ALTERNATIVE HEAT TREATMENT OF MnSi STEELS BY INTERCRITICAL ANNEALING AND QUENCHING AND PARTITIONING PROCESS

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Abstract

Today, advanced steels which are used in the automotive industry are required to possess high strength and ductility. Two heat treatment methods capable of meeting these requirements were tried in the present experimental programme that involved selected types of steels. These methods were the Q-P process (Quenching and Partitioning) and intercritical bainitic annealing. Favourable elongation levels combined with high ultimate strengths were obtained by stabilizing the retained austenite in the microstructure. The Q-P process, which can produce mixtures of martensite and a certain amount of retained austenite, led to strengths above 2000 MPa and elongation levels of 10-15 %. The intercritical annealing, which results in combinations of bainite, ferrite and retained austenite, provided strengths of up to 2000 MPa and elongation levels up to 25 %.

Keywords: Q-P process, intercritical annealing, retained austenite, AHSS

1. INTRODUCTION

Today's modern heat treatment methods for high-strength low-alloy steels include long-time austempering, intercritical annealing to obtain TRIP microstructure, and Q&P process (Quenching and Partitioning). The first one, long-time low-temperature austempering, can lead to tensile strengths of up to 2500 MPa and hardness levels of 600-670 HV10 [1]. It is characterised by long holding times of several tens of hours and low temperatures. The resulting microstructure consists of very fine bainitic ferrite. Owing to long process times, this method, however, has failed to find industrial use. The second method, intercritical annealing to obtain TRIP structure, can provide ultimate strengths up to 1500 MPa and elongation levels of about 25 %. The resulting microstructure which exhibits the desired mechanical properties is the so-called TRIP structure (Transformation-Induced Plasticity). It is a mixture of bainite, ferrite and retained austenite formed by intercritical annealing and isothermal holding at the bainitic transformation temperature during a controlled cooling process. Plastic deformation causes austenite to transform to deformation-induced martensite [3]. The third method is the Quenching and Partitioning (Q&P) process, which allows strengths of more than 2000 MPa to be achieved, together with an elongation level of about 10 %. It is characterized by rapid cooling from austenite region to a temperature between the M_s and M_f temperatures, during which martensite forms, although a portion of austenite remains untransformed [4]. In all these heat treatment methods, stabilisation of retained austenite is an important aspect. Depending on the method, retained austenite exists in the form either of thin foils between bainitic sheaves (**Figure 1**) and grains along ferrite grain boundaries (**Figure 2**) or as thin foil-like particles between martensite needles (**Figure 3**).

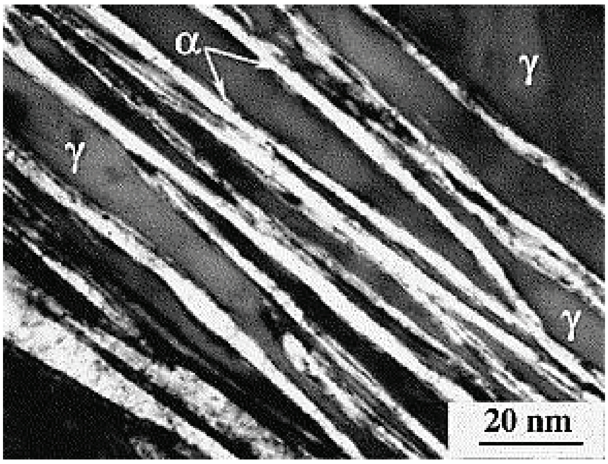

Figure 1 Microstructure produced by long-time austempering [1]

