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Lubricant-free forming by affecting thermoelectric currents

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Summary

Cold metal forming belongs to the most important manufacturing processes for sheet metal mass products. To meet increasing requirements concerning part quality and economic efficiency, tool wear has to be minimized. Therefore, most of the forming processes are only feasible with lubricant application. Especially for processes with high tool load, such as blanking or embossing, adhesive wear is a key challenge due to early initiation and high wear rates. Despite the high significance and consequences, like a reduction of part quality and process reliability as well as an increasing risk of severe tool damage, wear-causing interactions are insufficiently understood. One known influencing factor is the temperature in the forming zone, which arises due to the dissipation of conducted forming work. Besides the direct impact on adhesive wear, this temperature rise leads to thermoelectric voltages and currents, whose influence on adhesive wear development has been neglected so far. For this reason, typical tool and sheet materials have been characterized for the first time with regard to their thermoelectric behavior, represented by the Seebeck coefficient. Together with experimental blanking and embossing investigations, basic correlations between process parameters, temperatures, sheet and tool materials, thermoelectric currents as well as adhesive wear could be derived. The findings obtained confirm a strong influence of the direction and strength of thermoelectric currents, which are determined by the difference between the Seebeck coefficients of tool and sheet material, on adhesive wear. Similar thermoelectric behavior of both materials in contact suppresses thermocurrents and resulted in an adhesive wear reduction of 74% during blanking. In addition, the external generation of a regulated current enables to influence thermoelectric currents in strength and direction. An external current adapted to the process reduced adhesive wear by 31%. In sum, two new methods of adhesive wear reduction, which are applicable in every metal manufacturing process, were investigated within this project. Furthermore, the knowledge gained improves the fundamental understanding of wear-causing interactions.

Keywords: Thermoelectricity, Adhesive wear, Temperature, Embossing, Blanking

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1 Introduction

Since sheet metal parts can be found in various technical components, their processing is of great importance. Increasing demands concerning part quality and profitability require an optimization of manufacturing processes with regard to efficiency and overall output. Furthermore, the recent environment-conscious trend does not stop at the manufacturing industry. In this context, especially lubricant additives can be harmful to the environment and often entail further processing steps like a subsequent cleaning of workpieces. Therefore, the general objective is to reduce or even forego the use of lubricants. [1] As tool wear is the main decisive factor in this context, its reduction is one of the key challenges. [2] Wear typically results from an interaction of four

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main mechanisms: Adhesion, abrasion, tribochemical reaction and surface fatigue. During sheet metal processing, these mechanisms lead to different elementary interactions at the micro contacts between sheet metal and tool. In general, process forces and tensions between materials in contact trigger abrasion and surface fatigue. Interactions on the micro- and nanoscopic level basically cause adhesion and tribochemical reactions. [3] Although wear is usually an interaction of all wear mechanisms, one of them can dominate depending on the boundary conditions. [4] When processing aluminum, titanium and stainless steel, especially with manufacturing processes characterized by high surface pressures, like blanking or embossing, adhesive wear appears very early and with high wear rates. [5] For this reasons, an application of lubricant is currently necessary. Only an improved fundamental knowledge of wear-causing interactions makes a future implementation of such processes with a reduced amount or even without any lubricant possible.

The general explanation for adhesion formation is very vague and refers only to mechanical reasons. Local peak stresses at contacting asperities lead to plastic deformation, which cracks the oxide layer. Consequently, high reactive metal surfaces get in contact and a strong chemical bond is formed due to electron exchange. [6] Further relative movement between the contacting bodies results in a material transfer from the weaker to the stronger bonded material. [7] Besides roughness, temperature has a significant influence on adhesive wear as adhesions arise predominant in areas of high local stress where highest temperatures prevail. [8] According to Schulz, this temperature rise, which always occur during sheet metal processing, is attributable to two causes. The first one is the dissipation of plastic work into heat. Depending on the sheet material, up to 95% of the conducted forming work is converted into heat and only a small part is stored in the material structure as dislocations and defects of the crystal lattice. [9,10] The second temperature increasing mechanism is friction. On the one hand macroscopic friction between the surfaces of tool and workpiece. On the other hand internal friction on an atomic scale. [11]

Measuring the resulting temperature in the forming zone is complex due to geometrical conditions. For this reason, scientific literature offers a wide range of temperatures varying between 50 °C [12] and 600 °C [13]. The large variances can be traced back to an inadequate geometric and temporal evaluation of the temperature data, an insufficient measuring methodology as well as the dependence of simulative gained values from selected input parameters and material models. With a tool-workpiece-thermocouple, Demmel et al. were able to measure a precise temporal resolved temperature, in situ at the cutting edge of the punch, where temperatures of up to 300 °C occur. [14]

However, investigations about the impact of temperature on adhesive wear indicate further influencing factors besides temperature. During strip-drawing tests with aluminum, a temperature change of only 15 °C lead to a significant increase in adhesive wear, which cannot be only attributed to temperature. [15] In this context, one still insufficiently investigated factor is thermoelectricity. Due to the Seebeck effect, thermoelectric voltages and currents always occur when at least two different electrical conductors are connected and subjected to a temperature difference. [16] Their strength is mainly determined by the thermoelectric behavior of the connected conductors, represented by the Seebeck coefficient. Since this coefficient depends on a variety of influencing factors, such as temperature, alloying elements, structure or degree of deformation, a thermoelectrically material characterization is only possible experimentally. [17]

So far, studies on the correlation between thermoelectric phenomena and wear have solely been carried out in the field of machining. The contradicting results found can primarily be attributed to a missing thermoelectric characterization of the materials in contact as well as unknown interactions and influencing factors respectively. Opitz was one of the first to find out that thermoelectricity can reduce service life of tools. In a model experiment, where two different samples were pressed together and a direct current was applied, running oxidation processes between surfaces in contact depend on current direction and strength. During machining, an externally applied countercurrent, which was 20 times higher than the naturally arising thermocurrent, increased tool lifetime significantly. In addition, an interruption of the current flow by insulating the turning tool electrically lead to the same result. [18] In contrast, Hehenkamp was not able to confirm these findings. He explained the results by an electrical current flowing in the turning tool itself due to a temperature gradient. [19] Ellis and Borrow stated that the internal resistance of the machine determines whether the effect of insulation is positive or negative. [20] Uehara explained these differences with circular currents in the contact zone between tool and workpiece, which occur due to different temperatures, unequal plastic deformations and material inhomogeneity at contacting asperities. Depending on the flow direction, these currents either heat or cool down the contact areas due to the Peltier effect. [21] This effect describes a change in temperature due to an applied current, which corresponds to the reversal of the Seebeck effect. Apart from that, Shan and Pendey found basic correlations between current direction and wear development. Therefore, a current was applied in the contact zone between tool and workpiece, which was isolated from the surroundings. While an external current in the direction of the natural thermocurrent lead to a reduction in tool life, the opposite direction resulted in an increase. However, this relation is only valid when the current strength is adapted to process parameters and cutting conditions as well as further currents, which arise in other machine parts like bearings. [22,23] In the field of drilling, investigations concerning isolation and countercurrent confirmed the results mentioned. Furthermore, it turned out that the thermoelectric impact on wear behavior depends on the combination of tool and workpiece material. [24,25]

In general, the above-described results indicate that thermoelectricity influences wear significantly, but precise relationships as well as the fundamental interactions are unclear. Therefore, basic correlations between process parameters, temperature, tool and sheet material, thermoelectric current as well as adhesive wear has been investigated in the field of cold metal forming within this project. Based on a thermoelectric material characterization along with a precise measurement of temperature, thermoelectric currents and adhesive wear, fundamental correlations could be derived, improving the understanding of wear-causing interactions. In the following, this report describes the key scientific findings based on selected results.

2 The origin of thermoelectricity

If both ends of a conductive solid have different temperatures, thermodiffusion occurs. This shift of charge carriers arises due to their location-dependent velocity as seen in Figure 1a. Since their kinetic energy increases with temperature, the resulting average velocity vector points toward the cold end. Consequently, moving charge carriers induce an electrical field, which stops thermodiffusion. While the resulting displacement of charge carriers is the underlying cause of the Seebeck effect, the potential difference between both ends is determined by the Seebeck coefficient, which characterizes mobility and number of free electrons in materials. Therefore, this coefficient represents the material specific thermoelectric behavior and depends besides the material composition on a variety of other factors such as lattice structure, degree of deformation or even temperature. [17]

Once two different conductors are connected like in Figure 1b, the potential difference results in macroscopically measurable thermoelectric voltages and currents. If a temperature difference of 100 K between both junctions prevails, metal-metal-combinations generate thermoelectric voltages in the range of a few micro- and millivolts. Doped semiconductors reach the highest values of several hundred millivolts. Thermoelectric voltages are measureable in an open electrical circuit without current flow. Since they are proportional to the temperature difference, this setup is typically used for temperature determination. The difference between the Seebeck coefficients of conductor A and conductor B represents thereby the proportional factor. A material characterization in terms of thermoelectric behavior enables to derive a temperature from a thermoelectric voltage U_{th}. In a closed circuit, these voltages cause a stationary circular current I_{th}, which according to Ohm´s law depends on the electrical resistance of the circuit. Since it is very low in case of metals, thermoelectric currents can reach values up to 100 A. [16]

