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Designing Q&P Process for Experimental Steel with 0.47 % Carbon Content

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Abstract. The Q&P process (Quenching and Partitioning) is a heat treating method for high-strength low-alloyed steels. It delivers the desired combinations of high strength and adequate ductility. These properties are achieved thanks to the unique martensitic microstructure with a certain volume fraction of stable retained austenite. Retained austenite imparts plasticity to the otherwise brittle martensitic structure. Optimum mechanical properties are achieved by using correct processing parameters and chemistry of the material. The experimental material was a steel with 0.47 % carbon alloyed with silicon, manganese and chromium. The purpose of the effort was to optimise the heat treating parameters in order to obtain a strength level above 2000 MPa and an elongation of no less than 10%. In the first step, the appropriate austenitizing temperature was identified. In the second, effects of various quenching temperatures and cooling rates on the microstructure evolution were explored. In the third, the impact of raising the partitioning temperature on stabilization of retained austenite was examined. Adjustment of the parameters led to a strength of more than 2300 MPa and an elongation of 8 %.

Introduction

The developments in the field of heat treating high-strength materials in automotive industry lead to adoption of new technologies which allow mechanical properties to be improved at reduced manufacturing costs. One of such technologies is the Q&P process, a method of heat treating low-alloyed steels [1]. It produces hardening-type phases, typically martensite, with a small volume fraction of retained austenite. The Q&P process takes place in two stages. The first stage is heating and quenching to quench temperature (further only QT), which is between the M_s and M_f temperatures [2, 3]. During cooling, the martensitic transformation does not take place throughout the material and a certain volume fraction of untransformed austenite is retained. The ratio of both phases can be controlled through the QT. At the second stage, carbon partitioning occurs during holding at partitioning temperature (further only PT), where carbon redistribution by diffusion takes place between untransformed austenite and martensite. At this holding stage, retained austenite (further only RA) is stabilized prior to final cooling to room temperature. The degree of stability of RA depends on its volume fraction after the first treatment stage. If the volume fraction is high, the carbon content may prove insufficient for its stabilization. In order to prevent carbon from being used up in another process, such as austenite decomposition into bainite or pearlite and carbide precipitation, a suitable chemistry of the material should be chosen [3, 4]. This is why the alloying elements used include manganese, silicon and chromium which have profound impact on the progress of transformation processes and stabilize RA. [5]. Q&P process offers cost savings, as it eliminates cooling of the material to room temperature and the subsequent reheating.

Experimental

The experimental programme dealt with designing a Q&P procedure. As the experiment was performed on a material with a new chemistry, phase transformation temperatures and values of individual processing parameters had to be found. The experimental material was 0.47 % carbon steel. Manganese and silicon were used to stabilize RA and facilitate solid solution strengthening. Higher chromium level was chosen to improve hardenability of the material and the strength of the solid solution (Tab. 1). The initial microstructure of the steel consisted of pearlite and acicular ferrite. The material showed a yield strength of 627 MPa, ultimate tensile strength of 954 MPa, elongation (A_{5mm}) of 32 % and a hardness of 279 HV10.

Tab. 1: Chemical composition and properties of experimental steel

Chemical composition [wt. %]								
C	Si	Mn	Cr	Mo	Al	N	P	S
0.47	1.88	0.60	1.36	0.03	0.001	0.001	0.01	0.01

Transformation temperatures [°C]					Mechanical properties of initial material			
JMatPro		Dilatometer measurement		Andrews				
Ms	Mf	Ms – 200°C/s	Ms -20°C/s	Ms	$Rp_{0.2}$ [MPa]	Rm [MPa]	A_{5mm}[%]	HV10
252	126	246	258	284	627	954	32	279

For parameters of the Q&P process to be set phase transformation temperatures must be known. Among the most important transformation temperatures there are the martensitic transformation temperatures M_s and M_f. Their values were computed using JMatPro software on the basis of chemical composition for the austenitizing temperature of 900 °C. The M_s and M_f temperatures were 252 °C and 126 °C, respectively (Tab. 1). In order to confirm this analysis, the M_s temperature was also calculated using the phenomenological expression by Andrews (Tab. 1) and determined by means of a dilatometer. Two cooling rates of 200 and 20 °C/s were used in the dilatometer measurement. The A_{c3} temperature is an additional important parameter. Using JMatPro, its level was calculated as 793 °C.

