

A novel laboratory blanking apparatus for the experimental identification of blanking parameters

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Abstract

High-quality blanking depends on several blanking parameters that are difficult to investigate with industrial blanking presses. In this research, a novel laboratory blanking apparatus that allows quasi-static and dynamic blanking at different blanking speeds is presented. With a clear focus on the dynamics of the blanking process, the inertial correction of the punch force, the surface velocity and the surface temperature of sheet-metal are researched. In addition, measurements of the punch-die misalignment and the punch-die inclination-angle are discussed. The apparatus is also able to perform a partial penetration of the punch to a selected depth with an accuracy of better than $10\ \mu\text{m}$. The apparatus was shown to offer us a new insight into the blanking process that can increase our understanding and therefore result in better numerical models and better products.

Keywords: blanking apparatus, dynamic blanking, partial blanking, blanking temperature, sheet-metal vibrations

Please cite as: Slavič, J., Bolka, Š., Bratuš, V. and Boltežar, M.: **A novel laboratory blanking apparatus for the experimental identification of blanking parameters**. Accepted for publication in Journal of Materials Processing Technology.

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1. Introduction

Blanking is one of the most widely used metal-cutting processes in industry. Although the technology is relatively old, detailed experimental research is still required for a validation of the numerical models. A validated numerical model should give answers to questions like: what is the force-displacement relation, what are the accelerations of the punch/die, what is the effect of the punch inclination, what is the effect of the positioning of the punch vs. the die (clearance), how does the local shear-zone temperature increase, and finally, how does all this change with the punch speed?

There are several experimental results obtained on standard industrial machines that provide plenty of experimental details. For example, Česnik et al. (2009) used a hydraulic press to research the material's influence on the force vs. time during fine-blanking. For an experimental characterization of punching, Subramonian et al. (2013) used a high-speed mechanical press, Breitling et al. (1997) an electromagnetic press and Gaudillière et al. (2010) an air gun, combined with the Split-Hopkinson pressure bar. Goyal et al. (2010) used a shear testing apparatus.

Besides the frequently researched force-displacement diagram, other parameters have been investigated as well. For example, Mackensen et al. (2010) performed an analysis of the inclination angle of the punch on the maximum blanking force, concluding that a lower force is needed for blanking with an inclined punch.

Furthermore, the influence of the blanking speed was investigated by Goijaerts et al. (2002), who reported a lowering of the blanking force with an increase of the blanking speed for blanking speeds between 0.01 and 1000 mm/s. Breitling et al. (1997) presented similar conclusions for higher blanking speeds (1-4 m/s), but also showed the changes in the force-displacement diagram for various sheet-metal materials. Recently, Subramonian et al. (2013) indicated an increase in the dynamic effects at higher blanking speeds, compared to slower experiments. Neugebauer (2011) conducted detailed research on the effects of blanking speed on forming and machining. Breitling et al. (1997) measured the accelerations of the press during high-speed blanking, but reported that an identification of isolated parameters could not be performed.

The punch-die clearance affects not only the edge quality, but also the force-displacement diagram. For example, Rachik et al. (2002) reported a slight lowering of the blanking force for increased punch-die clearances, while

Mucha (2010) and Shivpuri et al. (2011) reported greater tool wears for greater punch-die clearances. Husson et al. (2008) found that the quality of the sheared edges is lower for greater punch-die clearances and/or tool wear. As shown by Bratuš et al. (2010), optimisation of the punch shape (and clearance) leads to a better geometrical accuracy of the blanked part.

Finally, the thermal effects in the shear-zone are known to change the blanking force and the edge quality. Goijaerts et al. (2002) found that the maximum blanking force decreased due to the thermal softening in the material. Mori et al. (2012) showed experimentally that the peak blanking force decreases with the pre-heating of the samples near the shear zone. Peng et al. (2004) showed numerically that a decrease of the maximum force of about 75% could be achieved with preheating. Sartkulvanich et al. (2010), on the other hand, numerically found only minor changes in the blanking force due to the temperature in the shear zone. Rafsanjani et al. (2009) numerically researched (and compared to published experimental results) the temperature increase due to the increased blanking speed; they found significant effects with a temperature increase. Rafsanjani et al. (2009) also numerically showed that the temperature in the shear-zone are increasing up to the point of fracture, followed by a rapid decrease; however, outside of the shear-zone, the temperature is increasing.

