Introduction

High-speed shear cutting can be characterized by a cutting speed of over 500 mm/s, since the fracture mechanism of the blanking process changes from this speed on [1]. Therefore, high-speed cutting has several advantages over the conventional shearing process. In addition to high dimensional accuracy and low deformation, the components have low burr height, cutting surfaces with a predominant fracture zone content and a particularly fine-grained surface at the same time. Furthermore, this process leads to a reduction of the deformation zone and less work hardening [2]. High-speed shearing consequently saves material as well as rework and eliminates the need for lubricants [3].

During the shear cutting process, the sheet metal is deformed both plastically and elastically until it is separated. For this, a defined amount of cutting work must be performed. A large part of the plastic deformation work, up to 95% according to Macdougall [4], is converted into heat. Only a small part is stored in the structure of the material [5].

If more forming heat is generated by increased forming speeds and, at the same time, only a limited amount can be dissipated by heat conduction, the originally isothermal process takes on an adiabatic character. Due to the high temperatures, softening processes occur in the forming zone. This adiabatic softening influences the fracture process during material separation and thus leads to an improvement in the quality of the blanking parts. [6]

In traditional blanking the punch speed is about 100 mm/s [3]. This paper deals with cutting with enhanced speed of up to 270 mm/s and investigates if the advantages for high-speed cutting also obtain here.

Although the high cutting speed leads to higher productivity and better part quality, it is also associated with the occurrence of high temperatures within the shear zone and in the contact area between the active element and the sheet.

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Knowing the values of these temperatures is of particular importance, since a significant influence of the temperature on the process can be assumed above a temperature of 200 °C. Especially increased tool wear due to local changes of the mechanical properties of the tool materials, thermally induced mechanical stresses in the tool surface [7] and increased adhesion behavior [6] result from an increased temperature. During cutting with a very small cutting clearance, thermal expansion of the active elements can also lead to tool damage [8]. Likewise, damage to the tool coating can occur due to the cyclic thermal stress [9] as well as a reduction in the lubricant effect [10]. The measurement of the resulting temperatures during cutting with high stroke rates under different process parameters is therefore indispensable to ensure an economical production process. However, profound knowledge of occurring temperatures while blanking is important to understand and improve the process. For example, wear phenomena such as adhesion formation, which is significantly influenced by temperature itself as well as side effects such as thermoelectricity [11].

In the past, several approaches to determine the temperature in the contact zone between sheet metal and active elements during shear cutting have been taken. These approaches can be divided into experimental, analytical and numerical. In experimental studies, thermocouples were often inserted into punches or cutting plates to determine temperatures [12]. Another method was the detection of thermal radiation from the punch surface [8]. Similarly, an examination of the microstructure of cut components can allow conclusions about temperatures. The temperatures determined range between 32 °C [12] and 600 °C [13].

Analytical calculations also led to values of around 500 °C in the forming zone [7]. In addition, investigations into the numerical modeling of the temperature rise have already been carried out several times. Gruner and Mauermann determined by far the highest values in cutting simulations with increased cutting speeds. Values from 450° to 500 °C were mentioned in this context [14].

In addition to these measured values, experts assume temperatures of up to 300 °C for conventional cutting speeds and up to 1000 °C for high-speed cutting when working with steel [15].

Demmel first pursued the approach of determining temperatures by means of thermoelectricity in shear cutting [16]. With his measurement method, he confirmed previous assumptions that the temperature in the shear zone increases with the cutting speed and reduces with die clearance. The sheet metal also has an influence on temperatures. When cutting steel sheet, temperatures are significantly higher compared to aluminum alloys [17]. Besides maximum temperatures, this measuring method also enables the possibility to determine the characteristic temperature profile for forming processes [16].

The thermoelectric phenomena, called the Seebeck effect, occurs when two different electrical conductors come into contact and are simultaneously subjected to a temperature gradient. During the blanking process, the punch and the sheet metal have electrical contact and therefore represent those two conductors. The temperature differences within the conductors induce the thermodiffusion of charge carriers in the punch as well as in the sheet. The resulting potential difference leads to an electric voltage measurable in an open circuit. As punch and sheet metal build the pair of conductors, the measuring principle is called tool-workpiece-thermocouple. With the use of this principle, temperature measurement is possible with minimal time delay, since the tool represents the sensor. Besides the temperature gradient, the difference in the material-specific Seebeck coefficients (SCs) of the contact partners determine the thermoelectric voltage. In turn, the SC is determined mainly by its chemical composition. However, the different crystal structures and grain sizes of the materials also change it. The SC describes the thermoelectric behavior of materials and is a measure of the increase in thermoelectric voltage with respect to temperature [18].

To infer temperatures from the measured thermoelectric voltages, it is necessary to know the Seebeck coefficients of both contact partners. These coefficients must be determined experimentally for the calibration of the measuring system.

