

# Analysis of Shear Localization in High-Speed Blanking of Press-Hardened 22MnB5 Steel

**O. Schrage\***, H. Dardaei Joghhan, M. Hahn, A. E. Tekkaya, Y. P. Korkolis

Institute of Forming Technology and Lightweight Components, TU Dortmund University, Germany

\*Corresponding author. Email: olaf.schrage@iul.tu-dortmund.de

## Abstract

*High-speed blanking induces a shear localization in high-strength steels, improving the quality of the blanked edge in terms of geometrical shape, separation surface roughness, and shear-influenced zone close to the cut edge. High-speed blanking experiments with a 20 mm punch diameter and 8 m/s velocity of 2 mm thick 22MnB5-sheets (ultimate tensile strength of 1550 MPa) utilizing a relative clearance of 2.5 % are carried out. Two types of shear bands are observed in the post-process: A 'deformation shear band,' characterized by elongated grains in shear direction, is distinguished from a 'transformation shear band' with a change in microstructure appearing as a white layer in optical microscopy. Previous investigations by transmission electron microscopy showed that this white layer consists of nanosized grains in 22MnB5 material. Light microscopic images show that the transformation shear band width varies over the sheet thickness. Independent of the occurrence of a transformation shear band, a localization with a width of less than 20  $\mu\text{m}$  is observed along the blanked edge. Fractographic analysis by scanning electron microscopy shows no evidence of brittle fracture. Characteristic areas of the separation surfaces coincide with the observed two types of shear bands at the blanked edge.*

## Keywords

High-speed blanking, Shear localization, High-strength steels, Microstructure

## 1 Introduction

High-speed blanking with punch speeds in the range of 5 to 12 m/s, two orders of magnitude higher than conventional blanking, can achieve high-quality blanked edges even for high-strength steels. High-speed blanked edges show a high geometric straightness, low rollover, and almost no burr formation (Landgrebe et al., 2017). High-speed blanking tests with punch speeds of 5.3 m/s of the three high-strength steels 22MnB5-press hardened, C75S-hardened, and a bainitic steel HR660Y760T-CP, were performed by Schmitz et al. (2020). Analyzing the microstructure at the blanked edge for 22MnB5-press hardened and C75S-hardened, a change in microstructure occurs at the blanked edge. The so-called transformation shear bands in those two materials have nanocrystalline microstructures, wherefore the grain boundaries cannot be etched and appear white in light microscopic imaging (Schmitz et al., 2020). A nano-scaled equiaxed narrow band in certain areas of the surface is also observed at the high-speed blanked edge of the steel alloy 42SiCr after quenching and partitioning (Birnbauer et al., 2024). In HR660Y760T-CP, no transformation shear band is observed; nonetheless, a very localized deformation with strongly elongated grains in the shear direction – a deformation shear band – occurs (Schmitz et al., 2020). Investigating two different states of the carbon spring steel C75S - reference state of 330 HV10 and in a hardened state with 450 HV10 - it is shown that for the reference state, a deformation shear band forms, whereby in the hardened state, a transformation shear band can be observed. Independent of the formation of either a deformation or transformation shear band, a high-quality blanked edge in terms of geometric accuracy is produced for both material states by high-speed blanking (Schmitz et al., 2024). An influence of punch speed, impact energy, and blanking clearance on the formation of the transformation shear band is shown in the high-speed blanking of 22MnB5-hardened by Winter et al. (2021).

The formation of a localized deformation shear band indicates ductile behavior even for high-strength steels with low formability. In this study, the separation mechanisms in high-speed blanking of 22MnB5-press hardened are analyzed by scanning electron microscopy analysis of the blanked edge surface. The characteristic areas of the separation surface, showing ductile separation mechanisms, are found to coincide with the two types of shear bands - transformation and deformation - at the blanked edge.

