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Effect of Quenching and Partitioning Temperatures in the Q-P Process on the Properties of AHSS with Various Amounts of Manganese and Silicon

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Abstract. The use of the combined influence of retained austenite and bainitic ferrite to improve strength and ductility has been known for many years from the treatment of multiphase steels. Recently, the very fine films of retained austenite along the martensitic laths have also become the centre of attention. This treatment is called the Q-P process (quenching and partitioning). In this experimental program the quenching temperature and the isothermal holding temperature for diffusion carbon distribution for three advanced high strength steels with carbon content of 0.43 % was examined. The alloying strategies have a different content of manganese and silicon, which leads to various martensite start and finish temperatures. The model treatment was carried out using a thermomechanical simulator. Tested regimes resulted in a tensile strength of over 2000MPa with a ductility of above 14 %. The increase of the partitioning temperature influenced the intensity of martensite tempering and caused the decrease of tensile strength by 400MPa down to 1600MPa and at the same time more than 10 % growth of ductility occurred, increasing it to more than 20%.

Introduction

The combination of high strength and ductility together with low economic demands are today's trends when proposing new steel types. These steels have been mostly developed for the automotive industry with the goal of increasing the safety of individual components while lowering their weight [1]. This also supports the current trend of emission reduction. An important role during processing of these steels is played by retained austenite, which is always present in different types of matrix. For example, it occurs in the ferritic-bainitic matrix of TRIP steels, whilst it is embedded in the martensite matrix in steels processed with the Q-P process. In the case of a combination of retained austenite with martensitic matrix higher strength values can be gained [2]. The appropriate heat treatment, through which the suitable combination of martensite and retained austenite can be obtained, was described for the first time in 2003 [3].

Q-P process (Quenching and Partitioning). Q-P process is a two stage integrated heat treatment, which can be described as follows. After heating to the full austenite field, or to the intercritical area, the steel is then cooled down to a temperature between M_s and M_f [2]. In this first stage it is necessary to select the suitable quenching temperature (QT) in order to obtain the required amount of martensite and to ensure that there is enough austenite retained in the structure. In the second stage the steel is heated to just below the M_s temperature, and then an isothermic hold at the partitioning temperature (PT) is performed. During this holding time carbon diffuses from the supersaturated martensite into the austenite [1-3].
This treatment depends on the appropriate selection of process parameters and on the suitable alloying strategy, which must hinder the formation of carbides, suppress the pearlitic and bainitic transformation and enable carbon to diffuse into austenite, thereby stabilizing it [1-5]. The most important parameters influencing the retained austenite fraction and thus mechanical properties are the quenching and partitioning temperatures.

The quenching temperatures highly depend on the carbon content in the steel [6], (Fig. 1). As its amount increases, the quenching temperature drops, while the ability to stabilize a higher austenite content grows. Conversely, with the carbon content decreasing, the interval of temperatures suitable for stabilization distinctively propagates. This creates better premises for the process control in industrial applications.

The ratio between martensite and untransformed austenite in relation to the total carbon content is of great importance. If the austenite fraction is too large, then the carbon available in the structure is insufficient and unable to stabilize it, causing it to partially decompose during the consequent quenching to room temperature.

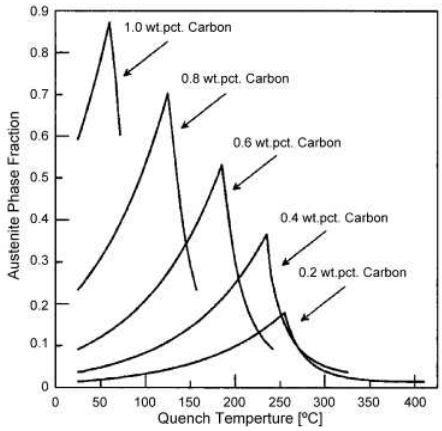

Fig. 1: Assumed RA fraction for various carbon contents [6]

Experimental programme

The influence of the quenching and partitioning temperatures on the structure development and mechanical properties was examined on three high strength low-alloy (HSLA) steels with various manganese and silicon contents (see Tab. 1).

