STABILITY OF RETAINED AUSTENITE IN HIGH-STRENGTH MARTENSITIC STEELS DURING COLD DEFORMATION

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Abstract

The toughness of high-strength steels is improved when their martensitic matrix is combined with the presence of retained austenite. The stability of retained austenite is crucial, both upon cooling to room temperature and during subsequent cold deformation. One of the advanced heat treatment methods, which produces larger amounts of retained austenite in martensitic matrix thanks to an appropriate combination of parameters, is the Q&P process (Quenching and Partitioning). It produces microstructures consisting of martensite and retained austenite which exhibit strengths above 2000 MPa and elongation levels of more than 10%. The steel which was designed for this experiment was alloyed with manganese, silicon, molybdenum and chromium and had a low M_s temperature.

This experimental heat treatment led to a martensitic microstructure with retained austenite, with ultimate strengths in the range of 2200-2400 MPa and A_{5mm} elongations of 7-10%. The largest fraction of retained austenite, according to X-ray diffraction analysis, was 10%. The behaviour of retained austenite under mechanical load was studied by means of compression tests to various strain levels. The resulting microstructures were observed using optical and scanning electron microscopes..

Keywords: Q-P process; AHSS steels; retained austenite; X-ray diffraction

1. Introduction

Retained austenite in the final microstructure of advanced steels is an important phase which provides a combination of strength and ductility. An advanced processing technique for achieving the same combination is the Q&P (Quenching and Partitioning) process by which strengths in the vicinity of 2000 MPa and elongation levels of approximately 10% can be obtained [1], [2], [3]. Q&P processing relies on cooling from the fully austenitic region to a region between the M_s and M_f , whereby the martensite transformation is arrested, and subsequent reheating to a partitioning temperature. The stock is held at this temperature while retained austenite becomes stabilized by carbon which diffuses from the super-saturated martensite [4], [5]. For the purpose of application of high-strength steels, both chemical and mechanical stability of retained austenite must be known, as it is the behaviour of retained austenite during cold deformation which substantially dictates final mechanical properties. As the growing use of such steels also expands their potential for components operating at elevated temperatures, the stability of retained austenite under various thermal loading temperatures becomes

relevant. The main factors determining whether retained austenite remains stable in martensitic matrix include its morphology, particle size and distribution. Its chemical stability also depends on alloying. Therefore, once appropriate heat treatment parameters are confirmed to provide a sufficient proportion of retained austenite, the behaviour of retained austenite under cold deformation must be ascertained as well.

2. Experimental programme

Since the Q&P process is characterized by interrupting the quench at a specific temperature between the M_s and M_f , its industrial use is technically demanding. For this reason, the proposed experimental steel had a manganese level of 2.45% (Table 1), which considerably depressed the M_s to 209°C and the M_f to 78°C. A very low M_f temperature is expected to simplify the entire heat treatment process. Manganese improves mechanical properties of steel through its effect on solid solution strengthening and retained austenite stabilization. The stability of retained austenite is also controlled by silicon which also prevents carbides from forming, and therefore provides sufficient super-saturation of martensite with carbon. The carbon content was 0.4%. Nickel was used for improving austenite stability and for better hardenability. Transformation temperatures were calculated by means of the JMatPro software [10].

C	Mn	Si	P	S	Cu	Cr	Ni	Al	Mo	Nb	M_s	M_f
0.419	2.45	2.09	0.005	0.002	0.06	1.34	0.56	0.005	0.04	0.03	209	78

Table 1. Chemical composition of experimental steel with reduced M_s temperature [wt %]

2.1. Q&P Process

Several different Q&P sequences were carried out on the experimental steel (Tab. 2). Their parameters were defined on the basis of earlier experiments [4]. Quenching temperature was chosen with reference to earlier experiments and a calculation using the Magee-Koistinen-Marburger formula (Eq. 1), [11], [12]. This equation yields an estimate of the martensite fraction dictated by the chosen quenching temperature (Fig. 1).

$$f_i^a = 1 - \exp[-1.10 \times 10^{-2}(M_s - T_q)] \quad (1)$$

where f_i^a is the volume fraction of martensite, T_q is the quenching temperature (QT) and M_s corresponds to the M_s temperature calculated using JMatPro. This calculation shows that at a quenching temperature of 150°C, the material retains 53% of austenite. While the stock is held at the partitioning temperature (PT), a certain amount of retained austenite becomes stabilized by carbon which migrates from super-saturated martensite, whereas the remaining portion of retained austenite decomposes into martensite as the stock is cooled to room temperature.

Fig. 1. Martensite volume fraction vs. quenching temperature (QT)

The Q&P process comprised heating to an austenitizing temperature (TA) of 850°C, soaking for 100 or 300 seconds (sequences 1, 2 and sequence 3) and quenching to QT at 16°C/s (sequence 1) or 1°C/s (sequences 2 and 3). The QT was 150°C in all sequences. This was followed by reheating to a partitioning temperature of 200°C, holding for 600 s and cooling to room temperature.

Since specific process parameters need to be used to obtain the desired mechanical properties, the heat treatment sequence was carried out in a thermomechanical simulator [6], [7], [8].