While using standard machines for blanking has the advantages that the experiment is relatively easy to prepare and usually also cost effective, the disadvantages is in the limited measurement possibilities one has. From the dynamical point of view, a serious problem is also the system's dynamics: in the measured response there are relatively low natural frequencies that distort the measurements (e.g., force/acceleration). A further disadvantage is that, due to limited space, additional sensors are hard to use (e.g., high-speed thermal camera, a laser Doppler vibrometer). For these reasons, here a laboratory blanking apparatus for quasi-static and dynamic blanking, with a clear focus on the real blanking force and acceleration/velocity measurements of the punch, die and steel sheet is introduced. The dynamics of the apparatus will be discussed, followed by a necessary inertial correction to the force measurement. In addition to the kinematic measurements at the punch, die and steel sheet, also surface-temperature measurements with a high-speed temperature camera are possible. Furthermore, with this apparatus, the above-discussed parameters can be researched: inclination-angle, blanking speed, and clearance. Additionally, partial (the punch penetrates the sample up to a desired depth) and sequential blanking experiments (full

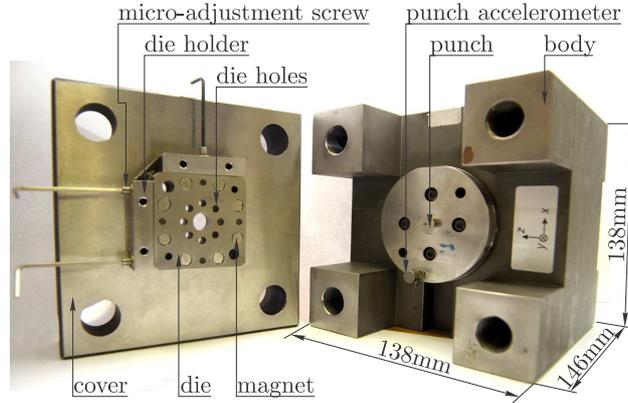


Figure 1: Opened cutting module.

penetration is achieved in several partial steps) are performed quasi-statically and dynamically.

The article is organised as follows. In Section 2, the novel blanking apparatus is discussed in detail. In Section 3, the experimental procedures and results are discussed. Section 4 then gives the conclusions of the investigation.

2. The blanking apparatus

The presented blanking apparatus consists of several parts, the most important being the cutting module.

2.1. The cutting module

The cutting module, shown in Figs. 1 and 2, is an assembly of the detachable housing (cover and body) and the cutting elements (die, die holder, punch and piston). The cover of the housing holds the die holder and the die, whereas the body contains the punch and the piston. The piston is accessible from the outside at the back end of the body. A detailed scheme of the cutting elements is shown in the small inset in Fig. 2.

The die lies in the die holder and has outer dimensions of $40 \times 40 \times 8$ mm. Three micro-adjustment screws in the die holder are used to adjust the die alignment. Around the die shape, eight strong magnets of diameter 6 mm are inserted (shown in Fig. 1). These magnets are used to hold the specimen

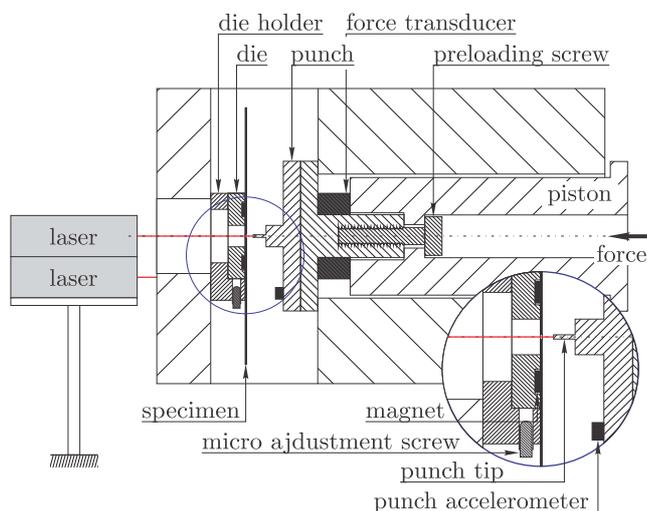


Figure 2: Simplified cross-section of the cutting module.