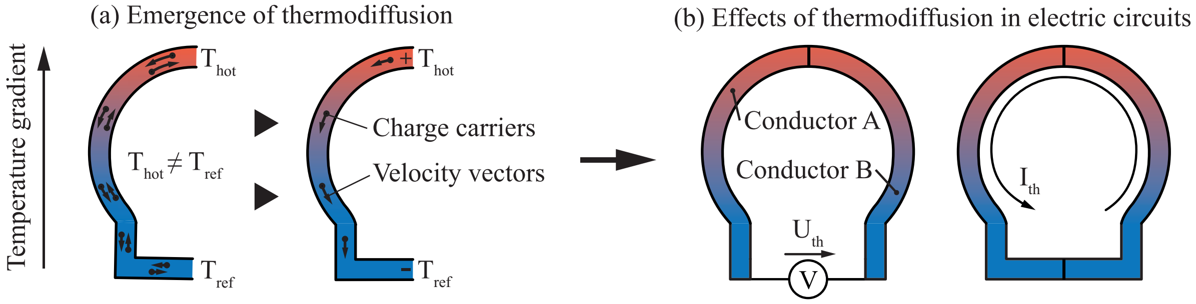

Fig. 1: (a) Thermodiffusion of charge carriers in an electrical conductor and (b) resulting effects in different electrical circuits consisting of two different conductors according to [26]

3 Experimental setup

3.1 Thermoelectric material characterization

During every sheet metal processing, the requirements for the Seebeck effect are fulfilled and thermoelectric voltages and currents arise. On the one hand, dissipation of conducted work and friction lead to a temperature increase in the forming zone and thus, a temperature gradient in the tool. On the other hand, tool and sheet material have different chemical compositions and consequently, different Seebeck coefficients. The determination of these coefficients is a key aspect of this project. Since the difference between both Seebeck coefficients determines thermoelectric current strength and direction, the knowledge about the material specific thermoelectric behavior is prerequisite for investigating a correlation between adhesive wear and thermoelectricity. Furthermore, measuring temperatures with a tool-workpiece-thermocouple is only possible by a preceding calibration and thus, a characterization of both tool and sheet material. Otherwise, a derivation of the prevailing temperature from the measured thermoelectric voltage is not possible. Figure 2a illustrates the basic principle for measuring Seebeck coefficients, which is based on a defined temperature gradient along the test sample. Therefore, one end is heated to a certain temperature T_{hot} while the other one is maintained at a constant reference temperature T_{ref}. As thermoelectric voltages are only measureable in a circuit with two different conductors, a reference material has to be attached to the sample. Due to its high corrosion resistance and chemical inertness, platinum was chosen. Therefore, the relative Seebeck coefficient of a sample material related to platinum is gained within this open electrical circuit. Depending on the Seebeck coefficients of the sample S_{B} and the reference material S_{A}, a defined thermoelectric voltage U_{th} according to Equation 1 arises:

$$U_{\mathrm{th}}(T) = \int_{T_{\mathrm{ref}}}^{T_{\mathrm{hot}}} (S_{\mathrm{B}}(T) - S_{\mathrm{A}}(T))dT = (S_{\mathrm{B}}(T) - S_{\mathrm{A}}(T)) * (T_{\mathrm{hot}} - T_{\mathrm{ref}})\ [V] \tag{1}$$

A differentiation of the resulting voltage curve according to Equation 2 corresponds to the relative Seebeck coefficient S_{AB} of the investigated test sample related to the reference material:

$$S_{\mathrm{AB}}(T_{\mathrm{hot}}) = S_{\mathrm{B}}(T_{\mathrm{hot}}) - S_{\mathrm{A}}(T_{\mathrm{hot}}) = \frac{d\,U_{\mathrm{th}}\,(T_{\mathrm{ref}}, T_{\mathrm{hot}})}{d\,T}\ [\mu V/°C] \tag{2}$$

Figure 2b shows the implementation of the schematic diagram in an experimental device, which is based on an integral measuring method. Therefore, the warm sample end is pushed against a block of pure copper to maintain constant heating. To ensure a well-defined and reproducible electric contact, the adjustable force is observed with a piezoelectric sensor. While the reference junction is kept at 0 °C, the hot junction is gradually heated until 500 °C. Argon in the sample compartment prevents an oxidation of the sample material and related measurements errors. Due to the very low thermoelectric voltages of only a few millivolts in this temperature range, a precision voltmeter records the previously amplified and filtered signal. Since calibration quality directly depends on temperature measurement accuracy, two high-precision thermocouples are placed directly at the hot and one at the reference junction. A small wire diameter minimizes signal delays due to heat conduction. The measurement of both materials of a standardized type-K thermocouple showed a maximum deviation of the measured thermoelectric voltage of 1.5%.

More details on this subject can be found in [17,27–31].

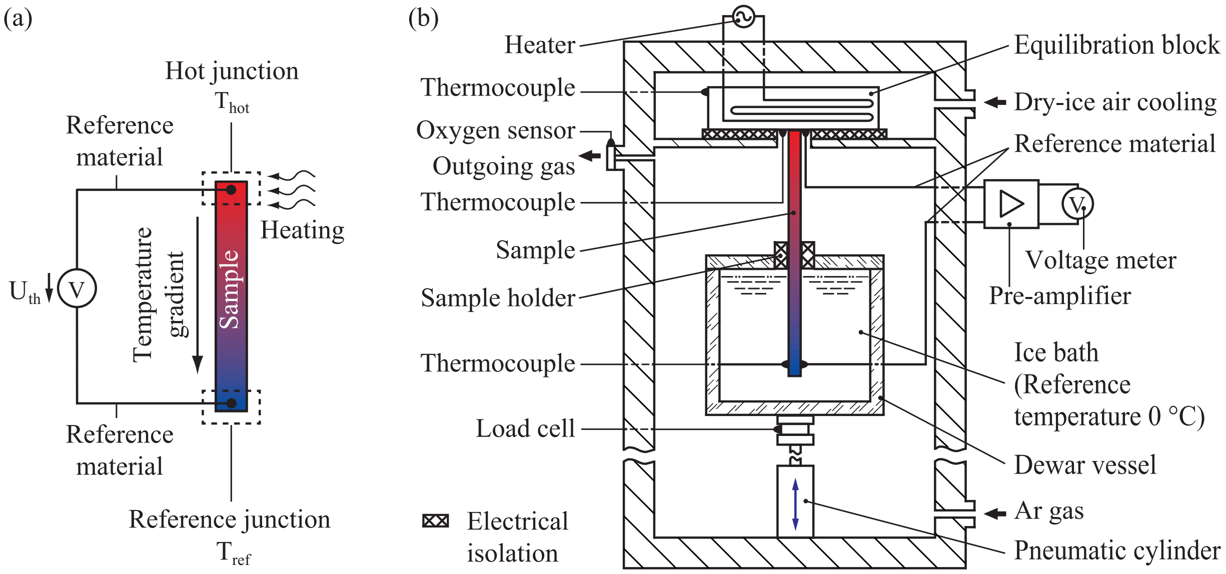

Fig. 2: (a) Schematic diagram of the integral method for measuring the relative Seebeck coefficient and (b) its implementation according to [17]

3.2 Blanking tool for temperature and thermoelectricity measurement

In order to derive fundamental interactions between process parameters, temperature, thermoelectric currents and adhesive wear during cold metal forming, the measurement setup has to meet several requirements. Despite the short period in which forming processes take place as well as the geometrical constraints in a forming tool, a high temporal resolution and a defined measurement point are necessary. Furthermore, it must be rugged to resist mechanical loads without affecting the forming process. Therefore, a special tool was developed, which enables an instantaneous and in situ measurement. Figure 3a schematically shows the electric circuits of voltage and current measurement, as well as how currents are externally applied to the tool.

Temperature determinations are carried out with a tool-workpiece-thermocouple. Therefore, punch and sheet metal are connected to a voltmeter and the arising thermoelectric voltage is measured. After its calibration according to Chapter 3.1, a temperature, averaged over the whole contact area of punch and sheet metal, can be derived from the thermoelectric voltage signal. Thermoelectric current measurements require a sensor, which does not change the electrical resistance of the circuit. Current clamps meet this requirement since they use the magnetic field of conductors, so that the measurement is potential-free. In combination with low resistance connection wires to close the short circuit, a negligible change in the electrical resistance is ensured. Connecting punch and sheet metal to a source-measure-unit allows influencing thermoelectric currents, wherefore an investigation of the correlation between external currents and adhesive tool wear is possible. Due to the accuracy of this unit and a simultaneous measuring and generating of signals, a regulated constant current can be applied to the tool in consideration of the naturally arising thermoelectric current.

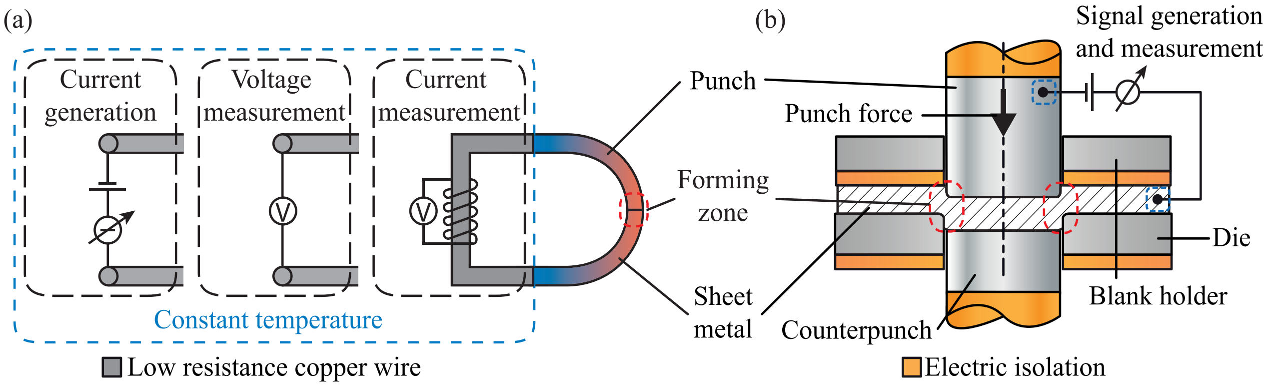

Fig. 3: (a) Electrical circuits for signal measurement and generation as well as (b) their schematic implementation in the embossing tool [26]

