# INFLUENCE OF THE OVERAGING TEMPERATURE ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF COMPLEX-PHASE BAINITIC STEEL

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**Abstract:**

The influence of an applied heat treatment on the evolution of the microstructure and the resulting mechanical properties of complex-phase bainitic steel is investigated. Annealing cycles are applied to study the impact of the overaging temperature. In addition to the characterization of the microstructure by means of light optical microscopy, the tensile and hole expansion properties are determined and discussed.

**Keywords:** AHS steels, heat treatment, microstructure, mechanical properties

## INTRODUCTION

Recent development in sheet steels has been dedicated mainly to automotive use because the requirements of the car producers concerning materials are high and challenging. Main emphasis is placed mainly on decreased car body weight, fuel consumption, adequate passenger safety, crash worthiness and also increased environmental protection. More advanced microstructure control technologies are required in order to produce materials fulfilling such demands. This task becomes feasible due to the recent advancements in simulation and heat treatment technologies. The already existing large group of widely applied high strength steels is therefore constantly optimized. In case of AHS steels the microstructure can be modified to enhance either total elongation property for stretch forming or local elongation for sheared edge stretching limits. The same microstructure generally does not provide high values for both total and local elongation values, therefore the exact knowledge about planned material application is of main interest. High strength bainitic single-phase and bainitic multi-phase (complex-phase) steels are besides TRIP and DP steels recently gaining considerable interest due to their excellent combination of high strength and good formability expressed by hole expansion ratio important for flanging and stretching operations, see Fig. 1.

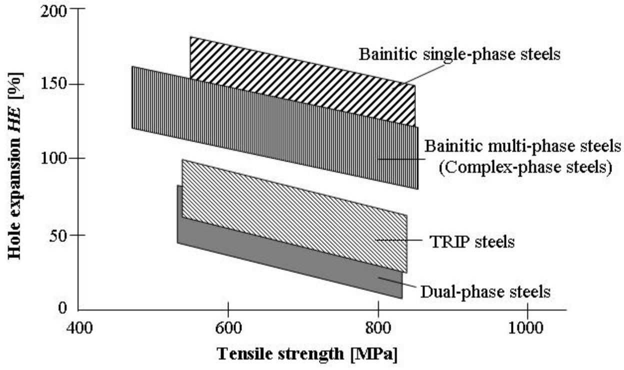



***Figure 1*** *Improvements in formability of high strength steels by modification of microstructure*

In the present work, the influence of the overaging temperature on the microstructure development and the resulting mechanical properties (tensile and hole expansion) of complex-phase bainitic steels is studied.

# EXPERIMENTAL PROCEDURE

## Investigated material

Low carbon low-alloyed cold rolled sheet steel was used for the investigation. The main alloying elements are in wt.%: 0,05 Al, 0,04 Si, <0,25 Cr+Mo, 0,005 Ti+Nb+B. Sheet material with a thickness of 1,2 mm was cut into specimens of dimensions 170x450 $mm^2$ for subsequent annealing simulations.

## Annealing simulation

The annealing simulations were conducted on the Multi-Purpose Annealing Simulator (MULTIPAS). The annealing simulator enables examination of the effects of various heat treatments on steel properties in the laboratory. The specimen is brought to necessary temperature by means of electrical resistance heating and subsequently cooled by a gas jet, air mist or by a hot/cold water cooling system. Cooling rates from the recrystallization temperature to the overaging temperature of up to 100 K/s can be attained.
Specimens were annealed at $T_{an}$ = 840°C for ~ 45s, then cooled to the quenching temperature $T_Q$ = 750°C, subsequently quenched with a cooling rate of 50 K/s and held at selected overaging temperatures $T_{OA}$ for 75s before cooling to the room temperature. The overaging temperature was varied between 400 and 500°C in increments of 25°C, as schematically shown in Fig. 2.