in position (position shown in Fig. 2). The die-holes around the die are used for measurements of the sheet-metal vibrations.

The punch is attached to an oil-lubricated piston to ensure well-guided movement of the punch during blanking. The oil compartment is sealed and the lubricant does not affect the blanking measurement. For measurement reasons (discussed later) the punch has a 1-mm-diameter punch-tip extension in the center.

In Fig. 1, the cutting module is shown with a circular punch-and-die set with nominal diameters of 10.000 mm and 10.050 mm, respectively.

2.2. Quasi-static experiments

Normally, blanking is performed using presses, modified testing machines or air guns. To achieve the quasi-static as well as the dynamic blanking, the apparatus presented here uses the principles of mechanical presses, as well as the principles of kinetic energy. In the following paragraph, the quasi-static experiment will be explained in detail.

The blanking apparatus for the quasi-static experiments is shown in Fig. 3. It consists of the support block (coloured light grey), the cutting module and the fixation block. The fixation block is used to drive the piston and thus ensure the punch's penetration into the specimen. The propagation

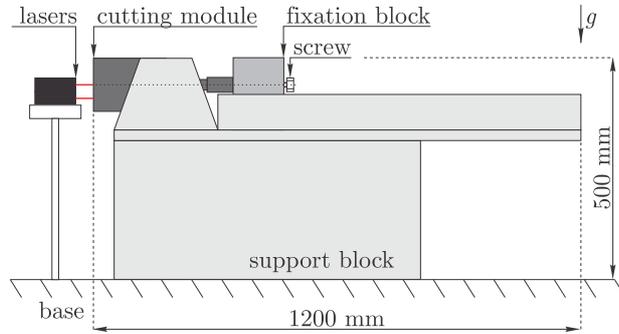


Figure 3: Scheme of the blanking apparatus for the quasi-static experiments.

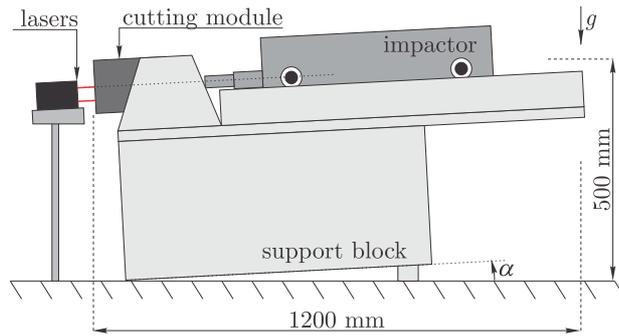


Figure 4: Scheme of the blanking apparatus for the dynamic experiments.

is achieved by turning a fine-threaded screw.

The total mass of the assembly for quasi-static experiments is about 550 kg.

2.3. Dynamic experiments

The blanking apparatus for dynamic measurements is shown in Fig. 4. The total mass of the assembly in this configuration is about 800 kg. During the experiment, the impactor collides with the rear end of the piston in the cutting module. The kinetic energy of the impactor (with a mass of 250 kg) at the bottom of the rails is transformed into work as an integral of the blanking force over the punch penetration.

The support block is elevated at an angle α (shown in Fig. 4) for the dynamic measurements. The elevation may be adjusted, depending on the

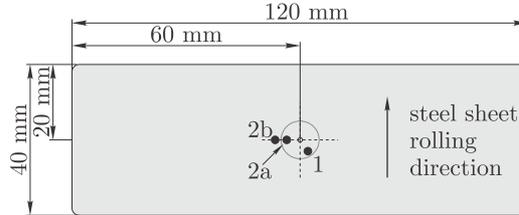


Figure 5: Dimensions of the specimens used.

impact speeds desired. For this research, the elevation was about 5° . The impactor is released from rest at an arbitrary initial position on the rails. Its initial displacement from the cutting module could be determined with an accuracy of up to 1 mm. The potential energy of the impactor at the initial position is changed into its kinetic energy at the end of the rails.

