Influence of intercritical annealing temperature on formability and mechanical properties of medium-manganese-steel in press hardening

TILLY Karl Johann[1,a *], PLUM Tobias[1,b], BAILLY David[1,c] and HIRT Gerhard[1,d]

[1] Institute of Metal Forming, RWTH Aachen University, Aachen, Germany

[a]karl.tilly@ibf.rwth-aachen.de, [b]tobias.plum@ibf.rwth-aachen.de, [c]david.bailly@ibf.rwth-aachen.de, [d]gerhard.hirt@ibf.rwth-aachen.de

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Abstract. Ultra-high-strength-steel parts produced by press hardening are widely used in the automotive sector for lightweight construction and passenger safety applications. Medium-manganese-steels (MMnS) are currently investigated as an alternative to boron-manganese steels. Their favorable mechanical properties of high strength and high ductility after quenching are often based on rather complex heat treatment strategies resulting in a multiphase microstructure. One possible way such a microstructure can be obtained, is intercritical annealing and subsequent quenching during the press hardening process. For this processing route formability during hot stamping and final properties of the quenched material are dependent on the annealing temperature. For a successful part production, an annealing temperature that satisfies both, in-process properties, as well as final mechanical properties is mandatory. In this paper, the suitability of the intercritical annealing process route for press hardening of MMnS is investigated for a specific MMnS alloy. Formability in hot stamping conditions with respect to different annealing temperatures (range 700°C – 800°C) are examined by performing hot tensile tests, as well as experimental trials using a hot stamping tool. Final properties are analyzed by tensile tests. The formability during hot tensile tests and hot stamping show a strong positive correlation to the annealing temperature, while the values for uniform and ultimate elongation of the quenched material shows a strong negative correlation to the annealing temperature. The tensile strength of the quenched material shows a low sensitivity to the annealing temperature. No annealing temperature that satisfies both, in-process and final properties, could be found for the investigated MMnS alloy.

Introduction

Increasing demands for passenger safety and reduction of CO_2 emissions in the automotive sector led to the increased usage of high strength steels in autobody applications. The main advantage of advanced-high-strength-steels is the lightweight construction potential due to their mechanical properties.[1] Direct press hardening, consisting of the three steps austenitization, hot stamping and tool-quenching, is a widely used process to produce high strength autobody parts from sheet metals.[2] The commonly used manganese-boron steels such as 22MnB5 typically achieve tensile strengths of 1500 MPa und residual formabilities of minimum 5 % in the quenched state with fully martensitic microstructure [3]. In order to improve the performance of parts produced from manganese boron steels strategies such as tailored heating, or the usage of tailored materials such as tailor-welded blanks or cladded material have been investigated. The strategies of tailored processes or properties for press hardening of manganese-boron-steels mostly rely on reducing the strength of sections of the structural component in exchange for an improved ductility. Therefore the overall component performance, for example total energy absorption in a crash, can be

improved. On the downside to the production process of parts with tailored properties is more complex as for example segmented tools or tailor welded blanks are necessary. [3,4]
As an alternative to the commonly used manganese-boron-steels, steels of the medium-manganese alloy class (MMnS) have been investigated, with the aim of providing a material with high strengths and simultaneously high ductility for press hardening processing. The favorable mechanical properties of MMnS are based on a fine-grained multi-phase microstructure after press hardening that consists of retained austenite and martensite. To achieve this microstructure, it is often necessary to employ multistep heat treatment procedures (for example Quench and Partitioning) before or after the hot stamping operation, wich leads to a more complex processing compared to manganese boron steels [5-9].
In this paper it will be investigated whether a single heat treatment of intercritical annealing is suitable for hot stamping processing of a specific MMnS alloy.

Investigated Alloy and Processing
For the investigations presented in this paper, 2 mm thick sheets of a medium manganese steel alloy were used. The chemical composition of the steel is shown in Tab. 1. The schematic temperature curve of the intercritical annealing and phase fractions before and after quenching are shown in Fig. 1. Before quenching, different fractions of austenite (γ) and primary martensite (α'_p) depend on the annealing temperature. After quenching, a phase transformation of the austenite to retained austenite (γ_r) and secondary martensite (α'_s) as shown is expected, while the primary martensite percentage is anticipated to be stable.