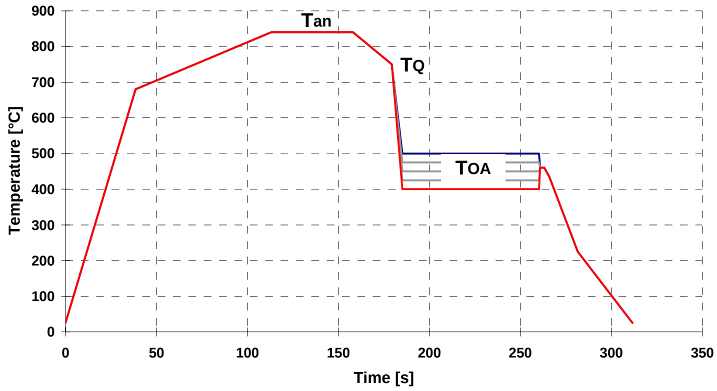



***Figure 2*** *Schematic representation of applied annealing cycles*

### Characterization of the microstructure and testing of mechanical properties

Specimens for the microstructural analysis and mechanical testing were wire cut from the annealed sheet materials. Standard light optical microscopy was used to characterize the microstructure of the heat treated samples. Specimens were taken parallel to the rolling direction of the sheet and were conventionally prepared and etched with LePera´s etchant. Line intercept measurements were conducted in order to quantify the martensite volume fraction in the analyzed microstructures. A magnetic volumetric method was used to measure the fraction of retained austenite [1]. Specimens for mechanical testing were prepared and tested according to the standard EN10 002. The tensile specimens were wire cut with their tensile axis parallel to the rolling direction and tested in the as-annealed condition. Specimens for hole expansion tests were prepared according to ISO/TS 16630:2003(E) (metallic materials – method of hole expansion test). For this purpose the steel sheets were cut into specimens of 100x100 $mm^2$. Holes with diameter of 10 mm were introduced by wire cutting. The hole expansion testing is conducted by expanding the hole using a conical punch with 60° top angle, until the crack at the hole edge is observed. The final hole diameter after testing is measured by averaging two readings taken perpendicularly to each other. The hole expansion ratio, *HE*, is then calculated according to

$$HE[\%] = \frac{d_f - d_0}{d_0} \times 100\%, \qquad (1)$$

where $d_f$ [mm] is the average hole diameter after testing, and $d_0$ [mm] is the initial diameter of the hole.
The specimens were tested using an instrumented hole-expansion testing device allowing load-drop control.

## RESULTS AND DISCUSSION

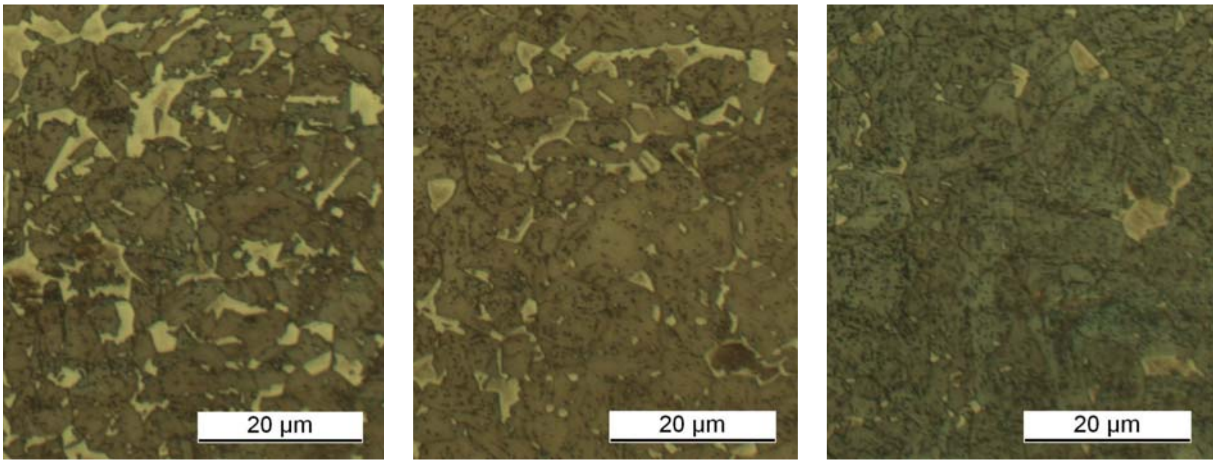
### Effect of overaging temperature on the microstructure development