3. Methodology

3.1. Specimens

The required geometry of the specimens and the location and shape of the slug for the 10-mm punch diameter are shown in Fig. 5. A hole with a diameter of 1.2 mm should be drilled into the specimen due to the requirements of the measurement (discussed later).

The specimens are inserted into the blanking apparatus as shown in Fig. 2.

In this investigation, a low-alloyed, final-annealed electrical steel sheet with a typical core loss of 4W/kg of 0.5 mm thickness with an approximately $1.5\text{-}\mu\text{m}$ silicate coating on each surface was used. All the specimens were prepared by water-jet cutting from the same part of the sheet-metal coil.

3.2. Measurement setup

During the experiment, the force, the absolute displacements of the punch-tip and the cutting module, and the acceleration of the punch can be measured directly. The positions of all the sensors are shown in Fig. 2. Additionally, the temperature and velocity of the sheet metal can be measured.

In this study, a Kistler type 9061A piezoelectric ring force transducer (up to 200kN) was used to measure the punch force. The force transducer was preloaded using a screw (shown in Fig. 2). The punch and the cutting-module displacements were measured with Keyence LK-G82 displacement lasers. The lasers were fixed to the base, as shown in Figs. 3 and 4, and

measured the absolute displacements. The punch displacement was measured on the punch tip (shown in the inset in Fig. 2) and the cutting-module displacement was measured on the front side of the cutting module. The punch acceleration was measured at the base of the punch with a Brüel&Kjær accelerometer, type 8309. A Kistler 9371 4-channel charge amplifier was used to amplify the charge signals from the sensors. The laser-displacement signals were conditioned by a Keyence LK-GD500 laser conditioner (at 25 kHz).

For the measurement of the blanking temperature the displacement lasers were replaced with a Thermo-Sensorik high-speed temperature camera. In order to achieve the frame rate of 3820fps, only a narrow window of 4×394 pixel points was used. The temperature was measured at point 1 (Fig. 5).

For the vibration of the sheet-metal measurement the displacement lasers were replaced by a Polytec PDV 100 velocity laser. The velocities of the slug and the sheet metal were measured at points 2a for the sheet metal and 2b for the slug (Fig. 5).

All the signals were acquired at 100 kHz with a National Instruments NI 9215 16-bit data-acquisition card.

3.3. *Experimental procedure*

The proposed blanking apparatus enables full (complete separation of the slug), partial (partial penetration of the punch into the material) and sequential (full blanking in consecutive partial steps) experiments, performed both quasi-statically and dynamically.

The quasi-static experiments are performed by turning the fine-threaded screw. The screw pushes the piston and the punch forward through the specimen with a constant force. The blanking-speed depends on the torque applied to the screw. The same procedure is applied for the full, partial and sequential experiments.

For the dynamic experiments, the minimal initial blanking speed for the given sheet metal must be determined first. It depends on the minimum energy that is required by the punch to fully penetrate the specimen:

$$E_b = F_b s, \quad (1)$$

where E_b is the blanking energy, F_b is the averaged blanking (punch) force and s is the path of the force. The maximum blanking force can be roughly estimated using the equation of Atkins (1980):

$$F_{b,est} = t L \tau, \quad (2)$$

where t is the specimen's thickness, L is the perimeter of the slug, and τ is the shear strength of the material. The kinetic energy of the impactor at the time of impact must be equal to or greater than the blanking energy required to perform a full blanking experiment.

If the initial blanking speed is lower than the minimum full blanking energy, a dynamic partial blanking experiment can be performed. Depending on the initial blanking speed, different depths of the punch penetration can be accurately obtained up to $10\ \mu\text{m}$. With consecutive partial dynamic experiments, a sequential dynamic experiment can be performed.

