Process design of press hardening with gradient material property influence

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Abstract. Press hardening is currently used in the production of automotive structures that require very high strength and controlled deformation during crash tests. Press hardening can achieve significant reductions of sheet thickness at constant strength and is therefore a promising technology for the production of lightweight and energy-efficient automobiles. The manganese-boron steel 22MnB5 have been implemented in sheet press hardening owing to their excellent hot formability, high hardenability, and good temperability even at low cooling rates. However, press-hardened components have shown poor ductility and cracking at relatively small strains. A possible solution to this problem is a selective increase of steel sheet ductility by press hardening process design in areas where the component is required to deform plastically during crash tests. To this end, process designers require information about microstructure and mechanical properties as a function of the wide spectrum of cooling rates and sequences and austenitizing treatment conditions that can be encountered in production environments. In the present work, a Continuous Cooling Transformation (CCT) diagram with corresponding material properties of sheet steel 22MnB5 was determined for a wide spectrum of cooling rates. Heating and cooling programs were conducted in a quenching dilatometer. Motivated by the importance of residual elasticity in crash test performance, this property was measured using a micro-bending test and the results were integrated into the CCT diagrams to complement the hardness testing results. This information is essential for the process design of press hardening of sheet components with gradient material properties.

Keywords: Hot Sheet Metal Forming, Material Characterization, Thermo-Mechanical Processing

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INTRODUCTION

It is possible to influence the material properties by modified thermo-mechanical treatment. The press hardening process of manganese-boron steels is based precisely on this fundamental principle. The properties of high strength steel are improved by the selective graduation of component properties to enhance collision performance.

For technological implementation the fundamental technical material knowledge, such as CCT diagrams is needed to derive process controls. The manganese-boron steel 22MnB5 has established itself in press-hardening production due to its excellent performance during hot forming. In the austenite phase it has similar formability to regular deep-drawing steels at room temperature. With heat treatment during the forming process tensile strengths ranging from 1000 MPa to 1500 MPa can be reached. The final properties of the formed components are primarily influenced by the
chemical composition of the material, the forming parameters such as forming temperature and deformation. The important alloying elements such as carbon, manganese, chromium and boron are responsible for hardening. In the initial state 22MnB5 shows a ferritic-pearlitic microstructure with carbide precipitation [7, 8, 9].

**THERMO MECHANICAL TREATMENTS**

Hot forming is basically a thermo-mechanical process, where process temperature and deformation are controlled by a time-dependent operational sequence. An important aim of this process is to set up specific mechanical properties in selected areas of the manufactured components [4]. The thermo-mechanical processes can be classified according to the phase transformations occurred before, during or after forming [5]. For the hot forming process, shaping is employed previous to phase transformation in a metastable region for thermo-mechanical treatment [5]. The process of shaping under Ac₃ temperature followed by a quenching procedure is also known as ausforming because the resulting microstructure consists in most cases of martensite or bainite (see Figure 1).

**FIGURE 1.** Ausforming with a martensitic transformation [5].

Ausforming is a special case of the thermo-mechanical treatments, where mechanical properties such as yield strength or toughness of steel sheet components can be selectively improved. This is especially applicable to the ultra high strength steels. Thereby, austenite and/or other phase combinations are cold or hot formed at a defined temperature.

**MATERIAL PROPERTIES**

The knowledge of the thermo mechanical material performance is important for the hot sheet metal pressing process design. During the thermo-mechanical process the temperature and deformation rate interaction influence directly the material properties. The first step of the characterization is the creation of the CCT diagram to represent the material behaviour at typical austenization temperatures and different cooling rates.

CCT diagrams can be represented in isothermal or continuous temperature-time processes. The fundamental difference is that with the isothermal heat treatment
process, the structural transformation takes place at constant temperature, while the transformation takes place during cooling in continuous heat treatment.

In this article the continuous CCT diagrams will be generated. With the dilatometer different cooling curves were measured and analyzed. The samples were heated to austenization temperature and cooled at different rates. The structural transition points can be identified by turning points in the cooling curve. By connecting the individual points the continuous CCT diagram is created.

**Determining the austenitizing temperature**

To determine the austenitization temperatures the following regression formulas can be used as a function of the steel alloying elements. The lower austenitization temperature $A_{c1}$ [1] and the upper austenitization temperature $A_{c3}$ [2] are essentially determined by the chemical composition of the materials.

\[
A_{c1}[\degree C] = 739 - 22 \times \%C + 2 \times \%Si - 7 \times \%Mn + 14 \times \%Cr + 13 \times \%Mo - 13 \times \%Ni + 20 \times \%V
\]

\[
A_{c3}[\degree C] = 902 - 255 \times \%C + 19 \times \%Si - 11 \times \%Mn + 5 \times \%Cr + 13 \times \%Mo - 20 \times \%Ni + 55 \times \%V
\]

The chemical compositions of the investigated materials were determined with spectral analysis using a Spectro-Tester (see Table 1).