Results of the quantitative analysis are summarized in Table 1. Micrographs of all investigated steel grades after application of defined annealing parameters are shown in Figs. 3-a-e.

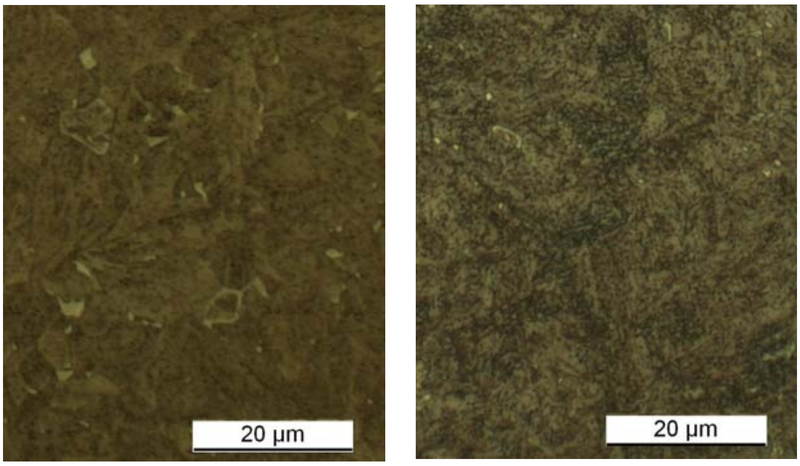
*Table 1 Microstructural characteristics in the dependence from the overaging temperature*

| $T_{OA}$ [°C] | RA [%] | "white" martensite [%] | "brown" martensite [%] |
|---|---|---|---|
| 500 | 4,2 | 11,5 | 9,4 |
| 475 | 3,4 | 5,2 | 7,8 |
| 450 | 2,3 | 2,6 | 6,7 |
| 425 | 0,6 | 2,0 | 4,4 |
| 400 | 0,6 | 0,6 | 3,0 |

As sketched in Fig. 2, all specimens are firstly heated to the austenitic region and held for the sufficiently long to ensure full austenization. After the moderate cooling to the quenching temperature (750°C), quenching to chosen overaging temperatures in the upper bainite transformation range (generally 550-400°C) takes place. The high cooling rate from the quenching temperature (50 K/s) prevents the formation of new ferrite and pearlite. During isothermal holding the bainitic transformation takes place. Upper bainite forms within two distinct stages. Firstly the formation of bainitic ferrite which has a very low solubility for carbon (< 0,02 wt.%) takes place. By the growth of this ferrite the remaining austenite is enriched with carbon. Eventually, cementite precipitates from the residual austenite layers in between the ferrite sub-units. The amount of precipitated cementite depends on the carbon concentration of the alloy. In the investigated low carbon steel, small discrete particles of cementite are formed. Since the precipitation of cementite is retarded due to the addition of Si, the matrix of the final microstructure consists at higher overaging temperatures (500-450°C) only of bainitic ferrite rather then of bainite as can be seen in Figs. 3-a-c. This residual austenite either transforms during the final cooling to room temperature to martensite, or remains as a retained austenite (RA). Two types of transformed martensite designed as "white" martensite and "brown" lath martensite are observed depending on the initial carbon content of the transforming residual austenite. Martensite with higher carbon content appears white, while lower a carbon content leads to "brown" martensite with a highly structured surface. The fractions of transformed martensite and untransformed retained austenite are decreasing by lowering the overaging temperature, see Table 1 and corresponding micrographs shown in Figs. 3-a-e.