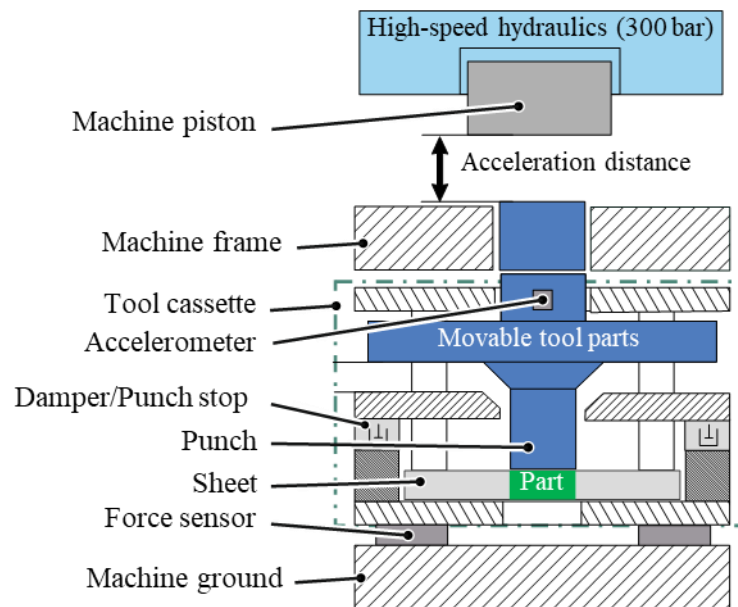
## 2 Methods

### 2.1 Material

The 22MnB5 sheet material was heat-treated in a manner similar to the press hardening of ultra-high-strength steel components. The 2-mm-thick sheets were austenitized in a chamber furnace at 930 °C for 6 minutes. Afterwards, the material was rapidly quenched using a water-cooled tool for flat sheets to induce a martensitic microstructure. The material's successful hardening is demonstrated by a Vickers hardness of 480 HV (HV 10) and a measured ultimate tensile strength of 1550 MPa.

## 2.2 High-speed blanking test setup

High-speed blanking experiments are carried out on a hydraulic impact press, ADI-AClip1000J® of MPM France (**Fig. 1**). To achieve high punch velocities in a range of 5 to 10 m/s, a hydraulic piston of the machine is accelerated by discharging a hydraulic accumulator with an initial pressure of 300 bar. After a free acceleration of 100 mm, the piston hits the tool, accelerating the punch, which is laying directly on the sheet at the beginning of the process. In this investigation a machine setting which achieves 8 m/s punch speed is used, determined by acceleration measurements (see Fig. 1). High-speed blanking tests are carried out with a punch diameter ( $d_{\text{punch}}$ ) of 20 mm in combination with a die diameter ( $d_{\text{die}}$ ) of 20.1 mm resulting in a relative clearance  $c_{\text{rel}} = (d_{\text{die}} - d_{\text{punch}})/(2 \cdot s_0)$  of 2.5 % for the 2 mm thick material.



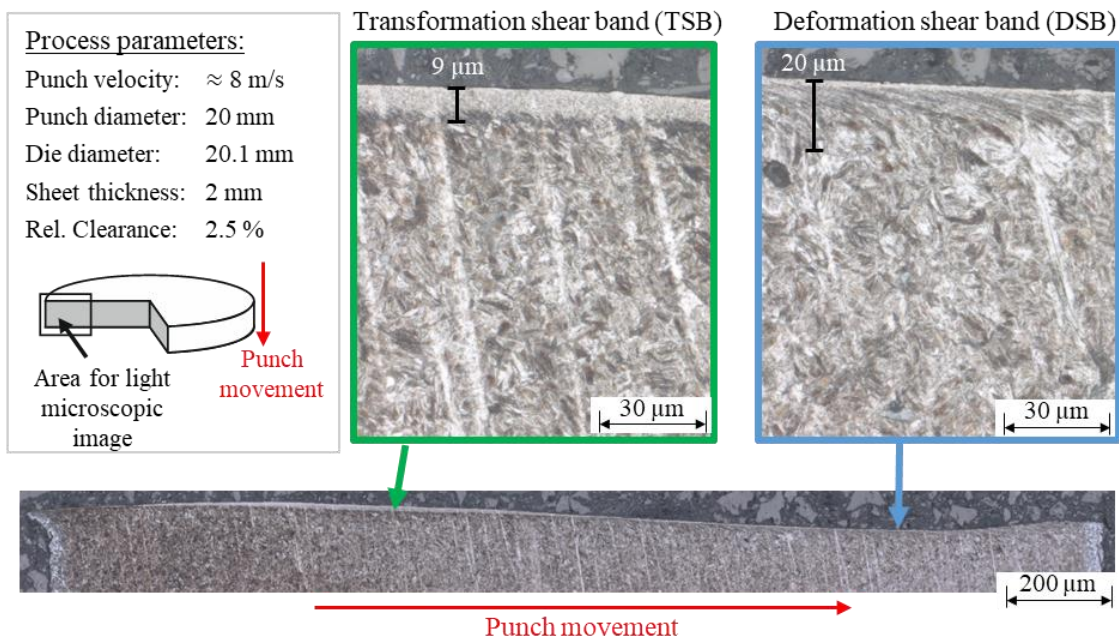
**Figure 1:** Working principle of the hydraulic impact press AdiaClip 1kJ, adapted from (Schmitz et al., 2024)