To prevent interfering signals, the above-mentioned measurement principles were implemented in a tool with electrically isolated sheet metal and active elements. Figure 3b shows the corresponding schematic diagram. This concept allows thermoelectric voltages and currents to be measured as averaged values over the whole contact area between punch and sheet metal. During this project, an adapted single stroke tool for hydraulic presses and a new designed tool for mechanical presses were used. As the exemplary results presented below were achieved with the latter due to an improved variability, only this tool will be described. Figure 4 illustrates the real tool as well as a sectional view of the last two stations. It was developed particular for investigations regarding thermoelectricity in single and continuous stroke examinations with reproducible punch velocity profiles throughout the whole stroke independent of the press force. The four-pillar construction ensures high stiffness and an application of smallest cutting clearances down to 25 µm. Due to its modular design, the tool is very suitable for parameter variations. A configurable blankholder force allows an analysis of sheet materials with different mechanical properties. Zirconium oxide applications on die, blankholder and punch with a compression strength of 2300 MPa, a thickness of 5 mm and a specific electrical resistance of 10^9 Ωmm electrically isolate punch and sheet metal. Fiberglass washers with a specific electrical resistance of 10^{14} Ωmm isolate all tool screws. Low noise cables serve as contacting wires in order to reduce interference currents generated through cable movement. A golden spring contact enables a defined and reproducible electrical contact to the sheet metal even during continuous stroke experiments. The whole tool consists of four stations where both forming and blanking operations are executable simultaneously under different electrical conditions. The fifth station can be used for cutting sheet metal strips during continuous stroke. Preloaded piezoelectric load cells measure both forming and retraction forces in every station and a precise contact-free eddy current sensor the punch travel.

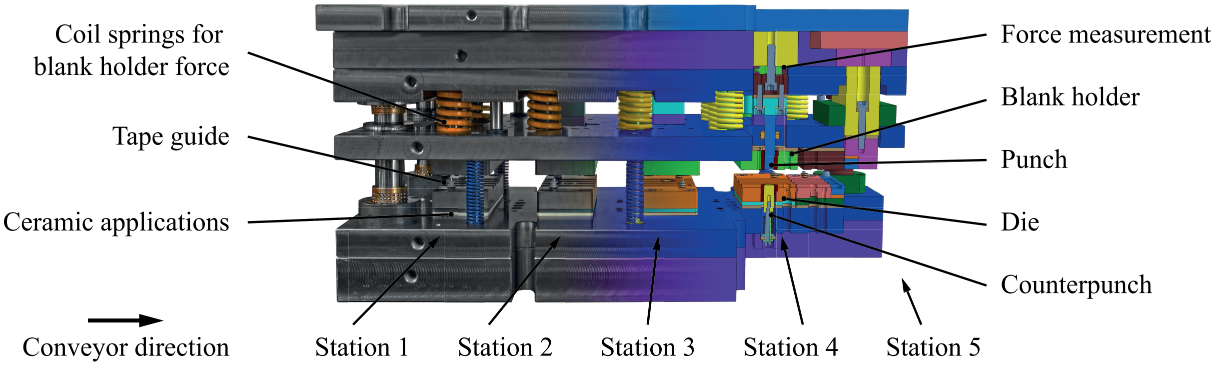

Fig. 4: Experimental tool for measuring and influencing thermoelectric signals during cold metal forming processes

3.3 Investigated materials

To derive material dependent influences on thermoelectric currents and adhesive wear, several frequently used tool and sheet materials were investigated during blanking and cold forming experiments. The aluminum alloy EN AW 5083, the hot-rolled fine-grain steel S355MC and the austenitic stainless steel 1.4301 served as sheet metal. Active elements were made out of the cold working steel 1.2379, the high-speed steel 1.3343, the cemented carbide CF-H40S and the austenitic stainless steel 1.4301. The sheet metals used have a thickness of 4 mm except the metal strip for continuous stroke experiments, whose thickness is 2.5 mm. All samples were cleaned before every experiment to ensure a lubricant free surface.

EN AW 5083 (AlMg4.5Mn0.7) provides a tensile strength of 270 MPa and finds application in the automotive, electronics and food industry as well as for household appliances. Due to its high tendency to form adhesions, it represents the central sample material for single stroke investigations. S355MC has a tensile strength of 491 MPa. This hot-rolled steel is representative for cold forming and blanking operations. 1.4301 (X5CrNi18-10) with a tensile strength of up to 720 MPa and a good corrosion resistance is the most commonly used stainless steel in industry. Like aluminum, this material tends to form adhesions and serves therefore as sheet material for continuous stroke experiments.

The cold working steel 1.2379 (X153CrMoV12) with a hardness of 58 HRC as well as the high-speed steel 1.3343 with 62 HRC represent typical tool steels. While bigger carbides characterize 1.2379, 1.3343 has a finer microstructure. CF-H40S is a powder metallurgical cemented carbide with a hardness of 1400 HV10. Its fine-grain structure and high homogeneity provide a constant Seebeck coefficient across the whole punch, ensuring accurate temperature measurements. Besides these commonly used materials for active elements in forming and blanking tools, punches made out of 1.4301 were investigated because of similar thermoelectric behavior compared to EN AW 5083. All punch materials have an electrical resistance of about $10^{-4}\Omega/\mathrm{mm}$. 1.4301 has a heat conductivity of 15 W/(m*K) compared to 22 W/(m*K) for 1.3343 and about 90 W/(m*K) for CF H40S. Table 1 shows the chemical composition of all utilized materials.

Tab. 1: Chemical composition of all used materials in weight-%

	C	Cr	Mg	Mn	Mo	Ni	Si	V	W	WC	Al	Fe	Co
EN AW 5083	-	0.1	5.8	0.5	-	-	0.1	-	-	-	balance	0.1	-
S355MC	0.1	-	-	0.45	-	-	-	-	-	-	-	balance	-
1.4301 (4 mm)	-	18.5	-	1.7	0.3	8	0.4	-	-	-	-	balance	-
1.4301 (2.5 mm)	-	19.0	-	1.3	0.4	10.8	0.7	-	-	-	-	balance	-
1.2379	1.2	13.0	-	0.3	0.7	0.1	0.3	0.6	-	-	-	balance	-
1.3343	0.8	4.2	-	-	8.4	0.3	0.4	2.2	5.6	-	-	balance	0.7
CF-H40S	-	-	-	-	-	-	-	-	-	88.0	-	-	balance

4 Thermoelectric behavior

Figure 5a illustrates the relative Seebeck coefficients of the investigated materials as a function of temperature between 0 °C and 500 °C. Since the chemical composition mainly determines the Seebeck coefficient, all materials show a completely different thermoelectric behavior over the whole temperature range. While the investigated steel and aluminum alloys have positive Seebeck coefficients, cemented carbide has a negative one.

This can be traced back to the Seebeck coefficients of alloying elements, which also vary in amount and algebraic sign. For this reason, Seebeck coefficients can almost be equal despite different material compositions. 1.4301, the stainless steel for example, has a similar Seebeck coefficient to the aluminum EN AW 5083, which highest deviation over the whole temperature range amounts to only 9%. Cold working steel generates a high Seebeck coefficient due to a high portion of chromium. Compared to 1.3343, the coefficients are also very similar, although this high-speed steel contains considerably less chromium. In case of 1.4301, nickel, having a very high negative coefficient, balances chromium and a lower entire coefficient results. Compared to all steel alloys, S355MC has the largest portion of pure iron and thus, exceedingly few alloying elements. Consequently, even the course of the Seebeck coefficient differs strongly. For this reason, a theoretical determination of the thermoelectric behavior is not possible at present. However, the strength of thermoelectric voltages and currents as well as the direction of the latter depends on Seebeck coefficients, the knowledge about them is indispensable with regard to experimental investigations. Hence, an experimental characterization of all used tool and sheet materials is necessary and has been done.

Mechanical properties and thicknesses of the sheet metals as well as process parameters mainly determine the occurring temperature in the forming zone during cold metal forming. Besides temperature, the combined Seebeck coefficient, which represents the difference between the Seebeck coefficients of sheet and tool material, determines the strength of thermoelectric voltages and currents as well as the direction of the latter. In order to investigate the precise impact on thermoelectric currents and adhesive wear during embossing, different tool materials were used in combination with the sheet metal EN AW 5083 and constant process parameters. Therefore, the same temperature occurs in the forming zone and only thermoelectric material behavior changes. Figure 5b illustrates three exemplary combined Seebeck coefficients, which were used in the experimental embossing investigations presented in Chapter 6 and Chapter 7 respectively. While the high-speed steel 1.3343 generates a positive Seebeck coefficient together with the aluminum EN AW 5083, the cemented carbide CF-H40S has a negative one and the stainless steel 1.4301 one close to zero. Beyond that, this precise determination also offers the possibility to investigate the impact of adhesive wear on the thermoelectric behavior of punch materials.

The references [17,27,30,31] offer further information regarding this topic.