Tab. 1: Chemical composition of all steel variants

Steel	C	Si	Mn	Cr	Mo	Al	Nb	P	S	Ni	M_s [°C]	M_f [°C]
H0	0.43	2.03	0.59	1.33	0.03	0.008	0.03	0.009	0.004	0.07	298	178
H1	0.43	2.6	0.59	1.33	0.03	0.008	0.03	0.01	0.01	0.01	309	190
H2	0.43	2.6	1.17	1.33	0.03	0.008	0.03	0.01	0.011	0.07	276	153

Manganese and silicon play an important role in the transformation control, as well as in the stabilization of retained austenite and hardening of the solid solution [7]. For each of the investigated steels a goal was set to achieve a high tensile strength with a ductility of about 10 to 15% through a combination of martensite and retained austenite (Fig. 2).

The initial structure was pearlitic with a small ferrite fraction in each case (Fig. 3). The ultimate strength ranged from 810MPa for material H1 with higher silicon content to 980MPa for material H0.

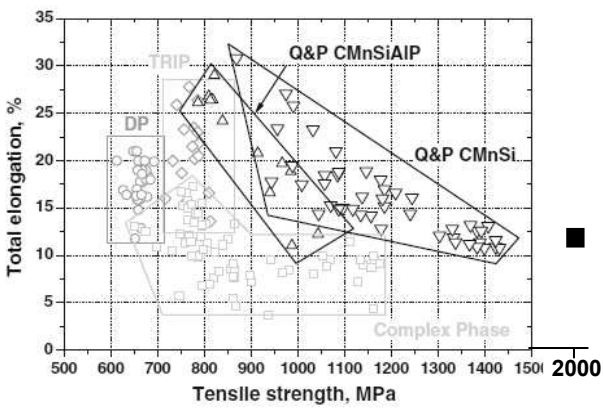

Fig. 2: An overview of various steel types with the experimental material marked [1]

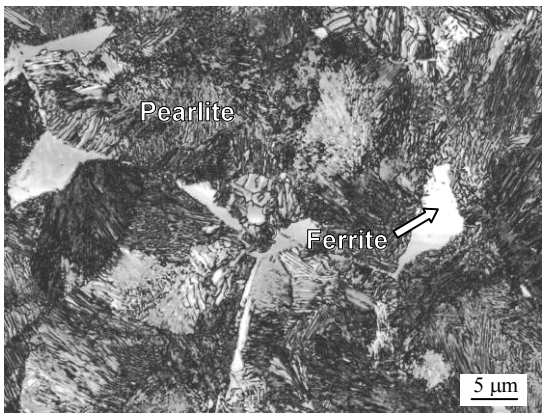

Fig. 3: Initial structure of the H0 steel

Phase transformation temperatures. In order to be able to propose adequate quenching and partitioning temperatures, Continuous Cooling Transformation (CCT) and Time-Temperature Transformation (TTT) diagrams were set up and M_s and M_f temperatures calculated using the JMatPro software (Fig. 4). The calculation was carried out for the austenitizing temperature of 950°C and the grain size of 30 μm. The increase of the silicon content raises the M_s temperature while fastening it at the same time. Conversely, higher manganese content decreases the M_s temperature (Tab. 1).

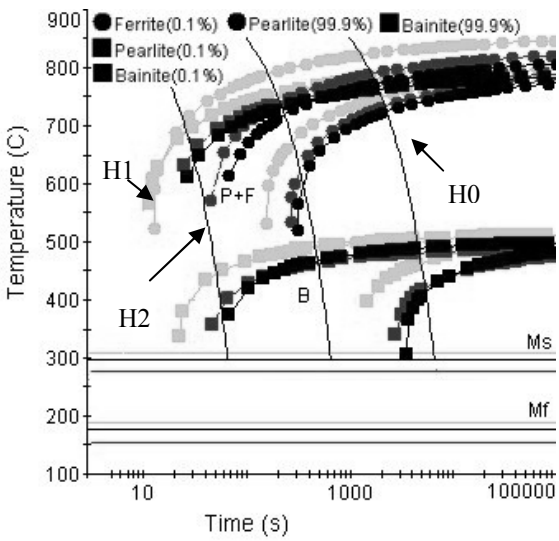

Fig. 4: The influence of Mn and Si on the phase transformations

Q-P process modelling. Processing via Q-P process was carried out on a thermomechanical simulator, which enables precise temperature and deformation control. Materials are heated through a combination of induction and resistance heating. With steels it is possible to achieve a controlled heat and cooling rate of ca. 250°C.s^{-1} with a steep gradient. The temperature is measured by a thermocouple.

