Experimental evaluation of tool wear throughout a continuous stroke blanking process of quenched 22MnB5 ultra-high-strength steel

S Vogt¹, F F Neumayer¹, I Serkyov¹, G Jesner², R Kelsch³, M Geile¹, A Sommer³, R Golle¹ and W Volk¹

¹Chair of Metal Forming and Casting (utg), Technical University of Munich, Walther-Meißner-Straße 4, 85748 Garching, Germany
²BÖHLER EDELSTAHL GMBH & CO KG, Mariazellerstraße 25, 8605 Kapfenberg, Austria
³voestalpine Automotive Components Schwäbisch Gmünd GmbH & Co. KG, voestalpine Straße 1, 73529 Schwäbisch Gmünd, Germany
⁴BÖHLER-UDDEHOLM Deutschland GmbH, Hansaallee 321, 40549 Düsseldorf, Germany

E-mail: info@utg.de

Abstract. Steel is the most common material used in vehicles’ chassis, which makes its research an important topic for the automotive industry. Recently developed ultra-high-strength steels (UHSS) provide extreme tensile strength up to 1,500 MPa and combine great crashworthiness with good weight reduction potential. However, in order to reach the final shape of sheet metal parts additional cutting steps such as trimming and piercing are often required. The final trimming of quenched metal sheets presents a huge challenge to a conventional process, mainly because of the required extreme cutting force. The high cutting impact, due to the materials’ brittleness, causes excessive tool wear or even sudden tool failure. Therefore, a laser is commonly used for the cutting process, which is time and energy consuming. The purpose of this paper is to demonstrate the capability of a conventional blanking tool design in a continuous stroke piercing process using boron steel 22MnB5 sheets. Two different types of tool steel were tested for their suitability as active cutting elements: electro-slag remelted (ESR) cold work tool steel Böhler K340 ISODUR and powder-metallurgic (PM) high speed steel Böhler S390 MICROCLEAN. A FEM study provided information about an optimized punch design, which withstands buckling under high cutting forces. The wear behaviour of the process was assessed by the tool wear of the active cutting elements as well as the quality of cut surfaces.

1. Introduction
Lightweight materials with high tensile strength are constantly in demand in many different industry sectors. Carbon composite structures and aluminum alloys, which used to be found only in applications for aircraft industry and motorsports, are nowadays ubiquitous. However, ultra-high-strength steels (UHSS) can also meet the challenges of lightweight constructions at a much lower price compared to carbon composites.
The automotive industry is one of the biggest innovation drivers concerning lightweight designs. The chassis’ weight of vehicles has a big impact on fuel consumption and therefore also CO$_2$-emission. Furthermore, crash tests are getting more demanding, not only with respect to statutory regulations, but also regarding consumer tests with star ratings. Newly developed UHSS provide both good crashworthiness and weight reduction at the same time. Compared to other conventional materials, the high tensile strength of UHSS yields the opportunity to decrease the sheets’ wall thickness, which results in a lower overall weight. [1]

UHSS are used particularly in parts, where extreme strength is required, for example in roof frames, a-pillars, b-pillars, and doorsills. They protect the occupants in the vehicle’s cabin in case of impact by absorbing most of the kinetic energy while remaining dimensionally stable. UHSS have an outstanding crash performance, but their manufacturing costs, especially the final trimming of body-in-white parts, are highly uneconomical compared to conventional steels.

Commonly used techniques for deep drawing of UHSS are the direct and indirect hot stamping process (also called press hardening). The direct hot stamping process is characterized by, first, austenitizing of the metal sheet blank, followed by simultaneous tempering and drawing at high temperatures. In the indirect process, deep drawing, including cutting operations, is performed prior to austenitizing and calibrating steps. In the final trimming of the hardened components, both drawing methods require the removal of excessive material. [1]

Currently, there are three common techniques for trimming and piercing of UHSS: laser cutting, warm blanking, and hard blanking [2]. In the automotive industry, laser cutting is the most common approach to cut hardened components. This frictionless separation method causes no tool wear, but it is more time and energy consuming than conventional blanking. For high quantities, conventional blanking would be preferred because of its economic advantages.

In recent years, the research of UHSS was focused mainly on warm blanking and the hot formability before quenching. After the quenching procedure, the obtained martensitic-bainitic structure provides an enormous increase in yield strength with only a small loss in ductility, which lowers the cold formability. However, blanking during the press hardening requires a complex tool design to perform quenching and blanking simultaneously. Hoffmann et al. [3] developed an algorithm for the optimal design of a tool cooling system during the hot stamping process. Mori et al. [4] describes the possibility to decrease the cutting force required for piercing UHSS by local resistance heating of the shear zone.