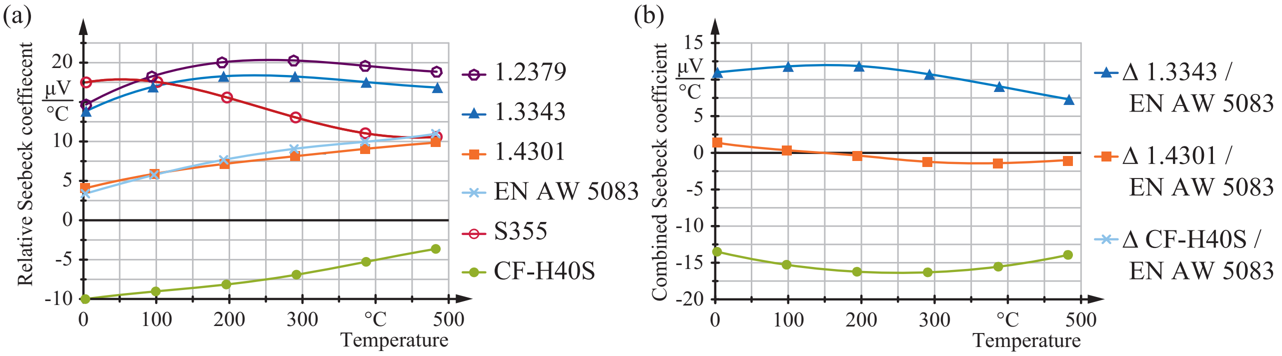

Fig. 5: (a) Seebeck coefficients of the investigated materials relative to platinum and (b) the difference between the Seebeck coefficients of the respective tool steel and the aluminum alloy EN AW 5083

5 Temperatures in the forming zone

The temperature in the forming zone is one of the most important factors in cold metal forming operations since it influences mechanical material properties, wear development and the choice of lubricants. Furthermore, together with the Seebeck coefficients of sheet and tool material, temperature determines slope and strength of thermoelectric currents and voltages. In order to investigate the correlation between process parameters, sheet metal properties and temperature during embossing, punch velocity, die clearance as well as sheet material and its thickness was varied. The highest temperature occurs at the maximum embossing depth, which corresponds to the end of clean cut formation during blanking. In order to relieve load on the punch and prevent punch failure without changing the maximum temperatures, a complete sheet metal separation was done during all presented experiments.

The stainless steel 1.4301 served as sheet metal and its thickness was varied between 2.5 mm and 4 mm. In order to reveal the consequences of different mechanical properties, S355MC with the same thickness was used as comparative steel. Furthermore, relative die clearances of 1%, 5% and 10% as well as stroke rates of

60 1/min, 150 1/min and 300 1/min, which correspond to approximate punch impact velocities of 50 mm/s, 140 mm/s and 270 mm/s, were investigated.

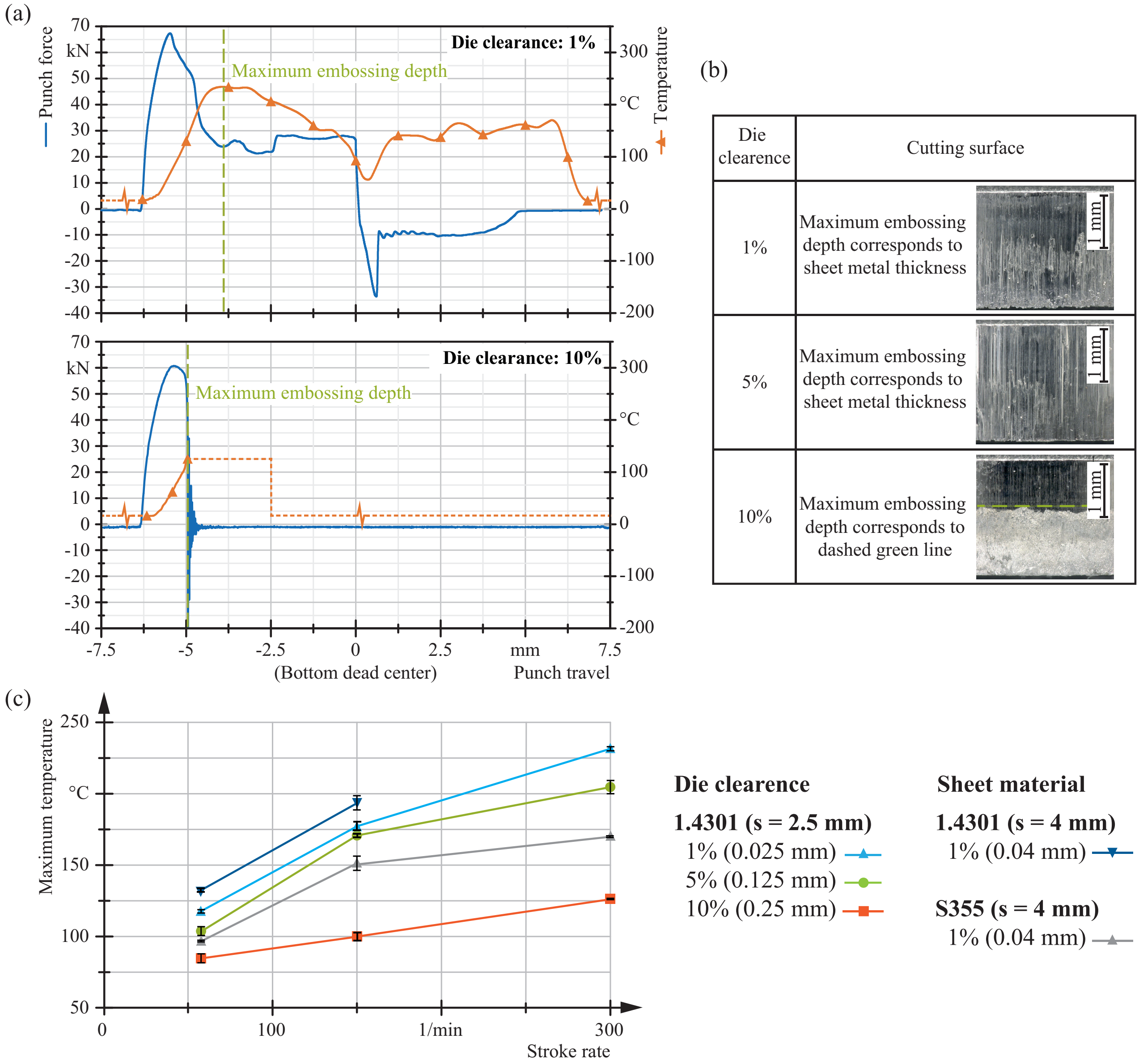

Fig. 6: (a) Temperature profiles when blanking a 2.5 mm thick 1.4301 with 1% and 10% die clearance, (b) related cutting surfaces and (c) maximum temperatures with respect to exemplary process parameters and sheet metals [28,29]

All measured temperature curves show characteristic features depending on the formed cutting surface. Therefore, Figure 6a illustrates two exemplary temperature curves for a relative die clearance of 1% and 10%, conducted with a stroke rate of 300 1/min and 2.5 mm thick stainless steel 1.4301 sheets. Negative values on the x-axis correspond to a punch travel downwards until the bottom dead center at 0 mm. In both cases, a thermoelectric voltage emerges with the contact of punch and sheet metal at -6.34 mm. The measured temperature of 22 °C corresponds to room temperature. During the elastic deformation at the beginning, a levelling of roughness asperities leads to a slight temperature rise until -5.90 mm. When the plastic deformation of the sheet metal starts, temperature increases significantly faster due to a higher amount of dissipating plastic work. Since the area under the force curve corresponds to conducted forming work, the current amount of dissipating work can be estimated. In case of 1% die clearance, a maximum temperature of 230 °C is reached shortly before the complete material separation at -3.93 mm at the maximum embossing depth, which corresponds almost to the sheet metal thickness. An increased friction between punch and metal strip due to adhesions on the lateral surface of the punch leads to a subsequent small rise in punch force and keeps the temperature on its maximum level. Afterwards, temperature decreases until the bottom dead center. A clamping slug from the previous stroke leads to a renewed punch force rise at -2.5 mm. However, friction between slug and die does not influence the temperature between punch and sheet metal. During the return stroke, adhesive wear causes a rise of the retraction force until it is sheared off, which leads to a short oscillation of the punch. Friction causes the temperature to rise again until a maximum of 171 °C at 5.92 mm. With the loss of contact between punch and sheet metal, no more thermoelectric voltage and thus, temperature is measurable. When comparing both die clearances, the qualitative course is similar until sheet metal separation. In case of 10%, the maximum temperature of 126 °C is also reached at the maximum embossing depth at -5 mm. However, the large die clearance prevents a clamping of the punch in the metal strip. Consequently, the stored elastic energy is suddenly released which leads to an oscillation of the punch. Since the contact between sheet metal and punch gets also lost, no more thermoelectric signal is measurable.

Figure 6b illustrates the cutting surfaces of the punching strip for 1%, 5% and 10% relative die clearance. Since 1% and 5% exhibit similar ones, the qualitative temperature profile is the same, too. Only the maximum temperature differs due to the size of the forming zone, which increases with die clearance. Consequently, the dissipation takes place in a bigger area, which reduces the maximum temperature by 22 °C.

Figure 6c shows the impact of the above-mentioned process parameters and sheet metal variation on the maximum temperatures during embossing. An increase in the maximum temperature with punch speed is evident for all investigations. Basic reason is the reduced time for heat equalization processes while the same amount of plastic work dissipates. In case of a 4 mm thick S355MC and a die clearance of 1%, temperature rises exemplarily from 96 °C at 60 1/min, over 151 °C at 150 1/min, to 165 °C at 300 1/min. A comparison between S355MC and 1.4301 reveals the influence of mechanical sheet material properties. While the tensile strength of S355MC is 32% smaller than the one of 1.4301, its maximum temperature is reduced by 29% in case of 60 1/min and by 23% in case of 150 1/min. For the stainless steel 1.4301, high retraction forces lead to a punch failure, wherefore a temperature measurement for a stroke rate of 300 1/min was not possible. However, the change in temperature due to different sheet metal thicknesses but equal relative die clearances was also investigated. Embossing experiments using 1.4301 sheets with 2.5 mm and 4 mm thickness and a relative die clearance of 1% show a relatively low increase in temperature from 119 °C to 136 °C at a stroke rate of 60 1/min and from 176 °C to 196 °C at 150 1/min. This can be traced back to the spatial expansion of the area where plastic work dissipates. Its enlargement with sheet metal thickness counteracts the bigger quantity of plastic work necessary for embossing operations. Furthermore, a change of the relative die clearance significantly influences maximum temperatures as the size of the forming zone changes but the amount of dissipated work is almost constant. For the 1.4301 2.5 mm sheet metal, the temperature rises from 84 °C with a die clearance of 10% to 119 °C with 1%, at a stroke rate of 60 1/min. At 300 1/min, an increase from 125 °C to 230 °C is measured. In conclusion, the maximum temperatures depend on spatial expansion of the forming zone, the time for heat equalization and the amount of conducted plastic work.