Table 1. Chemical composition (wt. %).

Fe	C	Mn	Si	Al	Cr	P	S	N
bal.	0.30	4.99	1.55	0.004	0.04	0.005	0.003	0.004

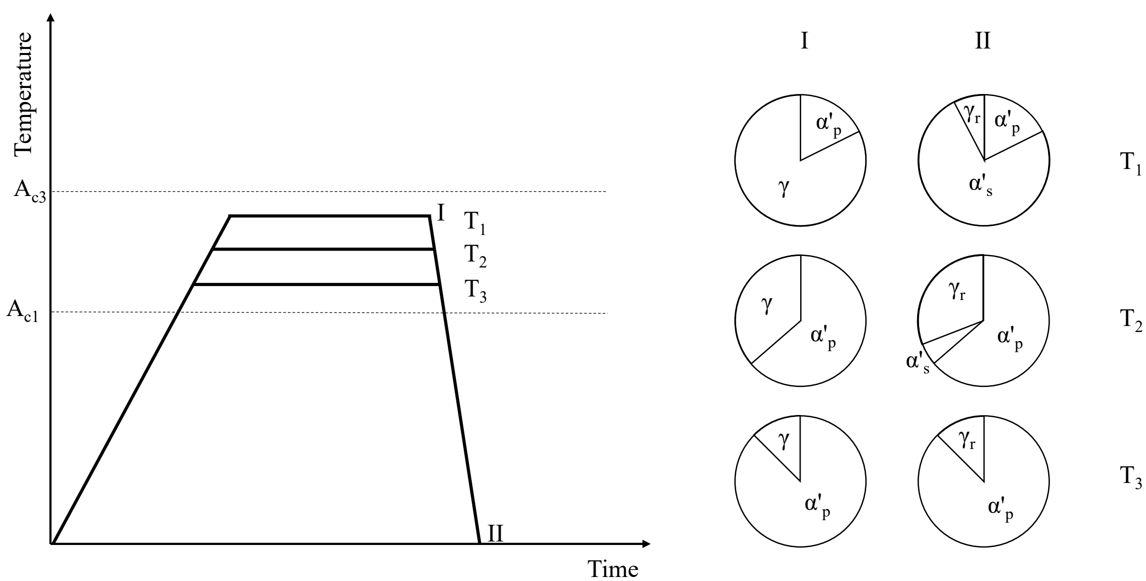

Fig. 1. Schematic illustration of phase fractions before and after quenching from different intercritical annealing temperatures.

Hot Tensile Tests

In order to verify the expected material behavior in terms of dependence of formability during hot stamping on the blank temperature during prior annealing, hot tensile tests were performed on a TA Instruments DIL805 dilatometer. The annealing temperature was varied in an interval of 700°C to 800°C. All specimens were inductively heated to the respective annealing temperature at a rate of 10 K/s. The soaking time was set to 5 min. After annealing, the specimens were quenched to 600°C and tensile tests were performed at a strain rate of 0.5 1/s. The uniform elongation is taken as an indicator of the materials formability with respect to the annealing temperature.

Fig. 2 shows the measured uniform elongation values at different annealing temperature. As expected, higher annealing temperatures, and therefore higher phase fractions of austenite, result in higher ductility. The highest uniform elongation could be found for an annealing temperature of 800°C (100 % austenite). It is notable that in a relatively small temperature interval from 720°C to 750°C the ductility of the material increases rapidly, indicating a switch between the materials behavior being dominated by the properties of the martensitic phase to being dominated by the properties of the austenitic phase.

A logistic function (Eq. 1) can be fitted to the data points to be able to approximate a continuous correlation between formability and annealing temperature. The formabilities of the single martensitic and austenitic phases are represented by the lower and upper limits of the curve.