Another major approach for trimming or piercing UHSS sheets is cold blanking. This is the least researched method of the ones already mentioned. So et al. [1] analyzed the cold blanking of press hardened 22MnB5 and determined rapidly increasing tool wear of the cutting tools during the experiments. In a recent study, Feistle et al. [6] developed an innovative method for blanking of UHSS in quenched state, called notch shear cutting, which reduces the cutting force. The main challenges with blanking of quenched UHSS are the necessary, extremely high cutting force and the resulting cutting impact, which is almost as high as the cutting force. This leads to a high alternating load on the punch and the entire cutting tool setup, which shortens the lifetime of the active cutting elements (punch and die) immensely. Therefore, it is almost impossible to apply the process in mass production, where a high endurance is an important requirement.

This paper introduces a tool design for a continuous stroke piercing process of quenched 22MnB5 UHSS. Therefore, the high cutting force and cutting impact as well as the punch design were investigated. The aim of this paper is to prove the suitability of the process setup and punch design for mass production applications. The quality of the cutting surfaces and the amount of tool wear were chosen as criteria to evaluate the process setup.
2. Approach

2.1. Materials
The objective of this study was to evaluate tool wear throughout a continuous cutting process of 1.5 mm thick, quenched boron steel 22MnB5 sheets. The chemical composition and mechanical properties of this UHSS are shown in table 1 and table 2, respectively.

Table 1. Chemical composition of 22MnB5 in weight percentage.

|   | C   | Si   | Mn   | P   | Cr+Mo | Ti   | B   |
|---|-----|------|------|-----|-------|------|-----|
|   | 0.250 | 0.400 | 1.400 | 0.010 | 0.500 | 0.050 | 0.005 |

Table 2. Mechanical properties of 22MnB5 UHSS.

|                                | Young’s modulus [MPa] | Yield strength [MPa] | Ultimate strength [MPa] | Failure strain [%] |
|--------------------------------|-----------------------|----------------------|-------------------------|-------------------|
|                                | 197,000               | 1,100                | 1,500                   | 3.50              |

Two different materials were tested for the cutting tool. One of them is the Böhler K340 ISODUR (Böhler Edelstahl GmbH & Co KG, Kapfenberg, Austria) is a cold work tool steel, commonly used in applications, where excellent wear resistance, compressive strength, and toughness are required. It is manufactured using the electro-slag remelting (ESR) method to achieve a highly pure and homogenous material. [7] The second material is the high-speed steel Böhler S390 MICROCLEAN (Böhler Edelstahl GmbH & Co KG, Kapfenberg, Austria), which has a good red hardness, compressive strength, and wear resistance. [8] The chemical compositions of both K340 and S390 are listed in table 3. A set of active tool parts was made of S390 and K340, respectively, with a hardness of 62 HRC.

Table 3. Chemical composition of both blanking tool materials in weight percentage. [7, 8]

| Tool material | C   | Si   | Mn   | Cr  | Mo  | V   | W   | Co  |
|---------------|-----|------|------|-----|-----|-----|-----|-----|
| K340          | 1.1 | 0.9  | 0.4  | 8.3 | 2.1 | 0.5 | + Nb, Al |
| S390          | 1.6 | 0.6  | 0.3  | 4.8 | 2.0 | 4.8 | 10.4 | 8.0 |

Each blanking tool setup was subjected to 50,000 piercing strokes. To quantify tool wear on the active piercing elements, tactile measurements on the frontal and lateral surfaces were performed every 10,000 strokes.

2.2. Blanking tool
The experiments were carried out on a high-performance stamping press BSTA 510-125 (Bruderer AG, Frasnacht, Switzerland) at the Chair of Metal Forming and Casting. The punching speed was set to 100 strokes per minute.

The blanking tool design was identical for both cutting tool materials. In figure 1 (a), the final experimental setup is illustrated as a cross section. Figure 1 (b) shows a detailed view “A” in a 3:1 scale, presenting the geometrical arrangement of the active elements during the cutting. The sheet metal was pulled by a servo feed BSV 75T (Bruderer AG, Frasnacht, Switzerland) (not shown in figure 1 (a)) through a closed tunnel. The punch, located in the upper part, pierced circular holes with 10 mm in diameter. The punch was attached to the load cell unit with 0.1 mm head-clearance and was guided
through a bush. Based on the system for basic shafts, the tolerance classes h6 for the shaft and H6 for the hole resulted in a clearance fit with 0 µm to 18 µm clearance.

![Diagram of blanking tool setup](image1)

**Figure 1.** (a) Cross section of the blanking tool setup and (b) a detailed view “A” in 3:1 scale.

Figure 2 shows a pierced (left) and an unpierced (right) stripe of quenched UHSS sheets, connected by a puzzle-piece geometry. This technique enabled a continuously feeding of the 1.5 mm thick sheet band through a tunnel into the press. The tool setup did not feature a blank holder, since even a moving one would allow the puzzle to release itself. To avoid cutting the puzzle joint, the feeder was operated in a pulling interval mode.