Further information on the temperature development in the forming zone is provided by [28,29,32,33].

6 Thermoelectric currents

In order to investigate the impact of thermoelectric currents on adhesive wear, profound knowledge about their course and strength is necessary. Therefore, several blanking experiments with different punch materials were conducted and arising thermoelectric currents were measured instantaneously. Figure 7 shows three exemplary force profiles (a) and the associated thermocurrent profiles (b) over the punch travel. During all experiments, 4 mm thick EN AW 5083 sheets, a relative die clearance of 1% and a stroke rate of 300 1/min was used. The presented curves are averaged over nine consecutive strokes and dashed lines indicate the maximum deviation. The algebraic sign of the thermocurrent specifies its direction. While positive currents stand for a technical current direction from sheet metal to punch, negative values represent the opposite direction. Together with the aluminum sheet, the chosen tool materials generate different combined Seebeck coefficients, which are illustrated in Figure 5b. The use of the high-speed steel 1.3343 results in a positive one, the cemented carbide CF-H40S in a negative one and the stainless steel 1.4301 in one close to zero since it has almost the same Seebeck coefficient as EN AW 5083. Since temperature in the forming zone is mainly determined by dissipating forming work, the similar force profiles shown in Figure 7a confirm that the measured maximum temperature of 75 °C is consistent during all experiments. Therefore, only the change due to the thermoelectric behavior of the punch material is apparent, which can be seen in Figure 7b. While the technical current direction in case of cemented carbide is from sheet metal to punch, it is in opposite direction for the high-speed and the stainless steel. Despite these differences, all thermocurrent courses show characteristic curve shapes because they are determined by the temperature development in the forming zone.

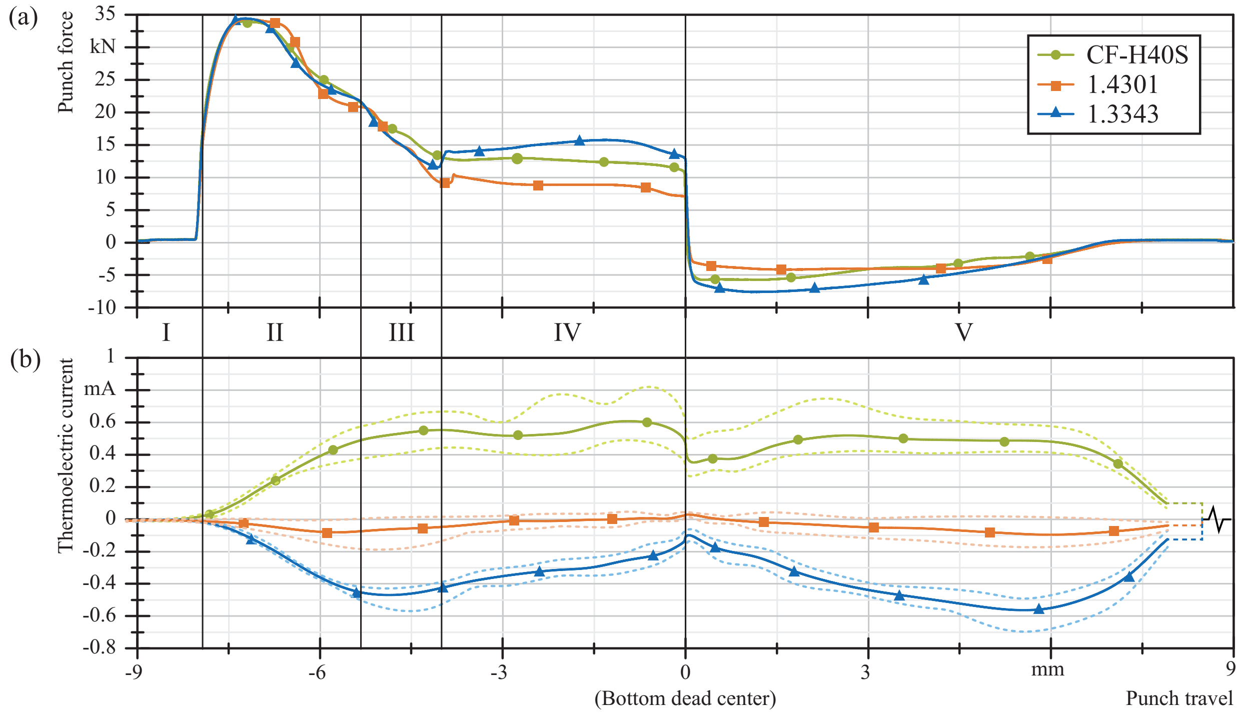

Fig. 7: (a) Force curves and (b) thermoelectric current profiles of different tool materials during blanking of 4 mm thick EN AW 5083 sheets with 1% die clearance and a stroke rate of 300 1/min [30]

Thermoelectric currents arise with the punch force increase in Phase I at -8 mm before the bottom dead center. During the elastic deformation of the sheet metal, a levelling of asperities causes a temperature increase and therefore, thermoelectric currents. In Phase II, starting at about -7.6 mm, the initiation of plastic deformation takes place, the clean cut is formed and the maximum force of about 34 kN is reached. While the thermocurrent of 1.3343 and CF-H40S rise constantly during this phase, the averaged profile of 1.4301 reaches a slight maximum. In sum, the occurring current in case of 1.4301 is very low and reaches only values below 0.1 mA. However, although its combined Seebeck coefficient with EN AW 5083 is almost zero, the averaged current course is negative. This can be traced back to adhesions on the lateral surface, which change the overall Seebeck coefficient of the punch. Since adhesions are strain hardened due to the preceding plastic deformation, their thermoelectric behavior differs from the sheet metal and thermoelectricity arises. This effect increases with the amount of adhesions on the punch and occurs independently from the material combination. With regard to the first stroke of 1.4301, which is represented by the dashed orange line close to zero, almost no thermoelectric current occurs.

In Phase III, both the high-speed steel and the cemented carbide reach the maximum thermocurrent, albeit at different times. The maximum thermocurrent of 0.07 mA in case of 1.4301 corresponds, compared to 0.59 mA for cemented carbide and 0.47 mA for 1.3343, to a reduction of 88% and 85% respectively, confirming a significant influence of the Seebeck coefficient on thermoelectric currents. The mentioned time delay between the maxima occurs due to a material dependent adhesive wear development, which will be explained in Chapter 7.2. The slight deviations in the force profile during Phase II and III occur due to different frictional forces between punch and stamping grid as well as between slug and die depending on the adhesive wear condition. Furthermore, the elastic deformation of the punch differs in dependence of its material. A numerical calculation shows a force induced radial widening in the area of the cutting edge of 7 µm for the 1.4301 punch. In case of 1.3343, this widening amounts to 5 µm and 2 µm for CF-H40S. Stress calculation and laser microscopic imaging exclude a permanent plastic deformation. The elastic deformation leads to changes in the die clearance what in turn affects the hydrostatic compression and crack initiation. [34] Consequently, a clean cut proportion of 75% for 1.3301, 69% for 1.3343 and 69% for CF-H40S results. With increasing relief of the punch due to decreasing forces, its original form returns and friction is reduced.

Together with the differing clean cut proportions and thus, contact conditions as well as the respective heat conductivity, the course of the thermoelectric current profile is material dependent during Phase IV. The force raise at the beginning, after the complete separation of the sheet metal, occurs due to a clamping slug from the previous stroke. Since this frictional force arises between clamped slug and die, thermoelectric currents measured between punch and stamping grid are not affected. The slight differences in force level are due the respective adhesive wear condition of the die.

During the return stroke in Phase V, friction between stamping grid and punch causes a dissipation of plastic work required for levelling of roughness asperities. Consequently, temperature and thus, thermoelectric currents rise again. The extent and the course of the thermocurrents in the return stroke depend mainly on the state of adhesive wear, the heat conductivity of the punch and its preceding elastic deformation, which influences the springback of the stamping grid, as well as the thermocurrent strength at the bottom dead center.

More information about this chapter can be found in the references [26,27,30,31,35–37].

7 Thermoelectricity and adhesive wear

The above-presented findings concerning thermoelectric material behavior, temperature development in the forming zone and occurring thermoelectric currents enable a derivation of correlations with the arising adhesive wear on the lateral surface of the punch. Therefore, several blanking examinations were conducted and the evolved wear pattern was examined. After a short introduction on adhesive wear formation, its change with varying punch materials and externally influenced thermoelectric currents will be presented.