Experimental Setup

Determination of the thermoelectric properties. An experimental determination of the SCs of the investigated tool and sheet materials was possible with a special test rig developed at the Chair of Metal Forming and Casting. For the measurement of the thermoelectric voltage, the two ends of the material samples are exposed to a defined temperature difference. This is achieved by cooling one end of the sample in an ice bath to 0 °C and heating the other end to 500 °C by contact with a copper block. The heated end is then cooled back down to 0 °C using dry ice. Due to the high inertness and temperature resistance, both sample ends were connected to a high precision voltmeter by platinum wires. This ensures a consistently high quality of the measurements. The maximum deviation of the voltage signals is 1.5 % in the measured temperature range. At the same time, platinum serves as a reference material for the thermoelectric characterization. Subsequently, the Seebeck coefficient is calculated from the measured thermoelectric voltage. [16]

Blanking tool and press. For the measurement of thermoelectric voltages during shear cutting and forming, a special tool was designed which, due to its four-track design, allows simultaneous investigation of different configurations. Both the punch and the sheet material are connected to the voltmeter by low resistance copper cables, as it can be seen in Fig. 1. The temperatures at the junctions were measured with high precision semiconductor temperature sensors. To minimize disturbances, the active elements and the sheet metal are electrically isolated from the rest of the tool. The single stroke tests were carried out on a BSTA 1600-181 high-performance stamping press, Bruderer, Frasnacht (Switzerland).

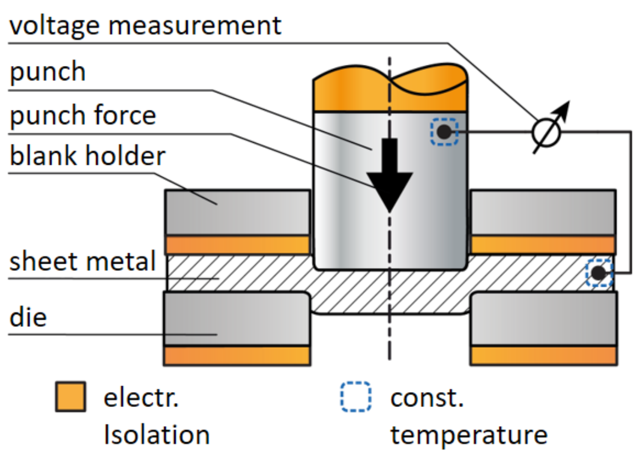

Fig. 1 Blanking tool [17]

Materials

In this publication, the hot-rolled fine-grain steel S355MC with a thickness of 4 mm serves as sheet material. It provides a tensile strength of 491 MPa and is a commonly used steel in cold forming and blanking operations. The punch material is a CF-H40S powder metallurgical cemented carbide. Due to its fine-grain structure, high homogeneity and negative Seebeck coefficient, the material ensures a high quality thermovoltage and thus temperature measurement. A hardness of 1400 HV 10 qualifies it for forming and blanking operations. Approximate temperature-dependent values of the relative Seebeck coefficient from a maximum of 17 µV/°C to a minimum of 10 µV/°C were determined for the sheet material and -10 µV/°C to

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-3 µV/°C for the punch material over a temperature range of 0°C to 500°C. Tab. 1 shows the chemical composition of both materials, measured by an optical emission spectrometer.

Table 1: Mass fraction of the chemical composition of the investigated materials (in percent).

CF-H40S	**WC**		**Co**
	88.0		balance
S355MC	**C**	**Mn**	**Fe**
	0.1	0.45	balance

Results

During this investigation, the temperature and the respective punch force during shear cutting for three different speeds were observed. To examine a high velocity range, from normal shear cutting to cutting with enhanced speeds, the stroke rate was varied between 60 1/min and 300 1/min, corresponding to a punch impact speed of 50 mm/s respective 270 mm/s. For every configuration, three measurements were conducted. Fig. 2 shows the averaged punch force (a) and temperature (b) profiles. The x-axis represents the punch travel. While negative values indicate punch movement towards the bottom dead center at 0 mm, the return stroke afterwards is represented by positive values. All experiments were carried out at least three times in order to exclude random measurement errors. The highest standard deviations are 1 kN for all force measurements and 6 °C for the temperature range.