Experimental Programme

The experimental programme was divided into three stages. At the first stage of the experiment a suitable austenitizing temperature was selected. The second stage was aimed at finding the appropriate QT and the rate of cooling from the austenitizing temperature. At the last stage of the experiment, quenching to QT was followed by reheating to PT and the effects of the carbon partitioning process at higher temperature were explored. The temperature increase was intended to facilitate carbon diffusion from super-saturated martensite to austenite and to stabilise a higher volume fraction of RA. Experiments were conducted in an electric box furnace. The tempering bath used for holding at PT and QT contained the AS 140 salt solution. The material was examined using laser confocal and scanning electron microscopes. The RA fraction was measured by means of X-ray diffraction analysis. Mechanical properties of the processed material were tested using miniature tensile specimens.

Austenitizing Temperature

In order for the entire Q&P process to run correctly, a suitable austenitizing temperature should be found so that homogeneous austenite with no residual ferrite can be obtained. At the same time, the temperature should not be too high, as it could lead to austenite coarsening. As the A_{c3} temperature calculated using the JMatPro software was 793 °C, two austenitizing temperatures were tried: 860 °C a 900 °C, as well as two soaking times of 20 and 40 minutes. The specimens were quenched in water.

QT and Cooling Rate

Once the appropriate austenitizing temperature was found, the QT was sought. Following heating to 860 °C and holding for 20 minutes, the specimens were quenched to 200 or 160 °C in a salt bath. The specimens were held for 20 minutes at these temperatures to permit carbon migration from the super-saturated martensite to RA. The carbon partitioning process was terminated by quenching in water. The impact of the cooling rate on the microstructure evolution was verified by cooling to 200 °C. In addition to the schedule involving direct quenching in the salt bath (H1) an additional schedule was used which comprised intensive water cooling to approx. 230 °C. Upon water cooling, the specimen was transferred to the salt bath and cooled to 200 °C (G1). In cooling directly in the salt bath, the average cooling rate was approx. 23 °C/s. Combined water/salt bath cooling involved a higher rate of cooling down to QT: approximately 60 °C/s.

Tab. 2: Q&P process parameters (W – water, SB – salt bath)*

Schedule	Heat treatment	HV10 [-]	$R_{p0.2}$ [MPa]	R_m [MPa]	$A_{5\,mm}$ [%]	RA [%]
G1	H5 – 860 °C/20min. - 200 °C/20 min. W/SB – W	704	1314	2344	8	8
H1	H5 – 860 °C/20min. - 200 °C/20 min. SB – W	629	1202	2128	14	13
I1	H5 – 860 °C/20min. - 160 °C/20 min. SB – W	662	1202	2318	7	10
G2	H5 – 900 °C/20min. - 200 °C W/SB – 250 °C/20 min. SB – W	655	1298	2074	14	17
G3	H5 – 900 °C/20min. - 150 °C W/SB – 200 °C/20 min. SB – W	698	1649	2298	8	9

Elevated PT

In the third stage, the impact of raising the PT on stabilization of RA was examined. The austenitizing temperature was raised to 900 °C. Austenitizing was followed by quenching in water and salt bath (Tab. 2). The QTs were 200 and 150 °C. The specimens were then transferred to the salt bath at PT of 250 and 200 °C. Once the specimen temperature equalized, the specimen was held for 20 minutes and then quenched in water. (Tab. 2).

Discussion of Results

Trials with various austenitizing temperatures and holding times showed that for a purely martensitic microstructure to be obtained, austenitizing at 860 °C must be followed by the longer holding time of 40 minutes, otherwise the resulting structure contains a mixture of martensite and bainite. Increasing the austenitizing temperature to 900 °C led to martensitic microstructures in the case of both holding times. Hardness values were very high. Upon austenitizing at 860 °C, hardness of 782 HV10 was achieved with the holding time of 20 minutes, whereas 799 HV10 was obtained with the 40-minute holding time. The highest level of 816 HV10 was achieved with the austenitizing temperature of 900 °C and the holding time of 40 minutes. Q&P processing without reheating to the PT led to hardening-type microstructure consisting of martensite and a small fraction of RA (Tab. 2, schedules G1, H1, I1) (Fig. 1). Detailed examination using a scanning electron microscope revealed a content of bainite (Fig. 2).