7.1 Adhesive wear formation and development

Although adhesive wear belongs to the biggest challenges in cold metal forming, both the exact processes involved in its formation and all influencing factors are insufficiently known. So far, adhesive wear formation is mainly attributed to mechanical interactions between surfaces in contact. According to Czichos and Habig, plastic deformations of the contacting asperities result in a crack in the oxide layer of both materials. [2] Due to the high reactivity of the exposed surfaces, electron exchange causes valence electrons to be shared which results in a chemical bond. The bond strength depends inter alia on material properties and the lattice structure of the materials in contact. [6] In case of a relative movement between surfaces in contact, a material separation takes place in the cohesive weaker bonded material. [38] During cold metal forming, these processes cause a material transfer from sheet metal to punch. Further processing leads to a shearing of adhesions due to friction. Consequently, tinsel arises, which reduce part quality and increase the risk of serious tool damage. [39] Furthermore, a second phenomenon causing adhesive wear appears. Due to a strong plastic deformation of the asperities, much work dissipates in a small area, which results in high temperatures. Together with the poor heat conductivity, especially at the top of the asperities, temperatures can even exceed the melting point of the materials in contact. [40,41] This effect is enhanced by the present thermoelectric current flow. [42]

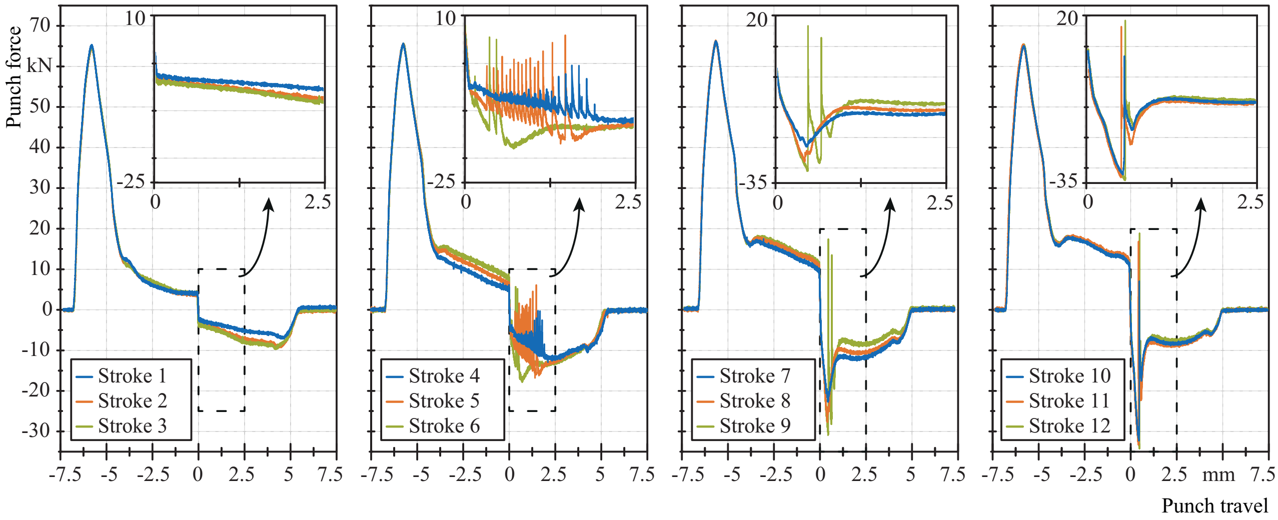

Fig. 8: Impact of adhesive wear development on the punch force during the first 12 consecutive strokes when blanking 2.5 mm thick 1.4301 sheets with a 1.3343 punch and 1% relative die clearance [43]

During cold metal forming, adhesive wear can appear within a few strokes, especially when no lubricant is applied. Sheet materials, which have a high adhesion tendency, like aluminum, stainless steel or titanium, can even accelerate wear initiation. Figure 8 illustrates force profiles of a continuous stroke blanking experiment. With 2.5 mm thick 1.4301 stainless steel sheets, the high-speed steel 1.3343 as punch material, a stroke rate of 60 1/min and a relative die clearance of 1%, adhesive wear increases friction forces before the bottom dead center and the retraction force in the return stroke already after the first stroke. After three strokes, strong oscillations appear due to adhesive wear on the lateral surface of the punch, which increase frictional forces between punch and stamping grid. From the fourth to the sixth stroke, a shearing of adhesions causes an oscillation in the force profile, which disappears for the next two strokes. Stroke 9 shows the highest oscillation amplitude but only two impulses. This force development confirms in sum the cyclic wear formation during blanking, a scratching in the stamping grid and a shearing of adhesions during the return stroke. Since the retraction force peak does not change significantly during the next strokes, a first maximum in adhesive wear is reached. Therefore, adhesive wear was always measured after nine strokes. [43]

7.2 Seebeck coefficients and adhesive wear

While the arising temperature in the forming zone during embossing mainly depends on mechanical sheet metal properties and process parameters, its change is only possible by an application of lubricants. In contrast, the existing variety of tool steels and carbides allows an influence of the occurring thermoelectric currents independent from the prevailing temperature in the forming zone by a material choice with regard to the thermoelectric behavior of the sheet metal. In order to show the impact on wear development, the stainless steel 1.4301, the high-speed steel 1.3343 and the cemented carbide CF-H40S were exemplarily chosen. A relative die clearance of 1% was used and 4 mm thick EN AW 5083 sheets served as sheet metal. The combined Seebeck coefficients between punch and sheet material are shown in Figure 5b and the respective thermocurrent profiles in Figure 7b. Figure 9 illustrates the elevation profiles of the respective punch material. As mentioned above, these elevation profiles of the wear patterns on the lateral surface of the punch were all taken after nine strokes, before a serious removing of adhesions begins. They represent an exemplary area of 1 mm x 7 mm on the lateral surface of the punch next to the cutting edge, which builds the basis for the calculation of the wear coefficient (WC). Therefore, the wear volume in this area is first measured. A subsequent subtraction of the initial surface roughness considers manufacturing disparities. Finally, this coefficient represents the height of the adhesive layer under the assumption of a homogenous distribution. Its value as well as the maximum thermocurrent of the respective punch material are also indicated in Figure 9.

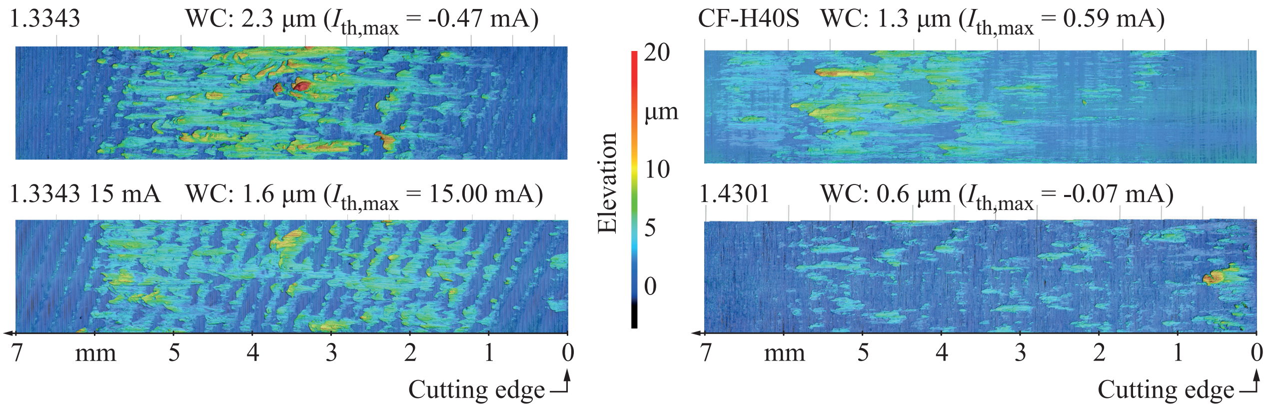

Fig. 9: Representative areas of worn lateral punch surfaces next to the cutting edge, the related wear coefficient (WC) and the respective maximum thermocurrent $I_{th,max}$ with regard to different electrical conditions after nine strokes [42]

A comparison of all wear patterns reveals fundamental differences. While the use of 1.3343 leads to a wear coefficient of 2.3 µm, it is 1.3 µm in case of CF-H40S. A combined Seebeck coefficient of zero for 1.4301 results in the lowest wear coefficient of 0.6 µm. This corresponds to a wear reduction of more than 74% compared to 1.3343 and 54% in case of CF-H40S. Although cemented carbide generates the highest thermoelectric current, its wear coefficient is 44% lower than the one of 1.3343. Since the second distinction between CF-H40S and 1.3343 is thermocurrent direction, these results show its significant influence on adhesive wear. In sum, a strong correlation between the amount of adhesive wear and both current direction and strength can be derived. While low thermoelectric currents result in little adhesive wear, thermoelectric current direction gains influence with increasing current strength. However, the amount of adhesive wear formation due to melting processes at the asperities grows simultaneously. At a certain current strength, these processes outweigh and despite the current direction, adhesive wear rises again.

Furthermore, a comparison between adhesive wear patterns and thermoelectric current profiles also reveals strong correlations. When regarding the 1.3343 punch surface, no adhesions at the cutting edge occur. After 0.5 mm, adhesions increase slightly until the maximum quantity is reached between 3 mm and 4.5 mm. The same course applies to the thermocurrent profile. Afterwards, both the amount of adhesive wear and thermoelectric current decline again until the bottom dead center. The cemented carbide CF-H40S shows an analogical behavior with only minor differences. Due to the opposing current direction, flatter adhesions occur and the maximum is less pronounced than in case of 1.3343. The adhesive wear pattern of 1.4301 is completely different. First, a maximum of adhesive wear occurs next to the cutting edge, which can be traced back to an elastic deformation of the punch during the intrusion in the sheet metal, as mentioned in Chapter 6. While the use of 1.4301 leads to a radial widening of 7 µm, 1.3343 to 5 µm and CF-H40S to 2 µm. This widening primarily influences the die clearance, resulting in different cutting surfaces of the sheet metal. Apart from secondary clean cut, the clean cut proportion amounts to 75% for stainless steel, 69% for high-speed steel and 60% for cemented carbide, which correlates very well to the deformation degree of the punch. Reduced die clearance and thus, increased hydrostatic pressure in case of stainless steel causes a formation of adhesions near the cutting edge at about 0.5 mm. Since these adhesions additionally lower the die clearance and act as nucleation centers itself, an accumulation of adhesions in this area develops. Afterwards, a homogenous adhesive wear pattern occurs, which is formed by chemical bonding due to valence electron exchange. The suppression of thermoelectric currents reduces the current density in the asperities and implies at least a reduction of melting processes. Consequently, less adhesive wear with a consistent dispersion arises. The presented results show in sum the importance of material choice with regard to thermoelectric behavior in order to reduce adhesive wear during cold metal forming.