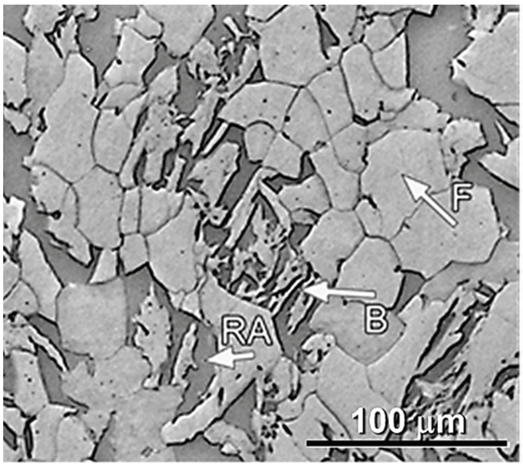

Figure 2 Microstructure of TRIP steel obtained by intercritical annealing

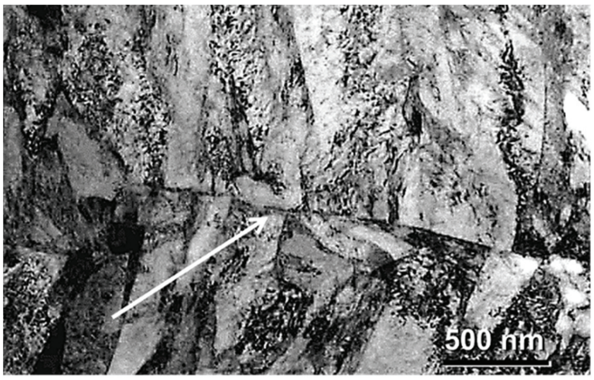

Figure 3 Prior austenite grain identified in martensitic matrix in a microstructure produced by Q&P processing

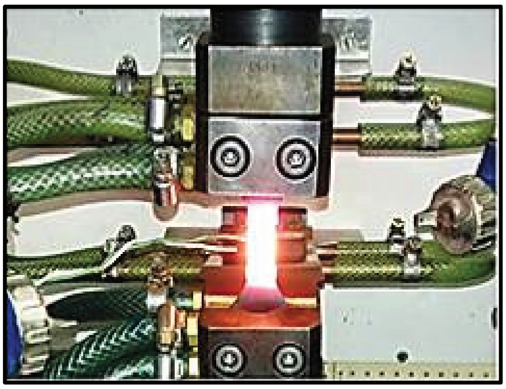

Figure 4 Physical simulation on a thermomechanical simulator

2. EXPERIMENTAL PROGRAMME

This experiment was focused on comparing microstructures produced by intercritical annealing and Q&P processing in two experimental steels of special chemistries which were designed to reduce the steels' M_s and M_f temperatures (**Table 1**). In both experimental steels, the M_s and M_f temperatures were depressed ba an addition of manganese. To increase the materials' strength, silicon and chromium have been added as well. Silicon was chosen in order to prevent carbide formation and thus to provide adequate super-saturation of martensite with carbon. Molybdenum was employed to both depress the M_s and M_f temperatures and shift the start of ferritic and pearlitic transformations towards lower cooling rates. Nickel was added in small amounts to stabilise austenite during cooling, to enhance hardenability, and to provide solid solution strengthening. The carbon content was the same in both steels: between 0.42 and 0.43 %.

Approximate values of transformation temperatures were found by means of calculation using the JMatPro software. In the AHSS-3 steel, the nickel level was increased to 0.56 %, as opposed to AHSS-1, to provide hardenability and depress the martensitic transformation temperatures. The M_s and M_f temperatures were 209 °C and 78 °C, respectively.

On these steels, two heat treatment methods were tested using a thermomechanical simulator (**Figure 4**): Q&P processing and intercritical annealing to obtain TRIP microstructure.

Table 1 Chemical compositions of the AHSS-1 and AHSS-3 experimental steels [wt. %]

	C	Mn	Si	P	S	Cu	Cr	Ni	Al	Mo	Nb	M_s	M_f
AHSS-1	0.43	2.5	2.03	0.005	0.003	0.07	1.33	0.07	0.008	0.03	0.03	218	88
AHSS-3	0.419	2.45	2.09	0.005	0.002	0.06	1.34	0.56	0.005	0.04	0.03	209	78

2.1. Q&P Process

Several heat treatment schedules were designed (**Table 2**). Adequate values of austenitizing temperature (T_A), quenching temperature (QT), and partitioning temperature (PT) were chosen. For this treatment method, the quenching temperature is normally set between the M_s and M_f. The partitioning temperature, at which carbon migrates from the super-saturated martensite to austenite, is of importance as well.