## 3 Results

### 3.1 Microstructure analysis at the blanked edge

After blanking, the blanked slug is molded, polished, and etched for light-microscopic imaging. **Fig. 2** shows the microstructure in the shear-affected zone in the form of a shear band along the blanked edge. Dodd and Bai (2012) defined a shear band as areas in the microstructure in which a transition from a homogeneous to a localized strain distribution has taken place. Thereby, according to Rogers (1979) two different types of shear bands: a transformation and deformation shear band can be identified at the high-speed blanking edge

(Fig. 2). The deformation shear band is characterized by strongly concentrated plastic deformation, in this case characterized by elongated and deformed grains in the shearing direction. A transformation shear band appears white in light microscopy, indicating a change of microstructure. Microstructure changes could be in the form of grain rotation, dynamic recrystallization, Amorphisation, formation of martensite, or heat-treated martensite (Yan et al., 2021). In high-speed blanking of press-hardened 22MnB5 with similar process parameters than in this investigation Schmitz et al. (2020) showed that the transformation shear band has a nanocrystalline microstructure. For the given process parameters and material of this investigation, the following types of bands can be observed at the blanked edge of the slug: A transformation shear band is induced at approximately one-third of the sheet thickness, whereby its width varies along the thickness direction. A deformation shear band can be observed at nearly two-thirds of the sheet thickness. The maximum width of the deformation shear band is 20  $\mu\text{m}$  from the edge, whereas a maximum width of 9  $\mu\text{m}$  for the transformation shear band was measured based on optical observation in the light-microscopic images (Fig. 2).

