Shear Cutting of Aluminum, Zinc, and Tin at Increased Speeds

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Abstract

The temperature and temperature evaluation during shear cutting, particularly at increased speeds, is crucial for understanding the material behavior during cutting, validating thermo-mechanical material models used in the finite element method, and predicting the tool wear. In this study, we measured the punch force and temperature for EN AW 6082, zinc, and tin for punch speeds 0.12, 0.2, 0.4, and 0.6 m/s using a cutting clearance of 0.075 mm. The temperature is evaluated based on the thermoelectric voltages arising from the sheet metal and tool material based on the Seebeck effect. The results demonstrate that the sheet metal strongly influences the thermal response during shear cutting. Higher temperature maxima were generally observed to occur later than the force maximum, likely due to additional frictional heating beyond plastic deformation.

Keywords

Blanking, Temperature, Measurement

1 Introduction

Understanding the temperature during shear cutting, particularly at increased speeds, is crucial for several reasons. Firstly, it is essential for the validation of thermo-mechanical material models used in finite element method (FEM) simulations. Accurate temperature data ensures that these models can reliably predict the behavior of materials under shear cutting, leading to more precise simulations. Secondly, observing the thermal effects within the material during shear cutting provides valuable insights into how the material responds to increased temperatures. This knowledge is critical for optimizing cutting parameters and improving the quality of the cut. Additionally, assessing the thermally induced mechanical stresses on the tool surface is vital for predicting tool wear and extending tool life. High temperatures can increase mechanical stresses, which may cause premature tool failure. Furthermore, elevated temperatures can enhance adhesion behavior (Tröber et al. 2021).

2 State of the Art

Various methodologies have been employed to determine the temperature within the contact zone between sheet metal and active elements during shear cutting. Most used are experimental and numerical methods. Experimental studies frequently utilized thermocouples embedded in punches or cutting plates (Chen et al. 2003) or connected to the sheet metal (Weiser et al. 2022) to measure temperatures. To measure the temperature right after the shearing of the part infrared (IR) cameras can be used (Schweinshaupt et al. 2024). However, this method does not give insight into the temperature evolution during the process. Furthermore, several investigations have focused on numerically modeling the temperature rise during shear cutting (Karantza et al. 2024; Galiev et al. 2023).

The thermoelectric phenomena provide the possibility of using the sheet metal and tool as a thermocouple based on different thermoelectric properties. Thermoelectric voltages are generated when two different electrical conductors are joined at one end, which has a different temperature than the other. The thermoelectric voltage is directly proportional to the temperature difference along the conductors. The proportional factor, known as the Seebeck coefficient, characterizes the thermoelectric properties of the materials (Demmel et al. 2015; Demmel 2014). This principle has been utilized to measure the temperature in forming for different materials and parameters. Demmel et al. (2015) measured a local temperature maximum of around 70 °C at material separation in shear cutting of hot rolled fine-grained steel S355MC with a thickness of 6.0 mm, a cutting clearance of 0.48 mm, and a 0.01 m/s punch speed. For the same material with a thickness of 4 mm and increased speeds up to 0.27 m/s and 0.04 mm clearance, Schrepfer, A., Welm, M. et al. (2023) measured 199 °C at the material separation. In cup drawing of the aluminum alloy EN AW 5083 with a thickness of 1 mm and a 1.3 mm drawing gap, Tröber et al. (2021) measured 38 °C at 10 mm drawing depth using the thermoelectric principle.

In this study, we measured the punch force and temperature based on thermoelectric voltages with a tool-workpiece-thermocouple for 1.5 mm thick aluminum EN AW 6082, zinc, and tin for increased punch speeds up to 0.6 m/s using an increased cutting clearance of 0.1 mm.

3 Experimental Setup

The experimental setup for the stamping experiments utilizes a Bruderer BSTA 1600-181 press (Frasnacht, Switzerland) with a stroke length of 68 mm. Stamping commenced 5 mm before the bottom dead center. Both the punch and die, as well as the sheet metal, are electrically isolated from the tool body. The stamping geometry is a coin with a 20 mm diameter, featuring a 0.075 mm cutting clearance (5 % relative clearance) and cutting edge radii of 2 µm and 30 µm for the punch and die, respectively. The velocity was varied by adjusting the number of strokes on the press, with the punch speed determined based on the manufacturer's stroke curve at the moment of punch and sheet contact. Single stroke testing was conducted at velocities of 0.12 m/s (60 strokes/min), 0.2 m/s (100 strokes/min), 0.4 m/s (200 strokes/min), and 0.6 m/s (300 strokes/min).