(a) $T_{OA}$= 500°C/75s (b) $T_{OA}$= 475°C/75s (c) $T_{OA}$= 450°C/75s




(d) $T_{OA}$= 425°C/75s (e) $T_{OA}$= 400°C/75s

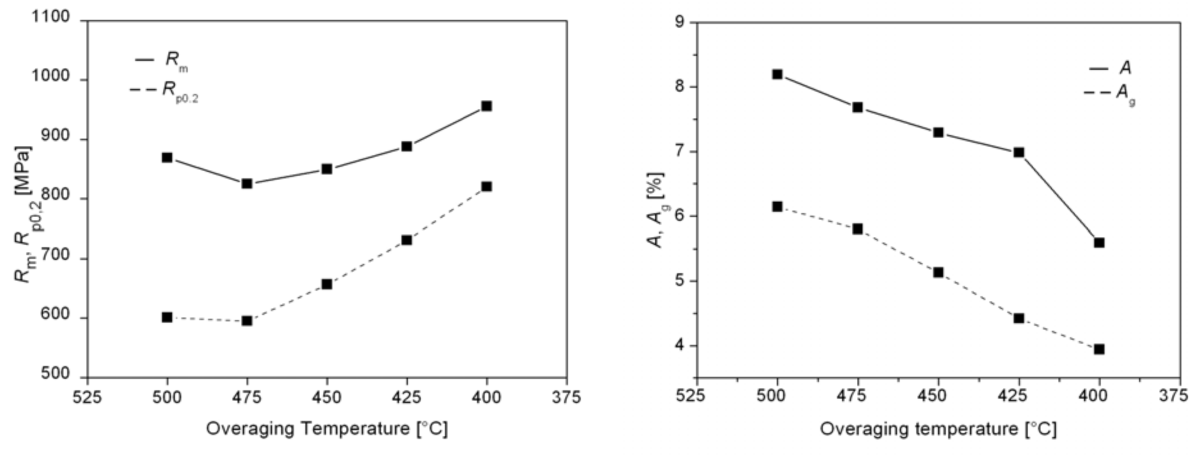
***Figure 3*** *Influence of overaging temperature on the microstructure*
*($T_{an}$ = 840°C/45s, $T_Q$ = 750°C)*

In plain carbon steels the bainitic transformation is kinetically shielded by ferrite and pearlite transformations which take place at higher temperatures and shorter times, therefore bainitic structures are rather difficult to obtain via continuous cooling. Addition of alloying elements results in retardation of the ferrite and pearlite transformations and shift the bainitic transformation to lower temperatures. A very effective means of isolating the bainitic reaction in low carbon steels is the addition of a certain amount of soluble boron. Boron markedly retards the ferrite transformation enabling the bainitic reaction to occur at shorter times [2-4]. Consequently, fully bainitic microstructures, as can be seen for example in Fig. 3-e (specimen overaged at 400°C), can be obtained.

**Effect of the overaging temperature on the mechanical properties**

The mechanical properties (tensile and hole expansion) of the materials as influenced by the overaging temperature are shown in Figs. 4 and 5. Both yield and tensile strengths increase with decreasing overaging temperature. A maximum tensile strength of 955 MPa and a yield strength of 820 MPa were reached by overaging at 400°C. The total elongation decreases from its maximum value of 8,2% at an overaging temperature of 500°C to 5,5% at 400°C.

The hole expansion ratio is an important measure to characterize the formability of sheet materials. Hole expansion is strongly linked to the material microstructure and its mechanical properties. It has been reported that steels with a high ratio of yield strength to ultimate tensile strength generally show better hole expansion values. This fact is proved also by our experiments, see Fig. 6. As shown in Fig. 3-a, the microstructure resulting from overaging at 500°C consists of a bainitic matrix with a high fraction of rather coarse grained "white" and "brown" martensite (mean grain size ~ 5μm) and some retained austenite. The phases differ markedly in their properties. As has been shown in [5-10], the difference of the constituting phases in strength (or hardness) significantly influences the global deformational characteristics of multi-phase materials. While a high strength difference is beneficial for tensile uniform elongation and deep drawability, stretch flangeability of such materials is poor. On the other hand, mechanical homogenity (i.e. small differences in strength) improves the latter property.