All of the quasi-static experiments were performed with a blanking speed of about $0.1\ \text{mm/s}$. Based on Eq. 1 and Eq. 2, the minimum dynamic initial blanking speed of the punch for this investigation is about $180\ \text{mm/s}$. To ensure full penetration of the punch, a minimum dynamic blanking speed of $200\ \text{mm/s}$ was used.

All the measurements were performed at room temperature and with a non-lubricated punch-die set. Unless stated otherwise, a centric punch-die set was used.

3.4. Inertial correction

Frequently, the inertial effects of the punch are neglected for blanking at higher blanking speeds (Subramonian et al. (2013)), leading to unrealistically high blanking forces. As the force transducer is placed between the punch (mass $m_i = 0.49\ \text{kg}$) and the piston in the cutting module, Fig. 2, it measures the actual blanking force as well as the inertial forces of the punch during the experiment. The acceleration of the punch during blanking can be up to $600g$ (for the experiments at $450\ \text{mm/s}$, g is the acceleration due to gravity), whereas it does not exceed $3g$ for the quasi-static measurements. Thus the dynamic measurements result in relatively high inertial forces and an inertial correction is required:

$$F = F_m - m_i \cdot a_m, \quad (3)$$

where F is the blanking force, F_m is the measured force, m_i is the inertial mass (the mass between the sample and the force transducer) and a_m is the measured acceleration of the punch. As an example, the inertial correction of a single measurement for the full blanking experiment is shown on the force-displacement diagram in Fig. 6.

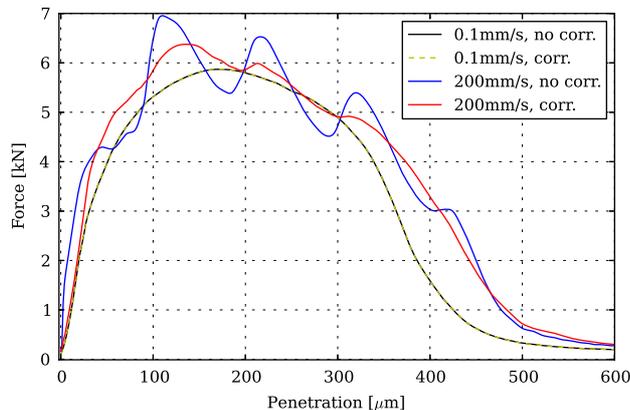


Figure 6: Inertial correction for the $F - s$ curve for a single measurement at a blanking speed of 200 mm/s.

3.5. Repeatability of the blanking apparatus

In this investigation, the data for each example is averaged over five or more experiments. For each experiment, data smoothing with a Hann window (length of 11 measurement points) is used. The typical scatter of the results and the averaged force-displacement curve are shown in Fig. 7.

3.6. Punch and die misalignment

Due to the punch and die misalignment, the actual clearance between the punch and die can differ from the expected one. In this research, a circular 10.000 mm diameter punch (a detailed measurement showed that the real diameter at any angle differed by a maximum of $5\mu\text{m}$) was used. As shown in Fig. 2, the micro-adjustment screws are used to micro-position the die. The final position validation was made optically: a strong LED light source at the punch side and a high-speed camera at the die side were used to track the clearance. As shown in Fig. 8, the clearance is easily visible and was used for a quantitative assessment of the misalignment.

With the 10 mm diameter punch, the misalignment resulted in a maximum force variation of up to 0.2 kN.