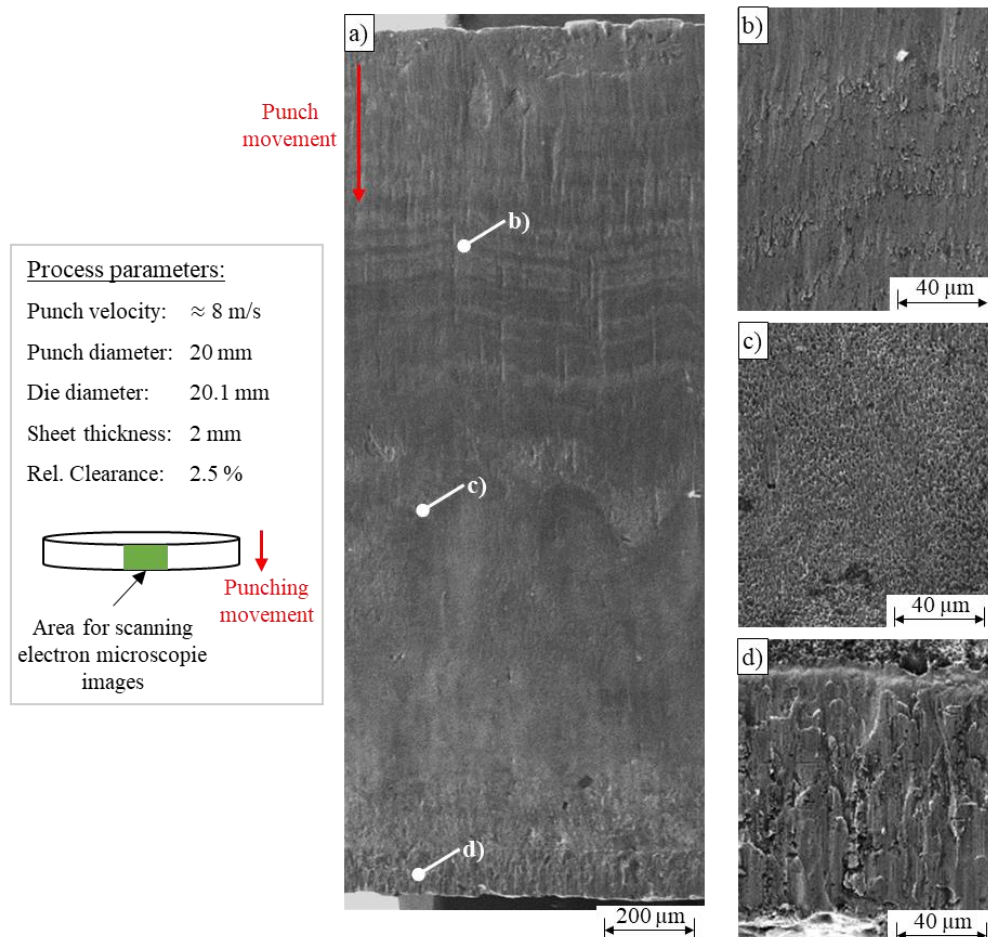


**Figure 2:** Microstructure analysis of the blanked edge

Looking at the blanked edge of the sheet, the deformation and transformation shear band appears point-symmetric compared to the blanked edge of the slug. This means that a deformation shear band is observed at approximately one-third of the sheet's thickness, from the top towards the middle. A transformation shear band is observed at approximately two-thirds of the sheet thickness at the bottom. Consequently, the zone affected by shear is limited to a band of deformation and transformation (respectively grain refinement) with a width of 1% of the sheet thickness. The band's width is smaller than the blanking clearance of 50  $\mu\text{m}$ .

### 3.2 Fractographic analysis by Scanning Electron Microscopy (SEM)

Fractographic analysis by scanning electron microscopy (SEM) shows a smooth fracture surface with a homogeneous, even fracture surface without cracks or break-outs (**Fig. 3a**). Three characteristic areas can be identified with further magnification. At the top of the blanked edge a fine shear surface is observed (**Fig. 3 b**). Qualitatively, this area coincides well with the occurrence of the transformation shear band in the cross-section view. This area merges continuously into an area characterized by ductile dimples elongated in the shear direction (**Fig. 3c**). This characteristic fracture surface is observed from approximately the middle of the sheet thickness towards the bottom. It coincides with a deformation shear band in the cross-section view. At the very bottom of the sheet, a smaller area with a less smooth, rather unclear fracture surface is observed (**Fig. 3d**). This surface area has undergone a frictional contact with the die during the process, wherefore the appearance is interpreted as a ductile fracture which is then smeared by friction in the shearing direction.



**Figure 3:** Scanning Electron Microscopic (SEM) analysis of fracture surface: a) Overview images of the blanked edge, and b-d) detail images of the three characteristic areas

## 4 Discussion

Even if a press-hardened 22MnB5 has a very low formability, the fractographic analysis shows that a ductile fracture mechanism is triggered in high-speed blanking. No evidence for brittle failure of the material could be found. Remarkable is also the concentration of the shear-affected zone to a very narrow band with a width of less than 1 % of the sheet thickness. Within the localized deformation, two types of shear bands occur: a deformation shear band and a transformation shear band. The transformation shear band, which has a nanocrystalline microstructure, coincides with a smooth shear surface at the top of the sheet. A shear-tensile separation surface, coinciding with a deformation shear band, indicates a superposition of tensile stresses to the dominant shear loads. A frictional contact with the die influences the third characteristic surface area at the bottom of the blanked edge.

Two explanations coexist for the formation of the localized shear band. On the one hand, it could be assumed that the temperature increase due to plastic work-to-heat conversion is leading to thermal softening, causing a localization (Klepaczko, 1998). The prerequisite for thermal softening is that high-speed blanking takes place under adiabatic conditions - Fourier number less than 0.01 - due to the short process time and the low thermal conductivity of steels (Schmitz, 2024). In contrast, it could be assumed that dynamic recrystallization (DRX) and its corresponding microstructural evolution lead to localized material softening prior to thermal softening (Rittel et al., 2008). New grain formation and grain rotation in DRX reduce the dislocation density, leading to a macroscopically reduced material flow stress (Yan et al., 2021). Unclear is whether one or both mechanisms are triggered, or if both are triggered in parallel or subsequently. Independent of the mechanisms for triggering the localization, the material's ductility is increased in the shear band. Therefore, both explanations could explain a ductile shear, respectively, tensile-shear separation mechanism at the whole blanked edge.

The formation of a transformation shear band could be explained by the mechanism of DRX, independent of whether DRX causes the localization or if DRX happens within a localization. DRX requires the subsequent steps of: dislocations rearrangement into elongated dislocation cells (i. e. dynamic recovery), formation of elongation subgrains, break up of subgrains into approximately equiaxed micrograins and grain rotation (Meyers et al., 2000). According to DRX mechanisms, a deformation shear band indicates a stage at which DRX has not been completed, for example, if it has been stopped during dislocation rearrangement. The steps of DRX are completed within a transformation shear band. The shear-tensile separation at the deformation shear band indicates that tensile stresses limit the plastic deformation required for completing the DRX. Nonetheless, the type of shear band coincides with characteristic surface areas of the blanked, wherefore the formation mechanisms and the corresponding separation mechanisms are most likely dependent on each other.