Punch force. The punch force profiles show a characteristic shape for blanking forces with five stages 1-5 but differ in detail. At the beginning (-8.0 mm) the punch comes into contact with the sheet metal and deforms it elastically (1), apparent in a rise in linear force that is the same for all velocities, since it represents the Young's Modulus. Afterwards, plastic deformation begins at -7.7 mm, as indicated by a change of curvature (2). For 60 1/min the force maximum is reached at -7.0 mm with 73 kN; for both higher velocities it amounts to 75 kN at -7.2 mm. Consequently, the force declines and the material is separated at -6.0 mm (3). For both lower speeds, the force profiles show a similar shape, with a strong decrease down to 18 kN for 60 1/min and 21 kN for 150 1/min. Both rise again for about 10 kN at -4.0 mm when the slug hits the slug from the previous stroke in the die channel. During cutting with a stroke rate of 300 1/min, after the maximum, the force stays higher at a plateau and decreases only to 36 kN. This difference can be traced back to the formation of adhesions in the die channel and on the lateral surface of the punch, resulting in varying frictional forces. Therefore, the punch force shows a slightly higher standard deviation of ± 2.5 kN in this phase. The force rebound because of the second slug is not especially sharp and amounts to only 4 kN. Towards the bottom dead center, a slight force decline can be observed for all profiles (4). The maximum return stroke forces amount to -21 kN for 60 1/min, -33 kN for 150 1/min and more than -50 kN for 300 1/min and exceed the maximum measurable tensile force (5).

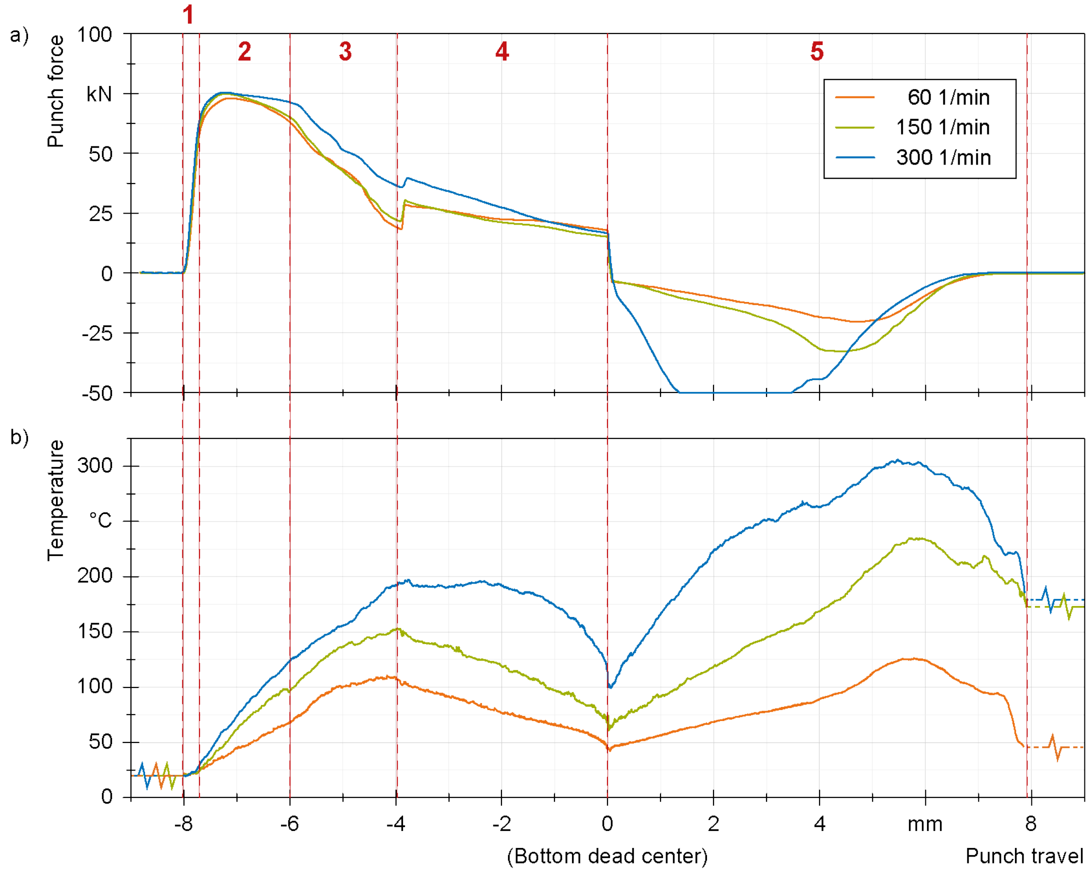

Fig. 2 Punch force (a) and temperature profiles (b) for three different cutting speeds and a die clearance of 1 %

Temperature Profiles. The five blanking stages can also be seen in the temperature profiles. While elastic deformation (1) does not entail heating, no temperature rise from the ambient temperature of 21 °C occurs in the beginning. This temperature corresponds to the volume temperature of the tool and remained constant over all experiments. When the sheet metal is plastically deformed (2), work dissipates and instantaneously triggers a temperature rise, more pronounced with higher cutting speeds. The temperatures increase during stages (2) and (3) and reach a local maximum at the final material separation at -4 mm, with 107 °C for 60 1/min, 156 °C for 150 1/min and 199 °C for 300 1/min, when the slug leaves the stamping grid. Both lower speeds show a slight temperature decrease when the slug comes into contact with the slug from the previous stroke, which is still in the die. Afterwards, the temperature declines toward the bottom dead center (4) to 42 °C, 65 °C and 97 °C. In the return stroke (5), high friction between stamping grid and punch occurs and causes the temperature to rise again, mainly due to frictional heating. All temperatures reach their respective global maximum of 124 °C, 237 °C and 292 °C at 5.7 mm.