The measurement technology setup for the stamping experiments involves measuring force, distance, and thermoelectric voltages. Force measurements were conducted using a Kistler (Winterthur, Switzerland) 9041C load washer with quartz sensing elements mounted in a force shunt directly above the punch. The force signals were amplified using a Kistler 5073A industrial charge amplifiers, which outputs an analog voltage signal. Distance measurements to determine the location of the bottom dead center were performed using a laser triangulation displacement sensor, optoNCDT1320-100 from Micro-Epsilon (Ortenburg, Germany) with an analog voltage output. Thermoelectric voltages were pre-amplified and filtered close to the tool using self-build precision instrumentation amplifier converting signals from the -10 to 10 mV range to a -10 to 10 V range (Demmel 2014). Data acquisition was done time-synchronously using a PCI-6280 and a PCI-6250, recording at 200 kHz with LabVIEW software, all from National Instruments (Austin, Texas, USA). Ambient temperature, used as a reference for calculating temperature differences from thermoelectric voltages, was measured with a Papouch TMU temperature sensor featuring a USB interface and a resolution of 0.1 °C by Papouch s.r.o. (Prague, Czech Republic).

4 Materials

This study utilized three materials for stamping experiments: aged aluminum EN AW 6082, 99.76 % pure zinc, and a tin alloy Sn95Sb4Cu1 with a tin content of 93.5 %. All materials are used in sheet metal form with a thickness of 1.5 mm.

The sheet metal is mechanically characterized using a quasi-static tensile test according to DIN EN ISO 6892-1. The results for the yield stress R_e and the ultimate tensile strength R_m for the materials are given in Table 1.

The material-specific Seebeck coefficient is required to convert the thermoelectric voltages measured between the tool and the sheet metal into a temperature difference. All sheet metal material and the tooling material steel 1.3343 were characterized using a special test rig developed at the Chair of Metal Forming and Casting. The sample is connected to two platinum wires, with one side maintained at 0°C while the other side is heated up to a maximum temperature (500°C for aluminum, 338°C for zinc, and 180°C for tin) and then cooled down. Platinum wires connect both sample ends to a high-precision voltmeter with a maximum deviation of 1.5 % in the temperature range. Additionally, the platinum serves as a reference material for the thermoelectric characterization and allows the calculation of the Seebeck coefficient from the measured thermoelectric voltage. Figure 1 illustrates the result of the thermoelectric characterization. The difference in relative thermoelectric voltage between the tool material 1.3343 and the sheet metal material relates to the temperature on the connecting surface. (Demmel 2014)

Material	R_e in MPa	R_m in MPa
EN AW 6082	173	335
Zinc	84	154
Tin	42	47

***Table 1:** Results of quasi-static tensile testing according to DIN EN ISO 6892-1*

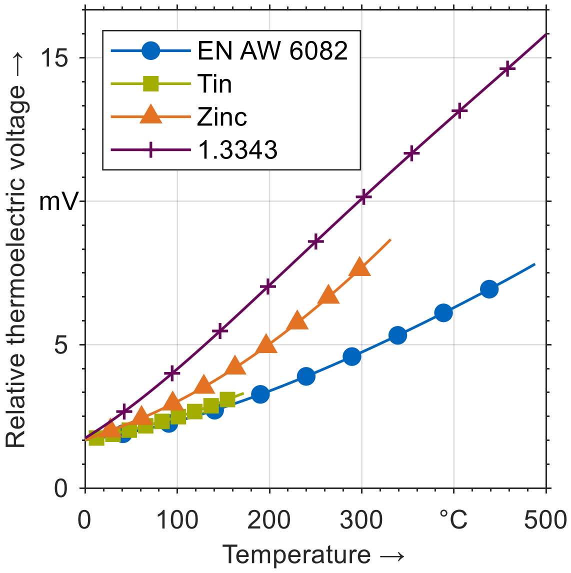


***Figure 1**: Results of thermoelectric characterization.*

5 Results

Five valid samples were stamped per material and punch speed. The maximum force was evaluated for every specimen and averaged. The measured thermoelectric voltages were filtered with a low-pass filter of 500 Hz, converted to temperature differences based on the thermoelectric characterization, and added to the ambient temperature. The temperature maximum was calculated for all five samples and averaged. These results and the corresponding standard deviation are given in Table 2 for EN AW 6082, in Table 3 for zinc, and in Table 4 for tin.