The simulated thermomechanical processing with the Q-P process consisted of austenitizing at a temperature of 900°C for the H0 material and at 950°C for materials H1 and H2 with a holding time of 100s followed by a twenty step incremental deformation with the accumulated true strain value of $\varphi = 5$ within the temperature interval 900-820°C. This deformation was inserted to achieve a structure refinement. After deformation a cooling to the following quenching temperatures was carried out: 150°C, 175°C, 200°C and 250°C. Immediately afterwards, the material was heated to different partitioning temperatures (Tab. 2). The quenching temperatures 200°C and 250°C lie for all examined steels within the temperature interval between M_s and M_f. The temperature of 175°C is already below the M_f temperature for both the H0 and H1 steels and the temperature of 150°C was tested for the H2 material only, which has an M_f temperature of 153°C.

Results and discussion

The analysis of the results focused on the influence of the quenching and the partitioning temperatures on the structure development, especially their impact on the formation and stabilisation of retained austenite. The lower the quenching temperature, the greater the martensite fraction within the structure and, at the same time, the smaller the amount of untransformed austenite which can be stabilized by the carbon diffusion. The smaller fraction of retained austenite enables saturation with higher carbon content, thus ensuring the stability of austenite up to room temperature. Therefore, an optimal quenching temperature with respect to the following partitioning had to be found, so that - in the shortest possible time - the largest possible amount of retained austenite could be stabilized.

Quenching temperature in the temperature interval between M_s and M_f. In the first part of the experiment quenching temperatures of 200 and 250°C lying between M_s and M_f temperatures were tested. The temperature 250°C lies just 26°C below M_s for the H2 material. It was discovered that the increase of the quenching temperature from 200 to 250°C caused a significant reduction of ca. 400MPa from the ultimate strength values of about 2000MPa, while enhancing the ductility by about ca. 5% in all cases. Also, the hardness corresponds with this phenomenon, as it decreases with the rising quenching temperature. The ultimate strength was lowered from 2096MPa at 200°C quenching temperature to 1648MPa at 250°C QT for the H0 material. The highest ultimate strength of 2118MPa was reached by the H2 material disposing of the higher amount of both manganese and silicon, while the ductility reached 14% (A_{5mm} value).

The final structure of materials H0 and H2 was martensitic and retained austenite was detected in form of a thin film along martensitic needles (Fig. 5). Material H1 with the amount of silicon enriched from 2 to 2.6% had free ferrite in its structure (Fig. 6).

Tab. 2: Impact of various overcooling temperatures on mechanical properties

Steel	Treatment	M_f [°C]	HV 10 [-]	R_m [MPa]	A_{5mm} [%]
H0	900°C/100s – 250°C/10s – 300°C/600s	178	-	1648	22
	900°C/100s – 200°C/10s – 250°C/600s		546	2096	12
	950°C/100s – 175°C/10s – 200°C/600s		654	1910	22
	950°C/100s – 175°C/10s – 250°C/600s		581	1669	23
H1	900°C/100s – 250°C/10s – 300°C/600s	190	515	1630	26
	900°C/100s – 200°C/10s – 250°C/600s		570	1965	17
	950°C/100s – 175°C/10s – 200°C/600s		610	1975	12
	950°C/100s – 175°C/10s – 250°C/600s		591	1857	20
H2	900°C/100s – 250°C/10s – 300°C/600s	153	563	1711	29
	900°C/100s – 200°C/10s – 250°C/600s		644	2118	14
	950°C/100s – 175°C/10s – 200°C/600s		645	2125	13
	950°C/100s – 175°C/10s – 250°C/600s		587	1829	15
	950°C/100s – 150°C/10s – 200°C/600s		636	1790	11

Quenching temperature under the M_f temperature. The decrease of the quenching temperature to 175°C was tested with two different partitioning temperatures of 200 and 250°C. The temperature of 175°C is very close to the M_f temperature for material H0. A martensitic structure with an ultimate strength of 1938MPa and A_{5mm} ductility of 17% was obtained. The higher amount of silicon in material H1 did not cause any significant ultimate strength reduction, although free ferrite was detected in the structure again (Fig. 7). Material H2, which has the lowest M_f temperature of all the examined steels, reached the highest ultimate strength of 2125MPa (with ductility A_{5mm} 13%), becoming the highest value from all the tests carried out so far. The final structure was martensitic without free ferrite. The increase of the isothermic hold temperature to 250°C while keeping the low quenching temperature again caused a reduction of ultimate strength.