Table 2 Q&P process parameters and fractions of retained austenite

Schedule number	T_A[°C] / t_A [s]	cooling rate [°C / s]	QT [°C]	PT [°C] / t_{PT} [s]	RA [%]
1	850 / 100	1	100	150 / 600	9
2	850 / 100	1	150	200 / 600	10

2.2. Intercritical Annealing

The second heat treatment method which was tested on the two experimental steels was intercritical annealing to obtain the so-called TRIP microstructure (**Table 3**). Using the JMatPro software, four sequences were designed with various austenitizing temperatures (T_A), rates of cooling to the bainitic transformation holding temperature (T_B), rate of cooling to a temperature above M_s, and rate of cooling to room temperature. The heating temperature was between the critical temperatures A_1 and A_3. Important was the holding at the bainitic transformation temperature where austenite becomes stabilised and the material strengthens. The resulting volume fractions of phases were affected by the holding time. The rate of cooling to ambient temperature affects the final amount of retained austenite.

Table 3 Parameters of intercritical annealing and fractions of retained austenite

Schedule number	T_A[°C] / t_A [s]	cooling rate to T_B [°C / s]	T_B[°C] / t_B [s]	cooling rate to 250°C [°C / s]	cooling rate to RT [°C / s]	RA [%]
01	850 / 100	14	400 / 240	0.1	14	21
02	900 / 180	2	400 / 180	0.1	14	6
03	850 / 100	0.1	400 / 240	0.1	14	7
04	850 / 100	2	400 / 240	0.1	14	5

3. DISCUSSION OF RESULTS

In both steels, the Q&P process led to predominantly martensitic microstructures with a small amount of bainite and a certain fraction of retained austenite which was probably located on the boundaries of martensitic needles (**Figures 5-8**). The amount of retained austenite in the martensitic matrix was up to 10 % in the AHSS-3 steel which had higher nickel content after schedule number 2 (**Table 2**). The intercritical annealing to obtain TRIP microstructure represented by schedule 01 resulted in a bainitic microstructure with martensite islands along prior austenite grains (**Figures 9, 10**). In response to this outcome, schedule 02 involved notably slower cooling to the holding temperature for bainitic transformation, as well shorter holding time. This led to martensitic-bainitic microstructure with some locations of bainitic ferrite (**Figures 11, 12**). The cooling rate was reduced even more in schedule 03. As a result, a martensitic-bainitic structure with fine pearlite along prior grain boundaries was obtained (**Figures 13, 14**). The last schedule, no. 04, involved a slightly higher rate of cooling to the holding temperature than schedule 03. All other variables remained the same. A bainitic structure with martensite islands was found. Proeutectoid ferrite was present on prior austenite grain boundaries (**Figures 15, 16**). In order to confirm the suspected presence of retained austenite on prior austenite grain boundaries, selected specimens were examined by means of X-ray diffraction. The largest fraction of retained austenite was found again in the steel AHSS-3 steel which had higher nickel content. After testing schedule number 01 was obtained 21 % of retained austenite.