*(a) Yield and tensile strength* *(b) Uniform and total elongation*

***Figure 4*** *Influence of the overaging temperature on the tensile properties*
*($T_{an}$ = 840°C/45s, $T_Q$ = 750°C)*

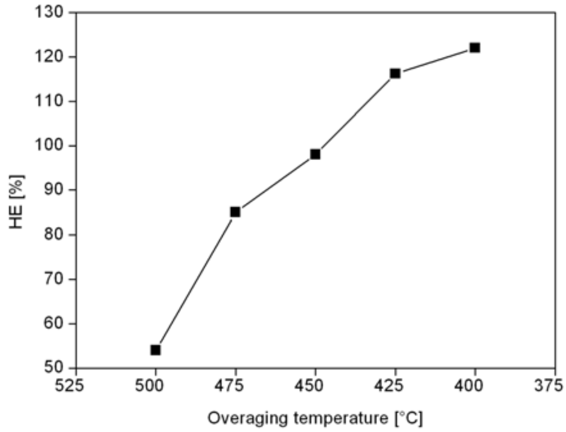



***Figure 5*** *Influence of the overaging temperature on hole expansion ratio HE ($T_{an}$ = 840°C/45s, $T_Q$ = 750°C)*

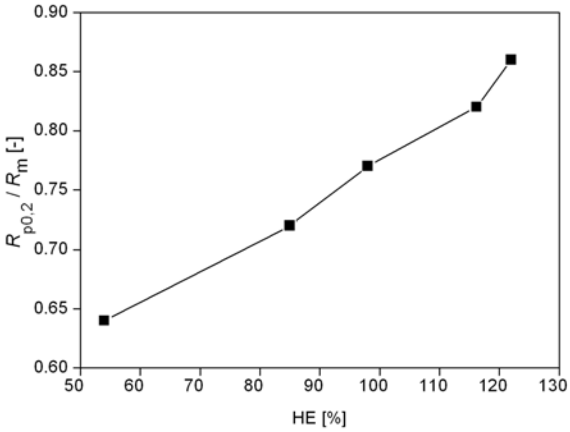



***Figure 6*** *Dependence of hole expansion ratio (HE) on yield to tensile strength ratio ($R_{p0,2}/R_m$)*

This is also true for the microstructure, at hand: At the very high level of the tensile strength (~ 950 MPa) the material overaged at 400°C exhibits the highest hole expansion ratio (~ 120 %) despite its poor elongation properties in tensile test. The opposite is true when overaging is done at 500°C. Even though the material sufficiently elongates in tensile test, its hole expansion ratio of ~ 55% is the lowest of all microstructures.

## SUMMARY


A laboratory study was conducted in order to shed light on the effect of a varying overaging temperature on the development of the microstructure and the mechanical properties of complex-phase bainitic high strength steel. The development of the microstructure, markedly influenced by the applied annealing conditions was studied by means of light optical microscopy. The microstructures range from complex-phase ferritic-bainitic-martensitic obtained after overaging at higher temperatures (500°C) to fully bainitic at lower overaging temperatures (400°C). It was found that a decrease of the overaging temperature improves strength and deteriorates elongation properties. Specimens with higher tensile strength and poor elongation properties in tensile tests exhibit high hole expansion ratios. This can be explained by the effects of the steel microstructure and the properties of phases present. Mechanical homogenity and a high yield strength ratio presented by fully bainitic fine grained bainitic microstructures should be aimed at, if high hole expansion ratios at high overall strength levels are desired.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