3.7. Punch inclination angle

By manufacturing punches with various inclination angles Mackensen et al. (2010) studied the effect of the punch inclination angle on the force-displacement diagram. The blanking apparatus presented here makes it possible to study

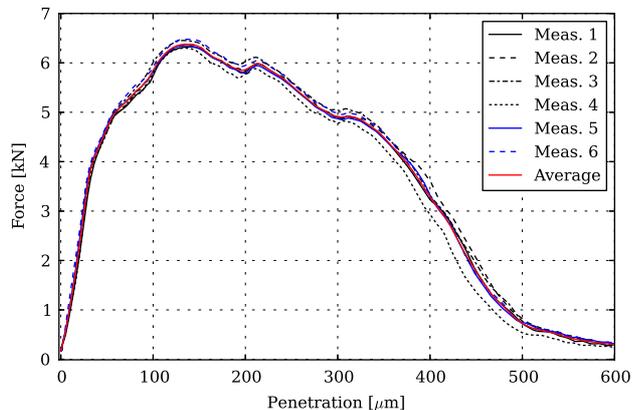


Figure 7: Data scattering and averaged $F - s$ curve for blanking speed of 200 mm/s.

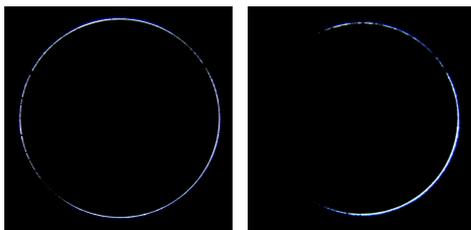


Figure 8: Photographs of centric (left) and eccentric (right) position of the punch and die.

the effect of the punch inclination angle with the originally flat punch. The desired inclination is achieved by putting a precision gauge tape between the punch and the punch-base, see Fig. 2. For example, adding a $10 \mu\text{m}$ precision gauge at a distance of 35 mm from the center of the punch results in an inclination angle of 0.008° . The results are shown in Fig. 9. A similar experiment can be performed by elevating the die.

Furthermore, with the partial blanking to a certain depth (e.g., $250 \mu\text{m}$) the real inclination angle can be identified by measuring the real penetration depth around the circumference of the specimen (as shown in Fig. 10).

3.8. Blanking speed

The blanking speed can be easily adjusted with the proper height of the impactor. As the angle α (Fig. 4) is small, the impactor height can be adjusted accurately, resulting in a blanking-speed accuracy of $\pm 2 \text{ mm/s}$. Fig. 11 shows the results of experiments at blanking speeds of 200, 250, 300,

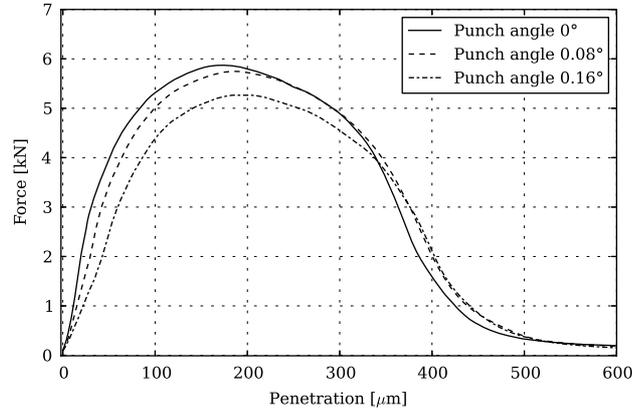


Figure 9: Effect of punch inclination on the $F - s$ diagram for the averaged quasi-static measurements.

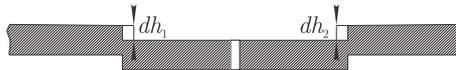


Figure 10: Measurement of punch inclination angle due to manufacturing uncertainty.

350, 400 and 450 mm/s.

Similar to the previous research (Breitling et al. (1997)), the blanking force decreases slightly with an increase of the blanking speed. The total penetration of the punch to fully blank the specimen is shallower at greater blanking speeds. In addition to the results of Subramonian et al. (2013) and Breitling et al. (1997), the inertial effects of the punch are included.