## 5 Conclusion

Fractographic analysis of the high-speed blanked edges draws a correlation between the microstructural observations of shear bands in the cross-section and the characteristics of the separation surface. A smooth shear surface matches the appearance of a transformation shear band, which is characterized by a nanocrystallized microstructure. A shear-tensile separation surface with ductile dimples elongated in the shear direction coincides with a deformation shear band characterized by elongated grains in the shearing direction. The deformation shear band could be seen as a previous stage of the transformation shear band, within the completion of the dynamic recrystallization is hindered by evolving tensile stresses in the process leading to material separation prior to the formation of the nanocrystallized microstructure. Nonetheless, for both bands, the maximum width is 20  $\mu\text{m}$ , wherefore the shear-affected zone is less than 1 % of sheet thickness and also smaller than the blanking clearance. A third characteristic surface area with ductile fracture smeared into the shearing direction by the frictional contact with the die is identified at the bottom of the slug.

In order to further enhance the quality of high-speed blanked edges in terms of a smooth, homogeneous separation surface and a minimal shear-affected zone close to the blanked edge, a transformation shear band needs to be formed over the whole sheet thickness. Evolving tensile loads, judged by the separation surface, at the bottom of the sheet might be the reason for the formation of a deformation instead of a transformation shear band since material separation happens at lower strains.

## 6 Acknowledgements

The authors kindly thank the German Research Foundation (DFG) for the financial support of project TP05 in the Collaborative Research Unit ‘Functional surfaces through adiabatic high-speed processes: Microstructure, mechanisms and model development - FUNDAM<sup>3</sup>ENT’ (Project number 460484491 – FOR 5380).

## References

- Birnbaum, P., Kunke, A., Kräusel, V., 2024. *High speed impact cutting (HSIC) of advanced high-strength steel 42SiCr under exploitation of adiabatic shear bands*. IOP Conference Series: Materials Science and Engineering (1307), pp. 12012.
- Dodd, B., Bai, Y., 2012. *Adiabatic shear localization*, Pergamon Press, Oxford.
- Klepaczko, J.R., 1998. *Remarks on impact shearing*. Journal of the Mechanics and Physics of Solids (46), pp. 2139–2153.
- Landgrebe, D., Barthel, T., Schieck, F., 2017. *Trimming of Flat and Tubular Components by High Speed Impact Cutting (HSIC)*, In: Proceedings of the ASME 2017 International Mechanical Engineering Congress and Exposition (2): Advanced Manufacturing., Tampa, Florida, USA, V002T02A066.
- Meyers, M.A., Nesterenko, V.F., LaSalvia, J.C., Xu, Y.B., Xue, Q., 2000. *Observation and modeling of dynamic recrystallization in high-strain, high-strain rate deformation of metals*. Le Journal de Physique IV (10), pp. 9–56.
- Rittel, D., Landau, P., Venkert, A., 2008. *Dynamic recrystallization as a potential cause for adiabatic shear failure*. Physical review letters (101), pp. 165501.
- Rogers, H.C., 1979. *Adiabatic Plastic Deformation*. Annual Review of Materials Science (9), pp. 283–311.
- Schmitz, F., 2024. *Prozessanalyse des Hochgeschwindigkeitsscherschneidens*. PhD thesis, TU Dortmund.
- Schmitz, F., Clausmeyer, T., Hahn, M., Tekkaya, A.E., 2024. *Determination of energies in high-speed blanking*. Journal of Manufacturing Processes (124), pp. 1554–1566.
- Schmitz, F., Winter, S., Clausmeyer, T., Wagner, M.F.-X., Tekkaya, A.E., 2020. *Adiabatic blanking of advanced high-strength steels*. CIRP Annals (69), pp. 269–272.
- Winter, S., Nestler, M., Galiev, E., Hartmann, F., Psyk, V., Kräusel, V., Dix, M., 2021. *Adiabatic Blanking: Influence of Clearance, Impact Energy, and Velocity on the Blanked Surface*. Journal of Manufacturing and Materials Processing (5), pp. 35.
- Yan, N., Li, Z., Xu, Y., Meyers, M.A., 2021. *Shear localization in metallic materials at high strain rates*. Progress in Materials Science (119), pp. 100755.