Averaged data curves are obtained by interpolating the single stroke data sets over the longest data set and averaged for every punch travel value. The data is plotted against the manufacturer's stroke curve, with 0 mm being the bottom dead center measured by the distance sensor. Please note that these curves show different maximum values, as small distance offsets lead to different averaging than averaging over maximum values, regardless of the punch position. The temperature curve at different punch speeds is shown in Figure 2 for aluminum only.

The punch travel between the occurrence of the force maximum and temperature maximum (ΔS) and the maximum temperature measured at different punch speeds for EN AW 6082, zinc and tin is plotted in Figure 3. A positive value of ΔS indicates by how much the punch has moved from the point of maximum force to reaching the maximum temperature.

Punch speed	Max. Force in kN	Standard deviation in kN	Max. Temperature in °C	Standard deviation in °C
0.12	14.35	0.060	44.47	4.05
0.2	14.26	0.114	57.54	4.63
0.4	14.45	0.032	80.97	3.06
0.6	15.09	0.102	70.22	3.39

***Table 2:** Resulting maximum force and maximum temperature, averaged over five samples, of single stroke testing of EN AW 6082.*

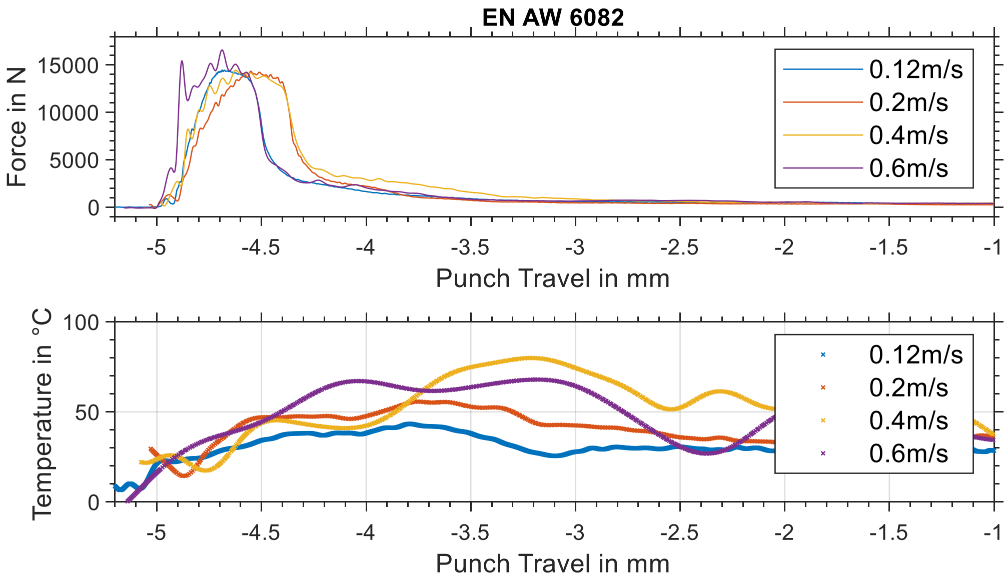
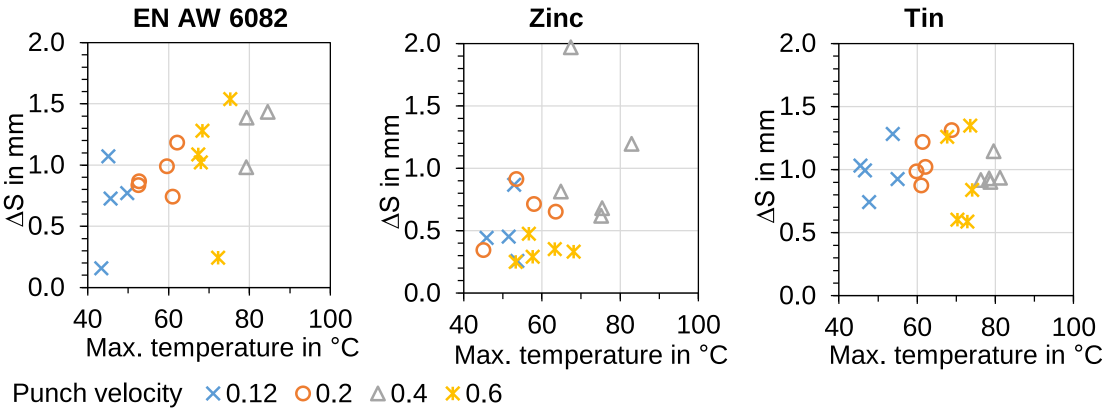