![Image of pierced and unpierced stripes](image2)

**Figure 2.** Pierced (left) and unpierced (right) stripes joined by puzzle geometry.

Common issues in blanking of quenched UHSS are punch fatigue chipping, growth of cracks, fractures, and galling of the punch [5]. The initial punches were manufactured according to ISO 8020, but they broke with head fractures after a few hundred strokes. In order to lower the notch sensitivity of the punches a trombone neck was chosen for the experiments instead. The cutting edges were rounded to a radius of 100 µm to reduce stresses on the edges [9] and therefore to counteract edge chipping. The length of the punches was adjusted in accordance with the critical buckling length.
3. Methods

3.1. Determining cutting force and cutting impact

The cutting force equals the maximum force on the punch and is quantified by the empirical equation (1). It correlates the theoretically required cutting force $F_s$ with the cut length $l$, sheet thickness $s$, ultimate strength $US$, and shear flow factor $f$. The shear flow factor is simplified to $f = 0.8$, when the punch diameter divided by the sheet metal thickness exceeds two. [10]

$$F_s = l \cdot s \cdot US \cdot f$$  

(1)

The theoretical maximum cutting force is calculated to $F_s = 56.54$ kN ($l = 31.41$ mm, $s = 1.50$ mm, $US = 1.500$ MPa, $f = 0.8$). The measurement in the load cell indicates a rapid increase of the cutting force, caused by the large tensile strength of UHSS. The combination of the high cutting force and the low ductility of quenched UHSS induces an oscillating cutting impact, which was approximately as high as the cutting force, see figure 3. However, the graph in figure 3 was taken from another similar experiment for piercing quenched 22MnB5, using a punch with a diameter of 20 mm and a 2 mm thick metal sheet. The ordinate axis is standardized to the cut length and metal sheet thickness. In the present experiments, the unexpectedly high cutting impact caused immense loosening of the load cell preloading screw. To measure both high compressive force and high tensile force a suitable preload of the load cell is essential. Figure 3 supports that the empirical equation (1) to approximate the real cutting force $F_s$. The cutting impact $F_i$ cannot be predicted in a similar way.

![Figure 3. Force-displacement curve through piercing process of quenched 22MnB5.](image)

3.2. FEM analysis of critical punch length according to Euler

An analytic approach to determine the critical buckling force is the equation (2) according to Euler, which defines the maximal axial load a column can withstand without buckling. It correlates Euler’s critical load $F$ with the Young’s modulus $E$, area moment of inertia of the column’s cross section $I$, and unsupported critical length of the column $l_c$.

$$F = \frac{\pi^2 EI}{(l_c)^2}$$  

(2)
The four different boundary conditions for Eulerian buckling modes are illustrated in figure 4. Mode 1 corresponds to a cutting tool setup where the punch’s head is fixed without a guide and the punch’s end is free. The punch in the experiments presented not only a guide but also a clearance at the mounting point of its head, which is not reflected in any of the four Euler buckling modes. The guide supported mode 4, while the lack of fixation at the punch’s head ruled out all but mode 2. Therefore, a maximum punch length between mode 2 and mode 4 was expected.

![Figure 4. Euler buckling cases adapted from [11].](image)

The Euler buckling analysis is fast and simple, but also faulty due to its idealized conditions, such as perfectly straight column, ideally axial directed load, frictionless bearings, etc. In addition, it is only a two-dimensional, static method, which excludes dynamic effects.

To increase the accuracy of the critical punch length, a three-dimensional FEM study was performed using Abaqus/Explicit (Version 6.12-3, Dessault Systèmes, Vélizy-Villacoublay, France). The FEM model contained a blanking punch with 120 mm in length and 10 mm in diameter. The metal sheet as well as the plate, which distributes the cutting force on the punch, were modelled as rigid, quadratic, plane surfaces. The plate had one degree of freedom in the longitudinal direction of the punch, in addition. The guide was modelled as a revolved, rigid surface. Two setups were designed, one with a sole punch and the other one with a guided punch. The simulated critical buckling forces were 69.00 kN and 73.00 kN, respectively. The simulated critical buckling forces were in the same order of magnitude as the maximum cutting forces calculated using equation (1).