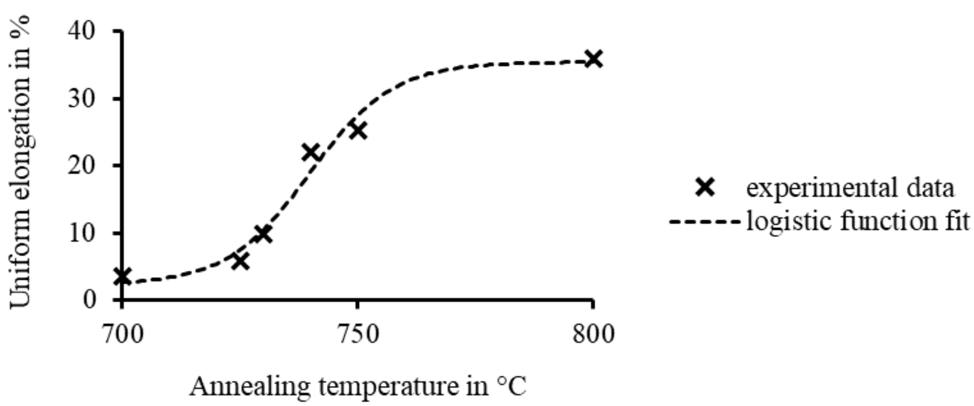

Fig. 2. Dependence of uniform elongation on the annealing temperature during hot tensile testing.

$$A_g = \frac{A_{g,max}}{1+e^{-k(T-T_0)}} \quad (1)$$

Hot Stamping Experiments

For further investigation of the material's formability at different annealing temperatures hot stamping experiments were performed on a single acting hydraulic deep drawing press using a hot stamping tool resembling a miniaturized b-pillar part. The tool does not have an active water-cooling system. However, as cycle times were larger than 10 minutes, the tool temperature can be assumed to be room temperature. Prior to annealing the blanks are spray-coated with boron nitride for friction reduction and basic scaling protection. The blanks were heated in a convection furnace for 7 minutes at different annealing temperatures (700°C, 730°C, 750°C, 800°C). After annealing the blanks were manually transferred to the pressing tool and formed with a constant tool speed of 35 mm/s (drawing depth of 25 mm). After forming the parts are quenched in the closed tool for 10 s.

Fig. 3 a) shows the dimensions of the hot stamped T-Shape profile. The notches at the bottom of the part are necessary for aligning the blank in the tool using two pilot rods. As can be seen in Fig. 3 b) only an annealing temperature of 800°C (fully austenitic microstructure) leads to a crack-free part. At annealing temperatures of 700°C, 730°C, and 750°C severe crack form at the upper part of the profile. With increasing annealing temperature additional cracks at the left and right shoulder part of the part start to appear. One possible explanation for cracks occurring at more locations with increasing annealing temperature is the increasing ductility of the material. At 700°C annealing temperature, the crack in the center part of the profile starts to form at very low drawing depths due to the poor ductility of the material. Therefore, almost all deformation for the rest of the drawing process takes place in the cracked region on the sheet. At higher annealing temperatures, the material is more ductile. The crack in the center appears at a higher drawing depth which leads to a more uniform thinning of the material which again leads to additional cracks forming.