7.3 External control of currents

Influencing thermoelectric currents by an external generation of regulated currents enables to apply infinitely variable currents in both directions to the contact area between punch and sheet metal. Therefore, a source-measure-unit was connected in order to examine the impact of external currents on the adhesive punch wear behavior. Several blanking experiments were conducted and both strength and direction of the applied current were varied. A relative die clearance of 1%, a punch stroke rate of 60 1/min and the use of EN AW 5083 with a thickness of 4 mm as sheet metal ensures a comparability with the material variation investigations of Chapter 7.2. Since 1.3343 has been chosen as punch material through all these experiments, this punch material without an external current serves as reference.

Figure 10 illustrates the impact of different current strengths and directions on the amount of adhesive wear by means of the wear coefficient after nine strokes. Additionally, the gained results from the material variation experiments are shown. The presented wear coefficients reveal basic relations between thermoelectric currents and adhesive wear. As already seen in Chapter 7.2, current direction plays an important role. When applying a regulated current of 15 mA with a technical current direction from punch to sheet metal, the wear coefficient increases compared to the reference by 13%. The same current in opposite direction reduces the wear coefficient by 31%. This confirms the significant impact of current direction on adhesive wear formation. However, its extent depends on current strength. A current of 1 mA from sheet metal to punch hardly affects adhesive wear. With increasing current, the wear coefficient declines until a minimum is reached with 15 mA before a renewed raise takes place. Despite the reduction with regard to the reference, compared to CF-H40S and 1.4301, the minimum wear coefficient is about 23% and 167% higher respectively.

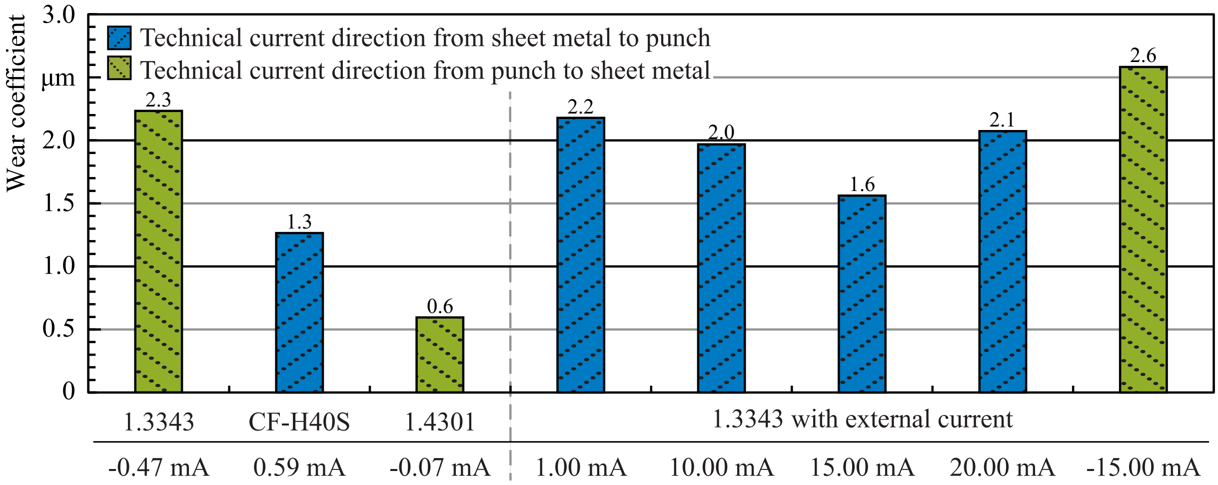

Fig. 10: Resulting wear coefficients after influencing thermoelectric currents by material choice and externally generated currents [41]

Besides the amount of adhesive wear, externally generated currents show a significant influence on the wear pattern. This can be seen in Figure 9, when comparing the wear patterns of the 1.3343 reference punch without any applied current and the externally influenced 1.3343 punch with an external current of 15 mA from sheet metal to punch. While adhesive wear accumulates next to the cutting edge on the lateral surface of the latter, the reference exhibits no adhesions in this area. This accumulation can be traced back to the constant regulated current at the beginning of the blanking process. Due to a small contact area between punch and sheet metal, high current densities arise, which strengthen adhesion formation. With an increasing contact area and thus, a decreasing current density, a relatively homogenous spread adhesive wear occurs. Adhesions arise mainly at the grinding marks of the surface, which confirms that adhesions are primarily formed at surface elevations where highest tensions and temperatures occur. For this reason, adhesions also act as nucleation centers itself. Due to the higher wear rate of the reference punch compared to the externally influenced punch, its wear pattern exhibits centers of adhesion accumulation with higher elevation especially between 3 mm and 4 mm away from the cutting edge. In case of the influenced punch, the current reduces adhesive wear formation, wherefore the overall elevation of the adhesions is lower.

These differences in adhesive wear development also affect the punch force during blanking, which can be seen when comparing the force curves of the first 12 consecutive strokes of the reference punch shown in Figure 8 and the externally influenced punch illustrated in Figure 11. Both force curves were measured during blanking of 2.5 mm 1.4301 sheets with a 1% relative die clearance. During all strokes, the force needed to push the slug through the die increases continuously for both punches. While the force right before the bottom dead center amounts to almost 5 kN for both punches in the first stroke, it reaches 15 kN in case of an external current and 12 kN for the reference punch during stroke 12. Since this force is mainly determined by adhesive die wear and only minor by friction between punch and stamping grid, its change do not affect adhesive wear on the punch. However, due to the difference in force, the external current seems to slightly strengthen adhesive wear in the die in this tool configuration with an electrical isolated die. With regard to the retraction forces, fundamental differences appear. During the reference experiments, adhesions on the punch cause strong oscillations starting from stroke 4. Contrary to that, oscillations in case of the externally influenced punch first occur during stroke 9. This can be traced back to a later initiation and more homogenous spread adhesive wear on the lateral surface of the punch, which reduces friction and inhibits the stick slip effect causing oscillations. Furthermore, an external current results in a much lower maximum retraction force of 25 kN compared to the reference, which amounts to 35 kN. Since both maxima stay almost constant during stroke 10 to 12, these results confirm the chosen interval of 9 strokes for an adhesive wear analysis.

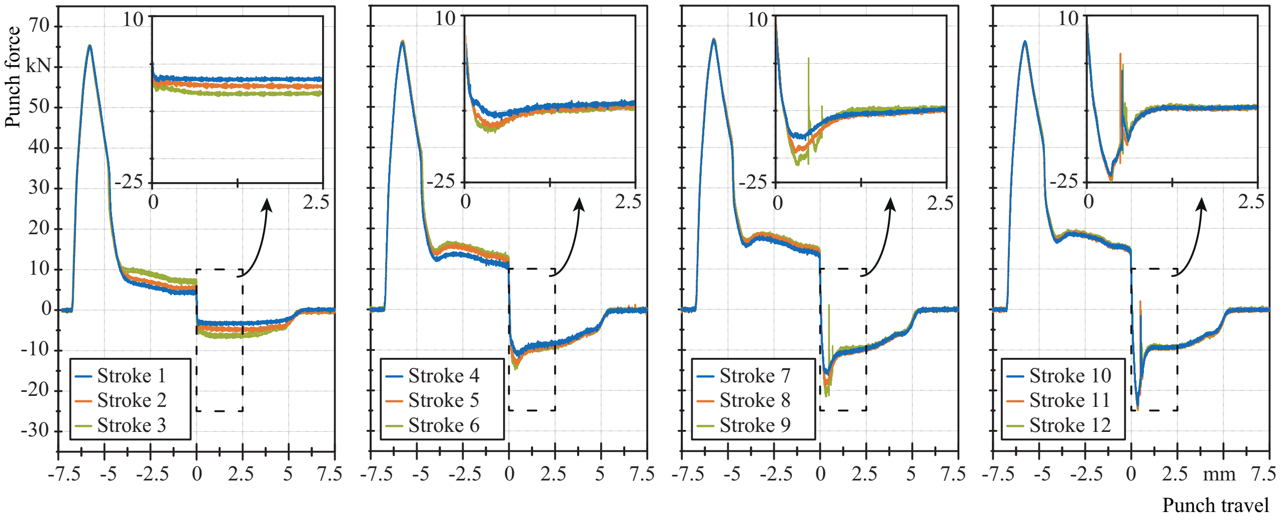

Fig. 8: Impact of adhesive wear development on the punch force during the first 12 consecutive strokes when blanking 2.5 mm thick 1.4301 sheets with a 1.3343 punch, 1% relative die clearance and an externally generated current of 15 mA from sheet metal to punch [43]

7.4 Fundamental interactions during adhesion formation

The presented results confirm a significant influence of thermoelectric currents on adhesive wear development. Based on all findings and the general description of adhesive wear formation, fundamental interactions on the atomic level with regard to temperature, thermoelectric currents and adhesive wear can be derived.

Figure 12 schematically shows the processes of adhesion formation during cold metal forming. As mentioned above, plastic deformations of asperities crack the oxide layer and thus lead to a high reactive metallic contact between punch and sheet metal. Electron exchange causes valence electrons to be shared between both contact partners, which results in a strong chemical bond. Comparable to most chemical reactions these processes are enhanced by increasing temperatures. More kinetic energy in metal lattice of the materials in contact supports diffusion processes and leads to a higher amount of collision processes, which rises the probability of chemical bonding. Therefore, temperatures should be as low as possible, in order reduce the interactions between the touching surfaces.