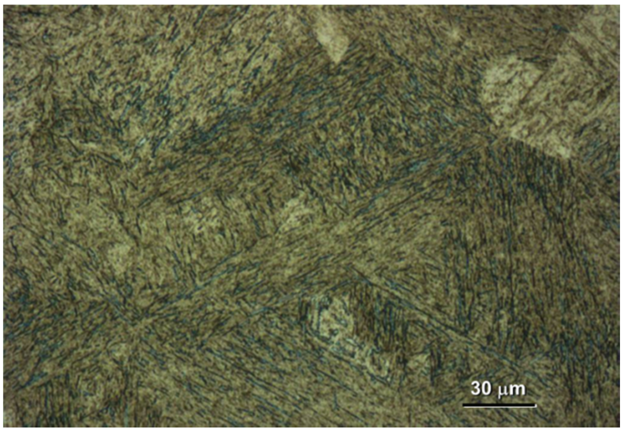

Figure 5 schedule 1 - cooling rate: 1 °C / s

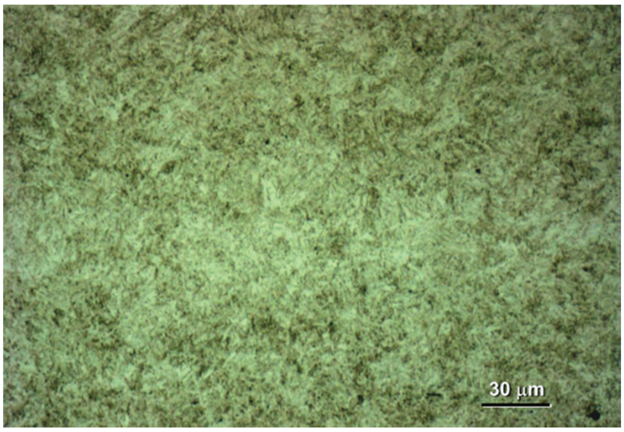

Figure 7 schedule 2- cooling rate: 1 °C / s

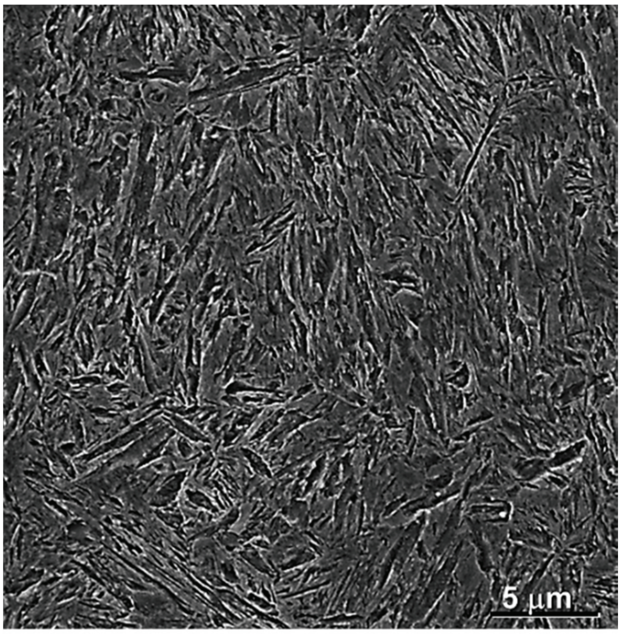

Figure 6 schedule 1 - martensitic-bainitic structure - scanning electron micrograph

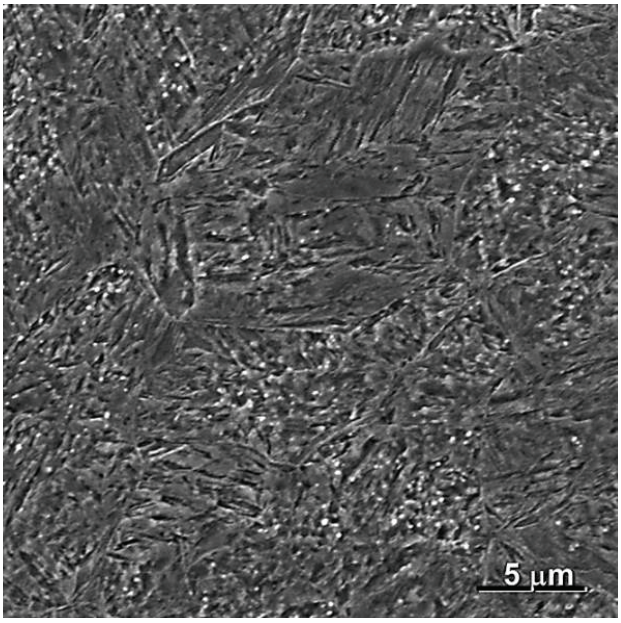

Figure 8 schedule 2 - martensitic-bainitic structure - scanning electron micrograph