3.9. Partial and sequential blanking experiments

To research the blanking process at different penetration depths (e.g., for elastic/plastic deformation, for microscopic crack-propagation analysis), this apparatus can perform (quasi-statically or dynamically) partial blanking experiments. If one continues a partially blanked sample with further partially blanked experiments, a sequential blanking is performed. Fig. 12 shows the (dynamic) partial blanking experiments up to depths of approximately 100, 200, 300 and 400 μm . Fig. 13 shows the (dynamic) sequential blanking at

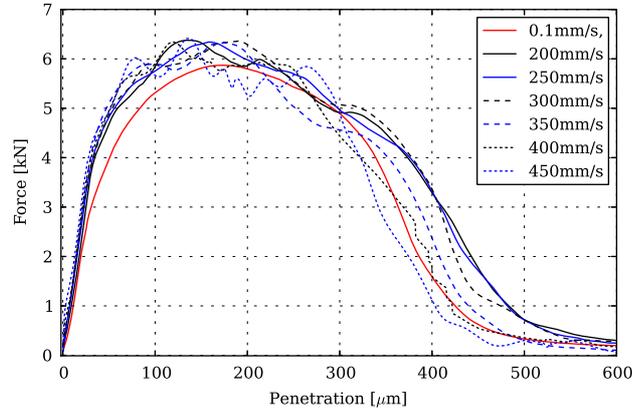


Figure 11: Effect of blanking speed on the $F - s$ diagram for averaged measurements.

steps of $50 \mu\text{m}$. As a comparison, Figs. 12 and 13 also show the results of a

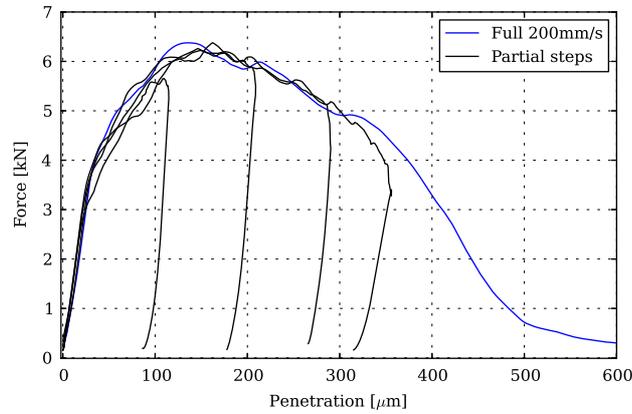


Figure 12: Comparison of averaged dynamic partial and full blanking experiments.

fully blanked sample.

3.10. Temperature of the sheet metal during blanking

Softening of the sheet metal due to the temperature increase in the shear zone may cause a decrease of the blanking force (Peng et al. (2004)). This effect may be even more pronounced at higher blanking speeds (Rafsanjani et al. (2009)). However, the predictions were based on a numerical analysis, as temperature in the shear zone was not possible to measure.

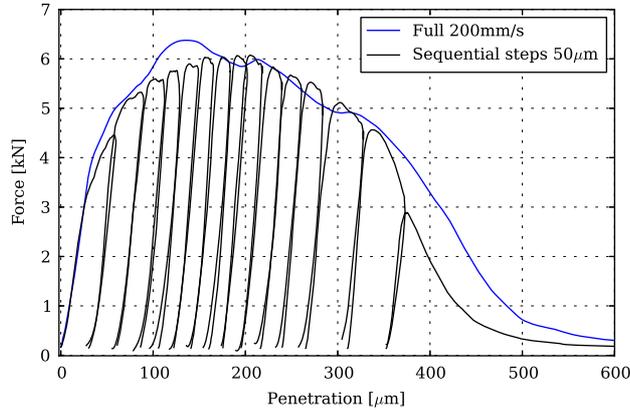


Figure 13: Comparison of averaged sequential and full blanking experiments.

The presented apparatus makes it possible to the temperature at the sheet-metal surface.

As an example, Fig. 14 shows the result at a blanking speed of 200 mm/s, measured with the Thermo-Sensorik high-speed thermal camera at a frame rate of 3820 fps. Due to the blanking with a blanking speed of 200 mm/s, the surface temperature increased by more than 22°C. It should be stressed that this is the surface temperature and that the surface area where the temperature is measured is several times larger than the surface area of the hot-spot of the shear-zone. Furthermore, the time-scale of the blanking process is in μs , while the time-scale of the thermic process is in seconds. As a result, the temperature increase at the hot-spot inside the sheet-metal could be several times larger than the temperature measured on the surface.