Besides temperature, thermoelectric currents influence adhesion formation during cold metal forming significantly. The movement of free electrons through asperities exerts two forces on the ions in the metal lattice, which influence chemical processes between punch and sheet material. First, impact processes between electrons and ions cause a transfer of kinetic energy and thus, a strong force in the direction of electron flow. Since the number of collisions increases with rising current density, the extent of this interaction depends on current strength. The second force arises due to an electrical field, which is induced by charge carrier movement. This electrostatic force is weak and contrary directed, which can be seen in Figure 12. Consequently, the diffusion and ionic migration acquire the same direction as the electron flow. These electromigration processes are well known from electrical devices. [44] The results show that a technical current direction from sheet metal to punch minimizes material transfer. In this case, electrons flow vice versa from punch to sheet metal and collisions with ions hinder material transfer from sheet metal to punch. A current flow in opposite direction results in more adhesions due to the impact force direction. The extent of these electromigration processes depends on current density, which is determined by the thermoelectric or external generated current strength respectively and the prevailing contact conditions. While low currents hardly influence adhesive wear due to low current densities in the asperities, the passage of high currents raises the amount of adhesive wear again. This can be traced back to Joule heating. Collision processes with phonons, electrons itself and ions, increase the natural oscillations in the metal lattice and thus, temperature. Together with the dissipated heat from conducted forming work, the probability that temperatures exceed the melting point in the asperities of the sheet metal rises. Since the sheet metal resolidifies with further relative movement and adheres to the punch, adhesive wear increases again with higher current strengths.

An externally regulated current enables a precise adjustment of the current flow in the forming zone. The results show that adhesive wear is reduced when the technical current direction is from sheet metal to punch and the strength is adapted to the material combination as well as the forming process. Therefore, the formation of adhesion is hindered and adhesive wear can be reduced by 31%. The higher applied current strength compared to the naturally arising thermoelectric currents can be traced back to the conditions of contact. Since the measured thermoelectric currents are averaged over the whole area of contact between punch and die, temperature development and thus thermoelectric currents in the asperities varies. In areas characterized by low deformations degrees like at the front face of the punch, almost no currents are generated. In contrast, strong deformations of the sheet metal in the forming zone cause high currents. In order to reach an adequately low and consistent current density over all asperities, current strengths causing a wear reduction are higher than the measured thermoelectric currents. Nevertheless, different deformation degrees of asperities and inhomogeneity on an atomic scale cause circular currents, flowing in both directions between the surfaces. Therefore, an externally generated current partly strengthens thermoelectric currents, wherefore the achievable wear reduction is higher compared to a complete suppression of thermoelectricity by the material choice with regard to the Seebeck coefficient.

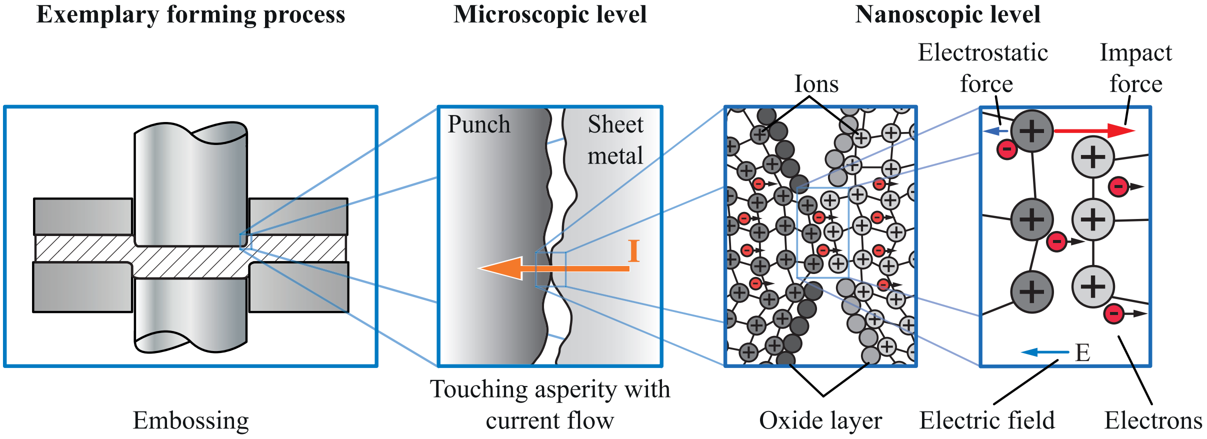

Fig. 12: Interactions between electrons and ions at touching asperities between punch and sheet metal according to [26]

The results gained by variating punch materials confirm the above-mentioned findings. With regard to current direction, a higher naturally arising thermocurrent from sheet metal to punch results in less adhesive wear compared to a lower current in opposite direction. Therefore, the Seebeck coefficient of the punch material should be lower than the one of the sheet metal in order to achieve the right current direction. However, adhesive wear is minimized when no thermoelectric currents flow and only chemical bonding occurs. The missing flow of electrons reduces melting processes due to Joule heating and the overall temperature in the asperities, which weakens chemical reactivity.

The references [26,27,30,31,33,36] offer more information on the correlation between thermoelectric currents and adhesive wear.

8 Transferability

In order to evaluate the validity range of the gained results and thus, the scope of application for this adhesive wear reduction method, additional deep drawing tests with externally influenced thermoelectric currents were carried out. Compared to blanking, deep drawing is characterized by lower temperatures and tool loads as well as different contact conditions between sheet metal and tool. Therefore, a transferability to all manufacturing processes is highly probable in case of similar results.

Since the biggest surface pressures and temperatures occur in the draw ring, the principle tool structure was turned. Contrary to the embossing experiments, the electrical circuit for current generation does not consist of punch and sheet metal but of die and sheet metal. Therefore, a wear quantification was conducted only in the removable draw ring. Nevertheless, the gained results correspond to those from blanking and embossing. While low currents show little impact on wear, higher currents result in a wear increase. With a well-adapted current strength, adhesive wear reductions of up to 54% could be achieved. These results confirm the transferability to other forming processes and suggest that an adhesive wear reduction is possible for every manufacturing process where two conductive materials are in contact. Detailed information about this topic will be published soon.

9 Conclusion

Plastic deformation and frictional heating lead to a temperature rise in the forming zone during cold metal forming. The resulting temperature gradient in the tool, combined with two connected conductors, punch and sheet metal, cause thermoelectric voltages and currents. During this project, thermoelectric phenomena and their influence on wear behavior has been investigated in the field of cold metal forming. In order to derive a correlation between thermoelectricity and adhesive wear, used punch and sheet materials were initially characterized with regard to their thermoelectric behavior. Therefore, Seebeck coefficients were determined relative to platinum. Most of them show varying behavior over the whole temperature range from 0 °C to 500 °C. After this material characterization, various embossing and blanking experiments were conducted. The occurring temperature development was measured instantaneously and in situ at the contact surface of punch and sheet metal by a tool-workpiece-thermocouple. Since temperatures in the forming zone arises mainly due to dissipating forming work, temperature profiles show characteristic curve shapes with regard to the respective forming process. The corresponding maximum mainly depends on mechanical properties of the sheet metal and its thickness as well as process parameters like die clearance and punch velocity. While the first ones mainly determine the amount of required forming force, process parameters change the spatial expansion of the forming zone where heat dissipation takes place and the time for heat equalization. Consequently, the maximum temperature increases with higher velocities and tensile strengths of the sheet metal as well as with declining die clearances.

Besides temperature, the difference between Seebeck coefficients of punch and sheet material determines the occurring thermoelectricity. Especially the thermoelectric current strength and its direction between punch and sheet metal depend on the material combination. Therefore, the measured maximum currents strongly differ. In contrary, all curves show characteristic curve shapes, since thermoelectric currents arise due to temperature development in the forming zone.

Electron transfer between the touching surfaces of sheet metal and punch generally forms adhesions. The occurring chemical reactions increase with temperature, wherefore adhesive wear is temperature dependent. Furthermore, the gained results show that electrical currents influence adhesive bonding in different ways. First, electromigration processes occur at the asperities in contact. Therefore, impacts between moving electrons and ions in the metal lattice cause a force in electron flow direction and thus, determine the direction of diffusion processes and influence chemical bonding. Depending on the current direction, this force strengthens or weakens adhesive wear formation, provided that the current has an adapted strength. If it is too low, the effect is negligible. With increasing current, Joule heating occurs and collision processes with phonons, electrons and ions increases the natural oscillation in the metal lattice and thus temperature. With higher currents, the temperature at the asperities can even exceed the melting point of the sheet material. This causes a transition from adhesion formation due to electron exchange to an increased melting of the sheet metal. Consequently, sheet material adheres at the punch after solidification and adhesive wear increases independent from the thermoelectric current direction.

Based on these findings, two new adhesive wear reducing methods can be derived. While an appropriate choice of punch and sheet material with regard to their Seebeck coefficients reduces the amount of adhesive wear by 74%, influencing thermoelectric currents by an externally regulated current, whose strength was adapted to the process, lead to a maximum reduction of 31%. Therefore, the suppression of thermoelectric currents in case of similar Seebeck coefficients of punch and sheet material leads to the highest wear reduction. This can be traced back to lower temperatures and thus less melting processes because of Joule heating. However, chemical bonding cannot be completely prevented and still a small amount of homogenous distributed adhesions occurs. An external current regulates the current density in the asperities and the local current direction. The results show that in case of an electron flow from punch to sheet metal, adhesion formation is weakened if its strength is well adapted to the process and the thermoelectric behavior of punch and sheet metal. In contrast, low currents hardly affect wear whereas higher currents lead to an increase of both chemical reactions and melting processes due to Joule heating. Due to circular currents in the contact zone of sheet metal and punch, the achievable adhesive wear reduction is lower compared to a thermoelectric material choice.

In sum, the findings within this project significantly improve the understanding of wear-causing interactions at touching asperities between sheet metal and punch. Furthermore, the transferability to other forming processes is verified by deep drawing experiments. Together with the scientific literature, it could be expected that these wear reducing methods are applicable in all metal manufacturing processes.

Acknowledgement

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