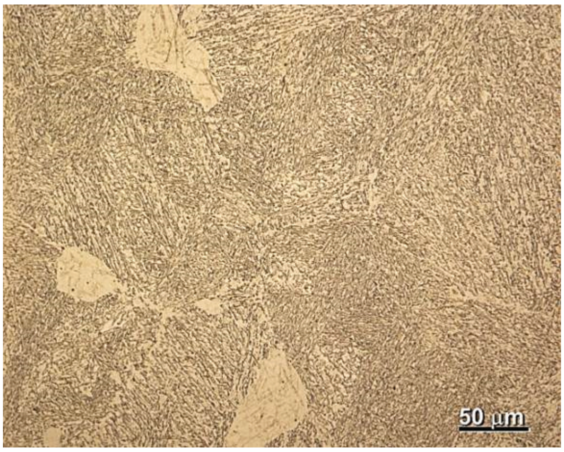

Figure 9 schedule 01 - rate of cooling to T_B: 14 °C / s

Figure 11 schedule 02 - rate of cooling to T_B: 2 °C / s

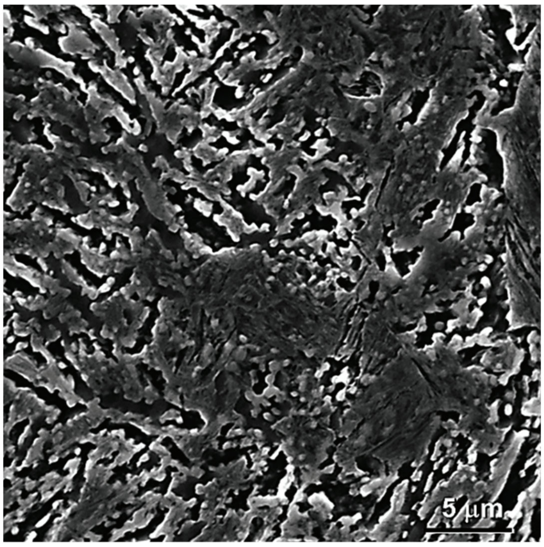

Figure 10 schedule 01 - bainitic structure with martensite islands along prior austenite grain boundaries - scanning electron micrograph

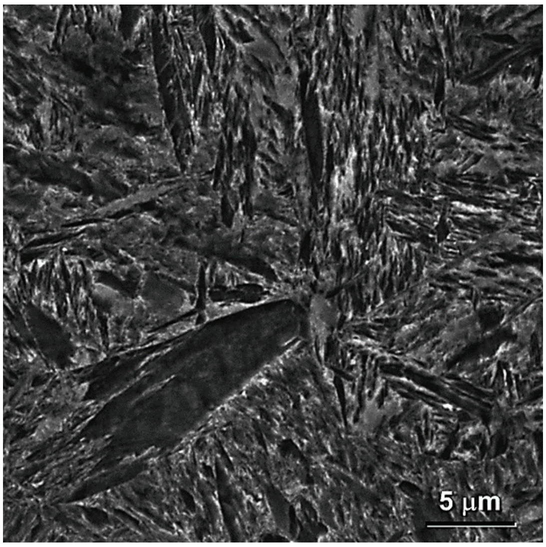

Figure 12 schedule 02 - martensitic-bainitic structure, scattered areas of bainitic ferrite - scanning electron micrograph