3.11. Vibrations of the sheet metal during blanking

For accurate blanking, it is important to have the dynamics of the blanked sheet-metal under control. How should the blanked sheet-metal be fixed? To help answer this question the die (Fig. 2) has additional holes for measuring the surface-velocity during blanking.

In this research a Polytec PDV 100 velocity laser was used. As an example, Fig. 15 shows the surface-velocity of the slug and scrap. It is clear that besides the slug, the scrap also responds dynamically.

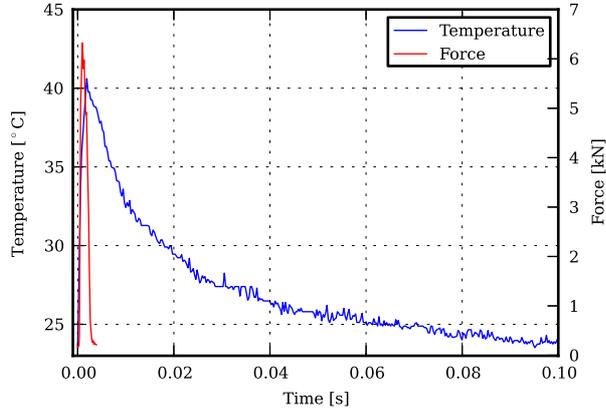


Figure 14: Averaged temperature of the sheet-metal surface with time.

4. Conclusions

In this research, a novel laboratory blanking apparatus, allowing quasi-static and dynamic blanking at different blanking speeds, is presented. With the focus on the dynamics of the blanking process, an inertial correction was introduced; the surface temperature and surface velocity were also researched and shown to provide an insight into the blanking process, which was not experimentally possible before. Furthermore, punch-die misalignment and punch-die inclination-angle measurements are possible. The partial and sequential blanking provide more information about the elastic/plastic process during blanking, and the crack formation analyzed at selected penetration depths can be used for a material-damage assessment.

The relevance of the researched parameters is shown for the example of a 10-mm punch and 0.5-mm-thick sheet metal. A comparison of the force-displacement diagram without the inertial correction showed good agreement with Subramonian et al. (2013); the inertial correction that was previously not taken into account was found to significantly affect the identified blanking force. Moreover, the punch-die misalignment (a non-constant clearance between the punch and the die) was shown to change the maximum force by up to 4%. Although misalignment was not previously researched, good agreement with the available research on clearance was found. The punch-die inclination-angle was shown to change the maximum force by up to 15%. Furthermore, the surface-temperature was shown to increase by approximately 20°C; however, it is believed that the hot-spot temperature inside the shear

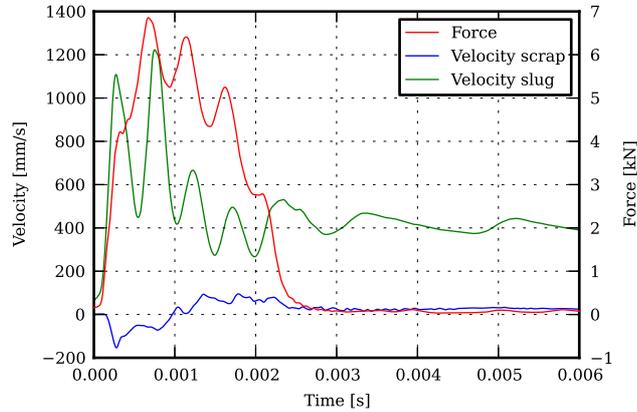


Figure 15: Averaged velocity of the sheet-metal surface (slug and scrap) with time (without inertial correction).

zone can be several times higher. The surface-velocity measurement indicated a significant velocity of the scrap (on the same scale as the punch speed).

With the new insights into the blanking process that are enabled by this novel laboratory blanking apparatus, an understanding of the blanking process can be exploited in greater detail and can lead to better numerical models and products.

5. Acknowledgments

This operation was partially financed by the European Union, European Social Fund.

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