2.2. Stability of retained austenite during cold deformation

The stability of retained austenite and its transformation to strain-induced martensite during cold deformation is of key importance, which is why the behaviour of retained austenite under load needs to be characterized. Based on earlier results, sequence 2 was selected which had produced 12% retained austenite (RA) (Table 2). Specimens processed according to this sequence were compressed in the thermomechanical simulator to $\phi = 0.13$ at room temperature and at various strain rates (10^{-3} , 10^{-1} , 10 s⁻¹). After this deformation, the retained austenite volume fraction was measured by X-ray diffraction again and compared with the value before deformation (Table 3).

Sequence No.	TA [°C]/t _A [s]	Cooling rate [°C/s]	QT [°C]	PT [°C/s] /t _{PT} [s]	HV10 [-]	R _m (UTS) [MPa]	A _{5mm} [%]	RA [%]
1	850/100	16	150	200/600	716	2200	5	-
2	850/100	1	150	200/600	679	2308	10	12
3	850/300	1	150	200/600	708	2367	9	9

Table 2. Q&P sequences and results of mechanical tests

Strain rate [s ⁻¹]	HV10 [-]	RA [%]
10^{-3}	452	6
10^{-1}	460	4
10	482	3

Table 3. Retained austenite volume fraction in relation to strain magnitude

The microstructures obtained by processing were examined using an optical microscope (Olympus XXX) and a scanning electron microscope (Tescan Vega 3).

Mechanical properties were determined via HV10 hardness and by means of tensile testing on miniature specimens with a gauge length of 5 mm.

The amount of retained austenite was measured by means of XRD phase analysis in the automatic powder diffractometer AXS Bruker D8 Discover with a position-sensitive area HI-STAR detector and a cobalt X-ray source ($\lambda K\alpha = 0.1790307$ nm).

3. Discussion of results

Three Q&P sequences were carried out on the experimental steel with a reduced martensite transformation temperature. They involved various soaking times and cooling rates of 16 and 1°C/s.

The first sequence, in which the austenitizing temperature was 850°C, the soaking time was 100 s and cooling took place at 16°C/s, ending at the quenching temperature of 150°C, produced a martensitic-bainitic microstructure with a hardness of 716 HV10 (Fig. 2). The ultimate strength reached 2200 MPa and elongation was $A_{5mm} = 5\%$. High hardness and low elongation were due to high cooling rate. Slowing down the cooling rate from 16°C/s to 1°C/s in sequence 2 has led to a larger bainite fraction and higher elongation: 10% (Fig. 3). Appreciable carbide precipitation and a small amount of ferrite were found by metallographic observation. Nevertheless, the volume fraction of retained austenite was high, reaching 12%. Extending the time at the austenitizing temperature from 100 s to 300 s in sequence 3 was not reflected in any way in microstructural evolution or mechanical properties (Table 2).

As the largest final fraction of retained austenite of 12% was found upon sequence 2, which involved a quenching temperature of 150°C and a cooling rate of 1°C/s, the specimens obtained with this sequence were selected for testing the stability of retained austenite upon after cold deformation.

Q&P-processed specimens were subjected to compressive deformation of $\phi = 0.13$ applied at various rates: 10^{-3} , 10^{-1} , 10 s^{-1} . The resulting microstructure was a mixture of martensite and bainite with small amounts of pearlite and retained austenite and exhibited no appreciable effects of deformation. The highest retained austenite 6% austenite was preserved at the lowest strain rate (Table 3). Influence to the high strain rate, the residual austenite was transformed into martensite, which corresponded to the higher hardness of 482 HV10 (Table 3).

Fig 2. Sequence 1 – Martensitic microstructure with a smaller amount of bainite and retained austenite – scanning electron micrograph

Fig 3. Sequence 2 – Martensitic microstructure with a larger amount of bainite and 12% of retained austenite – scanning electron micrograph

Fig 4. Sequence 2 – Post-compression condition, strain rate of 10^{-3} s^{-1} – martensitic-bainitic microstructure with a small volume fraction of pearlite and retained austenite – scanning electron micrograph

Fig 5. Sequence 2 – Post-compression condition, strain rate of 10^{-1} s^{-1} – martensitic-bainitic microstructure with a small volume fraction of pearlite and retained austenite – scanning electron micrograph

Fig 6. Sequence 2 – strain rate of 10^{-1} s $^{-1}$ – martensitic-bainitic microstructure with a small volume fraction of pearlite and retained austenite – scanning electron micrograph

4. Conclusion

An experimental AHS-type steel with a reduced M_s temperature and a carbon content of 0.4% and a manganese level of 2.5% was experimentally treated using the Q&P process with various times at the austenitizing temperature and various rates of cooling to the quenching temperature. Slowing down the cooling rate from 16°C/s to 1°C/s changed the character of the microstructure. A larger volume fraction of bainite was obtained, together with a small amount of pearlite. Despite that, XRD phase analysis revealed 12% of retained austenite in the material. The ultimate strength exceeded 2000 MPa and the elongation level was 10%.

Specimens processed in this manner were then compressed at room temperature and at various strain rates. Influence to the pressure deformation, retained austenite was transformed into martensite. The highest retained austenite rate was preserved at the lowest deformation rate of 6%.

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6. References

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