Figure 5 visualizes the von Mises stress field (S, Mises) of the punch in both configurations, the sole punch (figure 5 (a)) as well as the one with the guide as a whole (figure 5 (b) and in detail (figure 5 (c))). It also illustrates the contact pressure on the punch caused by the guide (figure 5 (d)). The simulation revealed that guiding the punch increased the critical buckling force, but at the cost of high contact pressure on the guided part of the punch.
Although a guided punch was used in the simulations, the resulting critical buckling length resembled the Eulerian assumption of an unguided punch. This discrepancy was caused by the initial problem that none of the four Eulerian buckling modes described the actual punch setup, which was guided at the shaft but not fixed at the head. Furthermore, the Eulerian theory assumed that the guide was rigid, frictionless, and without clearance between guide and punch. Since none of those assumptions agreed with the present setup, deviations were expected and, thus, merely a tendency towards one of the buckling modes was evaluated. Preliminary experiments yielded that 120 mm long punches tended to a combination of press welding and friction welding between punch and guide, which caused instantaneous breakage at the punch’s head or shaft.

A radial expansion of the punch, due to the cutting force, is relevant for press welding and fretting. Equation (3) describes the deformation of the punch’s diameter $\Delta d$ in relation to the Poisson’s ratio $\nu$, longitudinal strain $\Delta l/l$, and diameter $d$. Furthermore, the longitudinal strain was substituted by the maximum force on the punch $F_s$, its cross-section area $A$, and its Young’s modulus $E$, according to Hooke’s law. [11]

$$\Delta d = -\nu \cdot \frac{\Delta l}{l} \cdot d = -\nu \cdot \frac{F_s}{A \cdot E} \cdot d$$

An estimate of the diameter expansion reveals $\Delta d = 10.28 \mu m$, using setup specific values ($F_s = 56.54 kN$, $A = 78.54 mm^2$, $d = 10 mm$) and common material values for steel ($E = 210 GPa$, $\nu = 0.3$). This expansion is within the range of the clearance fit and causes only fretting, if the clearance is at the lower end of its range. Avoiding this problem by loosening the fit would counteract the purpose of the guide.

3.3. Evaluation of tool wear and cutting surfaces
The contour measuring station MarSurf XC 20 with PCV 200 drive unit (Mahr GmbH, Göttingen, Germany) was used to analyze the surface of the active cutting elements.

The tactile measurements to determine tool wear were performed four times at every stage and then averaged. A 45° angle between the frontal and lateral surface was chosen to indicate the wear length in
relation to the initial cutting edge radius of 100 µm. Figure 6 (a) and figure 6 (b) demonstrate the approach to measure the tool wear of a K340 punch and K340 die, every 10,000 strokes.

Figure 6. Quantitative wear development of the punch (a) and die (b) made of K340.

The characteristic parameters of the cutting surface, see figure 7 were evaluated according to VDI 2906-2 [12].

Figure 7. Characteristic parameters of a cutting surface according to [12].

4. Results

The wear of the tool setup and the cutting surface of the metal sheet were both evaluated after 50,000 strokes for each test series.

4.1. Evaluation of tool wear

The tool wear was quantified by tactile measurements using a contour measuring station. Figure 8 shows the 45° wear length for both punch and die of both material, K340 and S390, in relation to the number of strokes. In general, the K340 setup is more susceptible to wear than the one made of S390. As indicated in figure 6 (a) and figure 6 (b), the K340 tools show slight wear on the frontal surface, but
almost none on the lateral surface of both punch and die. In the S390 setup, a slight wear was detected on the frontal surface of the punch, but none on the die.

![Graph](image)

**Figure 8.** 45° wear measured on the cutting edge on the punch and die, in both blanking tool setups.

The behavior of the 45° wear length is almost linear for both materials, which indicates that the wear is still within a stable phase. After conducting 50,000 strokes, the punches show a 45° wear length of 45 µm (K340) and 11 µm (S390). The 45° wear length on the corresponding dies are 32 µm (K340) and 14 µm (S390). In both configurations, no fractures occurred.

### 4.2. Evaluation of cutting surfaces

The cutting surfaces of the metal sheet bands were analyzed using a contour measuring station. Throughout the experiment, the characteristic parameters of the cutting surface remained almost constant, as figure 9 (a) and figure 9 (b) indicate. Both tool setups provide comparable cutting surfaces. The minor fluctuations between the absolute values are due to statistical variance. The distribution of rollover, burnish, fracture, and burr is typical for quenched steel with low ductility.

![Graph](image)

**Figure 9.** Characteristic parameters of the cutting surfaces (a) K340 tool setup and (b) S390 tool setup.
5. Conclusion
The presented study about piercing of quenched UHSS (22MnB5) demonstrates that the conventional blanking process is a huge challenge for the entire setup and, especially, the active components. The required rigid tool design is difficult to implement in a serial production in the automotive industry. Due to the extreme cutting force and cutting impact, a slim punch design requires particular attention to avoid harmful buckling. Both K340 and S390 tool materials performed well and completed the experiments without fractures of the punches. The tool wear was consistently low and complied with an abrasion of the cutting edge. The evaluation of the cutting surfaces showed that tool wear has no influence on the characteristic parameters for both materials up to 50,000 strokes.

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