<table>
<thead>
<tr>
<th>TABLE 1. Chemical composition of the studied alloys</th>
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<td>Elements share [%]</td>
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<td>C</td>
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The austenitization temperatures were calculated by using the determined chemical composition. $A_{c1}$ and $A_{c3}$ temperatures for 22MnB5 alloy were determined to be 726 °C and 829 °C, respectively.

**Dilatometer investigations**

Based on the above calculation of the $A_{c3}$ temperature, an austenitization temperature of 900 °C was used during the dilatometer tests. A holding time of 10 min at this temperature was used as proposed in “Stahl-Eisen-Prüfblatt SEP 1680” [3]. For the determination of phase transformation temperatures a dilatometer DIL 805 A/D was used. Samples were cooled at rates between 0.2 and 60 K/s. The dilatometer used inductive heating and the measurements were carried out under an inert gas atmosphere. Figure 2 shows the determined CCT diagram of the 22MnB5 alloy, with the experimental cooling rates curves.
At a cooling rate of 8 K/s, the austenite begins to transform into the austenitic-ferritic phase with bainitic phase components. When increasing the cooling rate the martensitic phase transformation starts. At a cooling rate of about 25 K/s, the austenite transforms into martensite.

**Microstructural examination**

The dilatometer samples were prepared for micrographs, which were used to complete and analyse the CCT diagrams. The micrographs were taken with a scanning electron microscope (SEM).

The SEM micrographs of the 22MnB5 alloy (Figure 3) demonstrate how with increasing cooling rates, between 0.2 K/s and 60 K/s, the microstructure changes from ferritic-pearlitic to martensitic. When the cooling rate increases more than 25 K/s, the whole austenitic structure is converted into martensite.

**Hardness Test**

Mechanical properties were determined from the dilatometer samples. Vickers Hardness tests were performed using the load range HV 1. The hardness values for 22MnB5 started to rise at cooling rates higher than 8 K/s, because bainite was being formed giving hardness values of 194 HV 1 (see Figure 4). The martensite transformation starts from a cooling rate of about 25 K/s and shows a hardness of 447 HV 1. Bainitic and martensitic transformations affect the final mechanical material properties by increasing hardness.
Micro-bending test

As a complimentary test, to define the mechanical properties more precisely, micro-bending tests were performed on the specimens from the dilatometer. These tests were relevant due to the small size of the dilatometer samples and were conducted according to DIN EN ISO 7438 [6]. With the micro-bending test it is possible to determine the deformation and a reliable true loading case. For such purpose, bending moment was determinate in function of the bending angle (see Fig. 5).

The analysis showed that the dilatometer samples with a cooling rate of 60 K/s broke and only reached a maximum bending angle $\alpha$ of 60°. The samples with a cooling rate of 0.2 K/s to 25 K/s have all values of $\alpha \sim 80°$, which this is the maximum achievable bending angle in this experiment.

If the bending moment $M_b$ and bending angle $\alpha$ are known, it is possible to determinate the maximum stress and strain at the edge beam [10]. To this end, the edge tension can be determined by

$$
\sigma_R = \frac{2}{a^2 \cdot s_b} \left( 2 \cdot M_b + \alpha \cdot \frac{\partial M_b}{\partial \alpha} \right)
$$

(3)
where \( s_h \) designates the sample width. The edge strain \( \varepsilon_R \) can be determined by

\[
\varepsilon_R = \frac{\alpha \cdot a}{L}
\]

(4)

The results can be shown as smoothed stress-strain curves. The local inflection points do not allow a doubt-free statement about the end of the uniform deformation, however an evidence of the influence of the cooling rate on the strain can be clearly observed.

**CONCLUSIONS**

A CCT diagram for the 22MnB5 alloy was determined. The microstructure development of the investigated alloy was a function of the cooling rate and shows a good correlation with the resulting mechanical properties. The range of the studied cooling rates allows the application of these results on the process design for components with graded properties. The integration of the results obtained in the micro-bending test in the determination of the CCT diagram is of significance, since they showed a qualitative trend of the residual formability, which permits a preliminary estimation of the crash-performance.

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**REFERENCES**