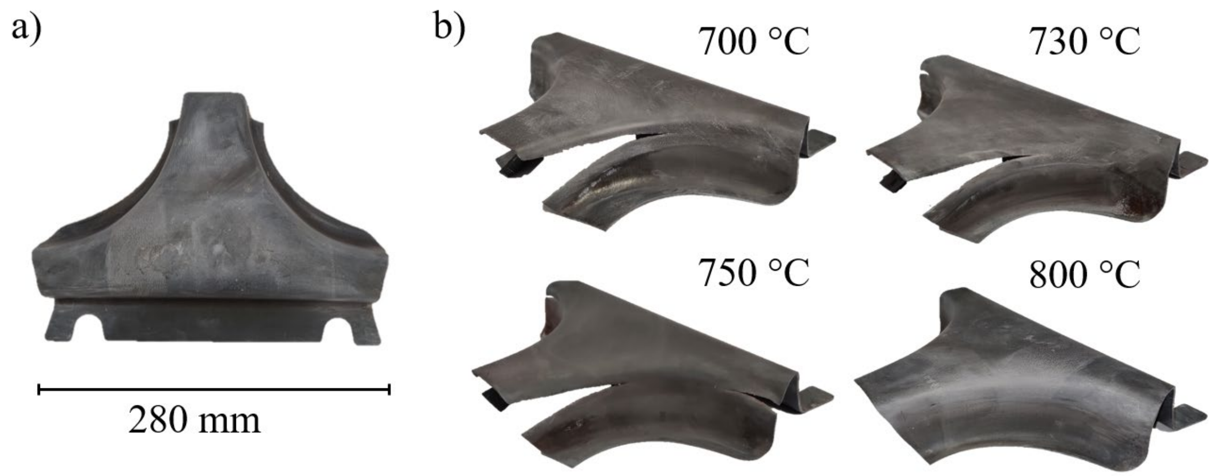

Fig. 3. a) Dimensions of T-shape profile. b) T-shape profiles processed with different annealing temperatures.

Material Properties of Quenched Specimens

In order to assess the mechanical properties of the quenched material with respect to the annealing temperature, further quenching experiments were conducted using the hot stamping tool. For each annealing temperature a rectangular sheet was heated according to the annealing of the T-shape profiles and quenched between the blank holder and the die of the hot stamping tool for 10s. Tensile test specimens were cut from the quenched sheets and quasi-static tensile tests were performed at room temperature. Table 2 shows the mechanical properties in the quenched state with respect to the different annealing temperatures.

Table 2. Mechanical properties in quenched state with respect to annealing temperature.

Annealing temperature [°C]	$R_{p0,2}$ [MPa]	R_m [MPa]	A_g [%]	A [%]
700	576	1250	21.0	21.2
730	420	1277	6.4	6.4
750	574	1263	2.4	2.4
800	877	1300	0.6	0.6

While yield strength and tensile strength only show a low sensitivity to the annealing temperature, uniform and total elongation show a strong dependence on the annealing temperature. An annealing temperature of 800°C results in a fully austenitic microstructure after annealing and a fully martensitic microstructure after quenching. This microstructure displays a very brittle behavior. With decreasing annealing temperature, and therefore higher phase fraction of retained austenite in the quenched state, the ductility of the material increases. At 730°C annealing temperature the ductility is comparable to standard manganese boron steels. At 700°C annealing temperature, the material displays very favorable mechanical properties in the quenched state.

Summary

This paper investigates the suitability of intercritical annealing and subsequent press hardening for processing high strength parts from medium manganese steel sheets. The choice of a specific annealing temperature influences phase fractions of austenite and martensite in the microstructure during hot stamping and after quenching. For different annealing temperatures formability was investigated by hot tensile tests and hot stamping experiments. Final mechanical properties were investigated by tensile tests. Hot tensile tests show an increasing formability with increasing annealing temperatures. In hot stamping experiments, part production without cracking was only possible for an annealing temperature of 800°C.

While yield strength and tensile strength in quenched material state show very low sensitivity to the annealing temperature, ductility increases heavily with decreasing annealing temperature. Mechanical properties of tensile strengths of 1250 MPa and total elongations of 21.2 % could be achieved at an annealing temperature of 700°C. While for both, in-process and final mechanical properties, an adequate annealing temperature could be found, no investigated annealing temperature satisfies both conditions, as a strong trade-off relationship between favorable final mechanical properties and formability during hot stamping was evident.

As a result, due to the identified trade-off relationship of the intercritical annealing route, it is not yet possible to achieve optimal processing conditions and final properties with the same annealing temperature. In this regard, further research has to be conducted in the processing of the investigated medium manganese steel alloy in press hardening.

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