Discussion

Regarding the force profiles, low-speed cutting (60 1/min and 150 1/min) shows a similar shape for the complete blanking process. Cutting with enhanced speed changes the slope in three ways. First, a force plateau occurs after the maximum force is reached; it is caused by a change in the material separation process, where the crack propagation is delayed and thus a higher area of clean cut occurs, which can clearly be seen in Fig. 3. Second, the force rise, when the slug from the previous stroke is hit, is not especially sharp and strong. This phenomenon can be traced back to the higher impact speed, thus the inertia force is higher and static friction is overcome faster. The third difference is the much higher return stroke force due to a clamping effect between stamping grid and punch, caused by the larger contact area resulting from a greater area of clean cut in combination with adhesions at the lateral surface of the punch due to the higher temperature. Regarding the temperature profiles, it becomes obvious that higher speeds entail higher temperatures. The reason is less time for heat conduction and equalizing effects, together with the higher forces and thus dissipation. Hampered heat conduction can also be seen at -4 mm, where the slug of the previous stroke produces a small cooling effect, visible in a small dip in the temperature profile, for only the two lower velocities.

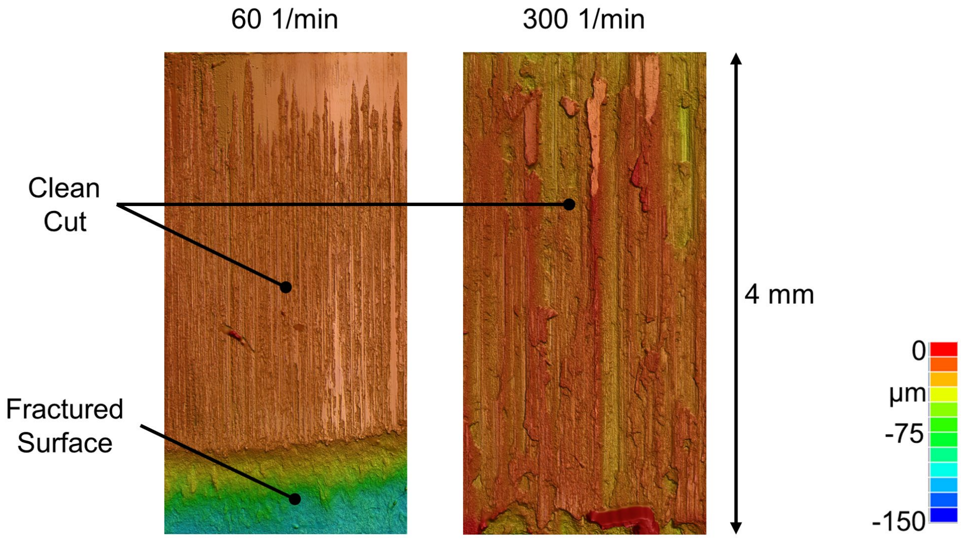

Fig. 3 Cutting surfaces of parts cut with 60 Strokes per minute (left) and 300 strokes per minute (right)

Conclusion

Cutting with enhanced speeds affects the blanking process in different ways. One is a change in the punch force slope, which entails a variation in the cutting result, apparent in a higher area of clean cut compared to components cut at slower speed. This shows that, although shear cutting leads to a very good cut surface quality due to the large clean cut area, the typical fracture behavior of a cut surface after shear cutting with high-speed is not yet evident here. Temperatures that lead to a loss of strength within the shear band and thus to the formation of a plane cut surface with a predominant fine-grained fracture zone are not reached with maximum temperatures of 292°C. The late failure point of the sheet material also leads to the disadvantage of high forces during cutting and the return stroke.

In addition, a clear difference compared to cutting with low speeds can be seen in an increase in temperatures during the whole cutting process. This difference is caused by the reduced time for heat equalization and the change in the higher forces. Currently, preparations are being made to accelerate the punching process into the range of high-speed blanking in order to measure temperatures at even higher punch velocities. In this way, on the one hand, the boundary between conventional and high-speed blanking can be precisely determined for the first time and, on the other hand, the separation mechanism in the adiabatic range can be investigated in more detail.

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