***Figure 2**: Averaged force and temperature curves plotted against the stroke curve at different punch speeds for EN AW 6082.*



ΔS – punch travel between force maximum and temperature maximum in mm

***Figure 3**: Punch travel between the occurrence of the force maximum and temperature maximum (ΔS) and the maximum temperature measured at different punch speeds for EN AW 6082, zinc and tin.*

Punch speed	Max. Force in kN	Standard deviation in kN	Max. Temperature in °C	Standard deviation in °C
0.12	16.24	0.162	50.48	3.23
0.2	16.71	0.069	54.84	6.78
0.4	16.64	0.153	73.10	7.18
0.6	17.66	0.223	59.77	5.88

Table 3: *Resulting maximum force and maximum temperature, averaged over five samples, of single stroke testing of zinc.*

Punch speed	Max. Force in kN	Standard deviation in kN	Max. Temperature in °C	Standard deviation in °C
0.12	5.34	0.056	49.74	4.33
0.2	5.62	0.028	62.68	3.54
0.4	5.94	0.100	78.86	1.79
0.6	6.49	0.124	71.72	2.64

Table 4: *Resulting maximum force and maximum temperature, averaged over five samples, of single stroke testing of tin.*

6 Discussion

The measurement of temperature based on thermoelectric voltages shows promising results. At increased punch speeds it is not possible to differentiate blanking stages (e.g. plastic deformation) from the temperature data as shown in earlier publications with punch speeds up to 0.27 m/s (Demmel et al. 2015; Tröber et al. 2021; Schrepfer, A., Welm, M. et al. 2023). Reasons can be found in the increased punch speed, the increased cutting clearance, the reduce sheet metal thickness as well as the punch material used. To enhance thermoelectric voltage generation and thereby improve the stability of temperature measurements, the punch material CF-H40S, characterized by a negative Seebeck coefficient, could be used.

The type of sheet metal utilized in shear cutting influences the temperature data measured. The following findings were derived from the experimental data. Zinc demonstrated the highest standard deviation in temperature maxima. A reason can be the smaller difference in relative thermoelectric voltage of zinc to the punch material 1.3343. Small voltages are more prone to interference and more complex to amplify. Tin showed the most consistent temperature data, with the occurrence of the temperature maximum remaining stable across all tested punch speeds. The temperature maxima consistently appeared within a punch displacement of $\Delta S = 0.5 - 1.5$ mm following the force maximum.

Generally, higher temperature maxima were associated with a later occurrence relative to the force maximum (i.e., larger punch travel ΔS). This delay is likely attributable to increased frictional heating between the punch and the sheet metal, in addition to the heat generated by plastic deformation during shear cutting. Contrary to expectations, higher temperatures were recorded at a punch speed of 0.4 m/s rather than at 0.6 m/s. This anomaly may be due to limitations in the amplifier's capacity to accurately process the heat signals generated at higher speeds or due process instabilities leading to varying friction between punch and sheet metal.

7 Summary and conclusion

In this study, we measured the punch force and temperature based on thermoelectric voltages for EN AW 6082, zinc, and tin for punch speeds 0.12, 0.2, 0.4, and 0.6 m/s using a cutting clearance of 0.075 mm.

The results indicate that the type of sheet metal significantly affects thermal behavior during shear cutting. Aluminum exhibited the highest average temperature maxima, while zinc showed the greatest variability, likely due to its low thermoelectric voltage differential with the punch material (1.3343). Tin demonstrated the most consistent thermal response across all punch speeds.

A general trend was observed where higher temperature maxima were associated with a delayed occurrence relative to the force maximum, attributed to frictional heating in addition to plastic deformation. Unexpectedly, the highest temperatures were recorded at 0.4 m/s rather than 0.6 m/s. These findings suggest that thermoelectric voltage-based temperature measurement is a viable method for analyzing thermal effects in high-speed shear cutting, though improvements in signal amplification and material selection (e.g., using CF-H40S with a negative Seebeck coefficient) may enhance measurement reliability at higher punch speeds.

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