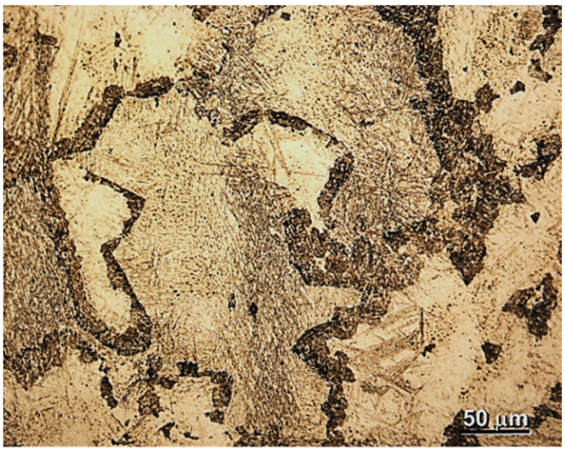

Figure 13 schedule 03 - rate of cooling to T_B: 0.1 °C / s

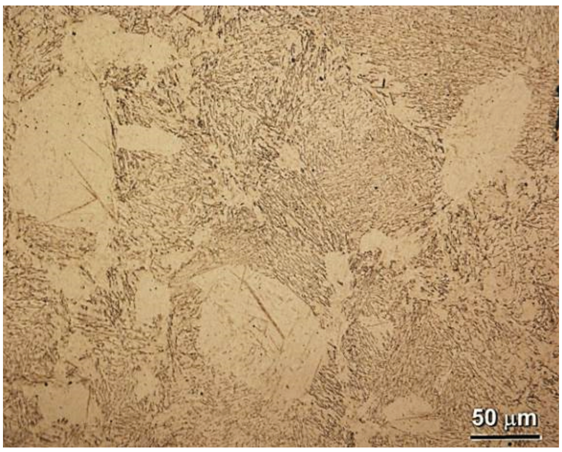

Figure 14 schedule 04 - rate of cooling to T_B: 2 °C / s

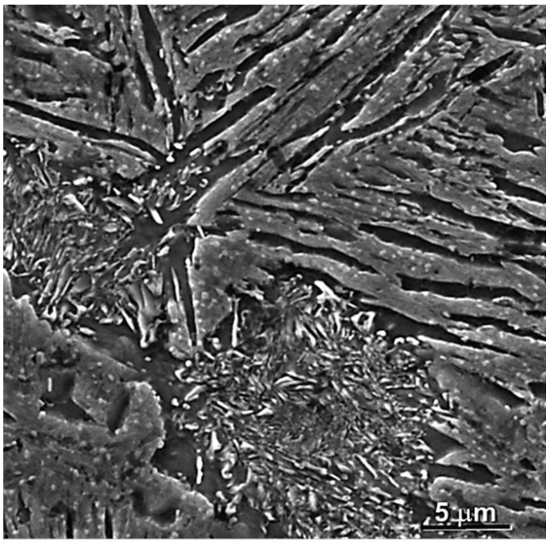

Figure 15 schedule 03 - martensitic-bainitic structure with fine pearlite along prior austenite grain boundaries - scanning electron micrograph

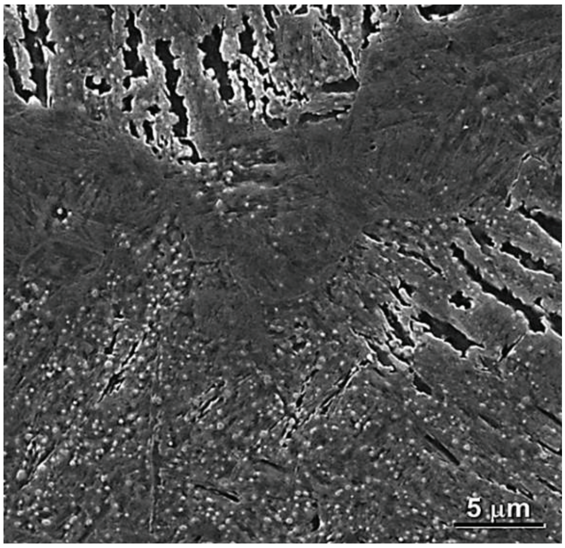

Figure 16 schedule 04 - bainitic structure with martensite islands, proeutectoid ferrite along prior austenite grain boundaries - scanning electron micrograph

4. CONCLUSION

Two heat treatment methods (Q&P process and intercritical annealing to obtain bainite) were tested on newly-developed AHSS-type low-alloy steels containing the additions of manganese, silicon, chromium, molybdenum and nickel. These different heat treatment sequences showed that in these high-strength steels one can obtain not only martensite-based hardening microstructures. After intercritical annealing to obtain bainite, the microstructure consisted of bainitic ferrite, and in the case of schedule 04 even proeutectoid ferrite which considerably increases the plasticity of steel. In the heat with the nickel content increased to 0.56 %, Q&P processing led to a retained austenite fraction in martensitic matrix of up to 10 %. Intercritical annealing to obtain bainite resulted in up to 21 % of retained austenite. A lot of retained austenite is probably between martensite needles.

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