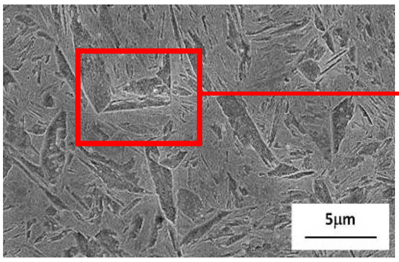

Fig. 1:G1-860 °C/20 min.-water-200 °C/20 min.-water: martensite/bainite, scanning electron micrograph

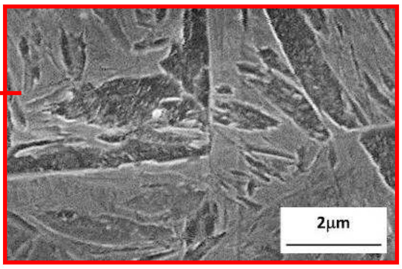

Fig. 2: G1–860 °C/20 min.-water-200 °C/20 min.-water: martensite/bainite, scanning electron micrograph

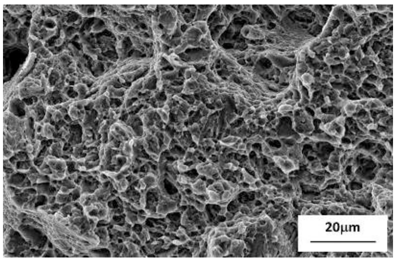

Fig. 3: G1-detail of fracture surface upon tensile testing, scanning electron micrograph

Differences between processing schedules manifested themselves most notably in terms of mechanical properties. Specimens quenched to 200 °C using two different procedures showed a difference in strength of almost 200 MPa. The schedule with direct cooling in the salt bath at 200 °C led to a strength of 2128 MPa and an elongation of 14 %. The RA volume fraction was 13 %. By increasing the cooling rate from the initial 23 °C/s applied solely in the salt bath to the 60 °C/s achieved using the water/salt bath combination, hardness rose from 629 to 704 HV10 and ultimate strength increased to 2344 MPa; and the A_{5mm} elongation of 8 %. The RA volume fraction decreased to 8 %. Despite this high strength, the fracture produced in tension test was predominantly ductile with dimple morphology (Fig. 3).Reducing QT to 160 °C and using only the salt bath for cooling led to an increase in strength by 190 MPa to 2318 MPa and an increase in hardness to 662 HV10. Elongation rose slightly to 7 %.

Although QT was 160 °C, which is a mere 34 °C above the M_f, the RA volume fraction decreased only slightly to 10 % (Tab. 2). Schedules involving reheating to two different PT produced martensitic structures with bainite and RA (Fig. 4). Based on prior results, combined water/salt bath cooling was used. The heat treating schedule with the QT of 200 °C and the PT of 250 °C led to a strength of 2074 MPa combined with the elongation of 14 %. The RA volume fraction was 17 %. The considerable increase in the austenite volume fraction when compared to specimens processed without increased PT may be attributed to accelerated carbon diffusion at the higher tempering temperature. Reducing the QT to 150 °C and the PT to 200 °C caused the ultimate strength to rise up to 2298 MPa; at the elongation of 8 %. The reduction in the QT was reflected in the reduced RA volume fraction of 9 %.

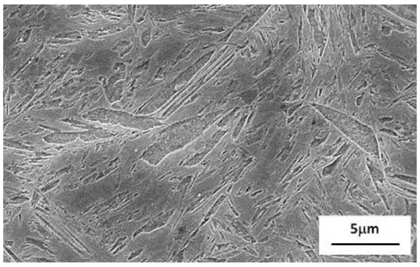

Fig. 4: G3 – 900 °C/20 min. - 150 °C-200 °C/20 min.-water: martensite/bainite, scanning electron micrograph

Conclusion

In the experimental programme, a Q&P procedure was proposed for a newly-developed UHS steel, whose cost-effective chemistry is based on an appropriate combination of elements such as carbon, manganese and silicon. The purpose of this unconventional heat treating procedure was to obtain very high ultimate and yield strengths while maintaining adequate plasticity. The results show that important factors include not just the QT, which affects both mechanical properties and the RA volume fraction, but also the rate of cooling from the austenitizing temperature. When cooling was accelerated from 25 to 60 °C/s, the ultimate strength increased from 2128 to 2344 MPa, whereas elongation declined from 14 to 8 %. A similar effect was seen upon changing the QT from 200 °C to 160 °C, where the ultimate strength rose from 2128 MPa to 2318 MPa and elongation decreased from 14 to 7 %. Narrowing the difference from the M_f temperature caused a lower volume fraction of RA to be stabilized. The experiment also involved exploration of the effects of reheating to the PT, which improved the RA volume fraction, raising it to 17 %. The study revealed the large potential of the application of Q&P processing to a steel with cost-effective chemistry, most notably in terms of mechanical properties. In this UHS steel with a cost-effective chemistry, the Q&P process provided interesting combinations of mechanical properties, most notably strength and ductility, in ranges which show that this know-how may be applied to a number of heavy-duty structural parts.

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