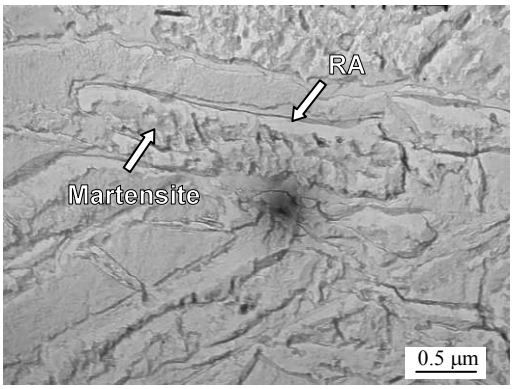

Fig. 5: H0 – QT:200°C/10s – PT: 250°C/600s, carbon replica, TEM

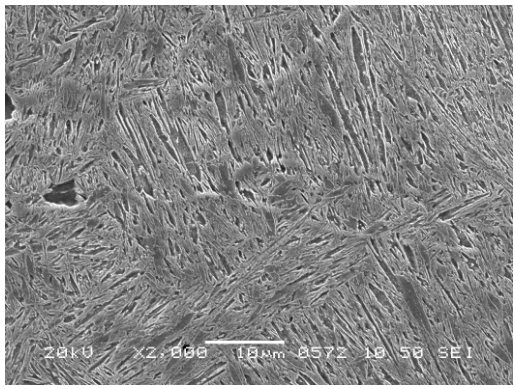

Fig. 6: H1 – QT:200°C/10s – PT: 250°C/600s, SEM

Lowering of the quenching temperature to 150°C led to worse mechanical properties of the H2 material compared to the process with a higher quenching temperature. The ultimate strength reached 1790MPa. Interestingly, the ultimate strength of this material did not rise as expected, though the entire volume of the structure probably transformed to martensite. The ductility was over 10%.

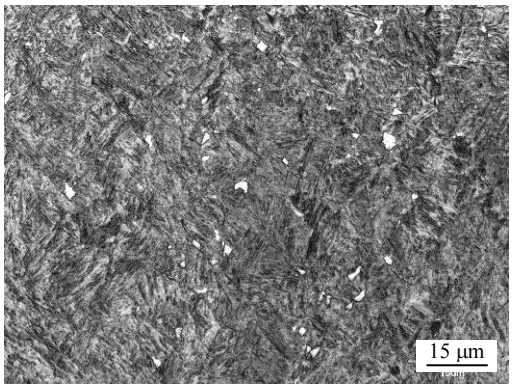

Fig. 7: H1 – QT: 175°C/10s – PT: 250°C/600s, confocal microscopy

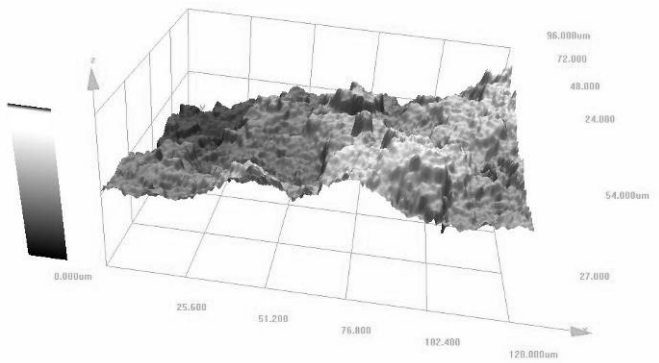

Fig. 8: H2 – QT:200°C/10s – PT: 350°C/600s, fracture area – 3D model – confocal microscopy

Influence of the partitioning temperature. In the second part the influence of the partitioning temperature on the structure development was examined, especially its impact on the retained austenite stabilization. On the basis of previous results the best quenching temperature of 200°C was selected and successively tested together with three partitioning temperatures of 250, 300 and 350°C (Tab. 3).

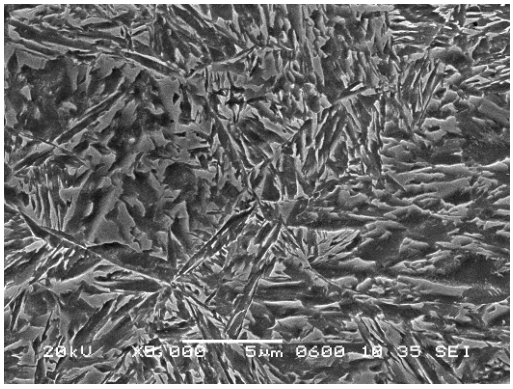

Fig. 9: H2 – QT: 200°C/10s – PT: 350°C/600s, SEM

Increasing the isothermic hold temperature caused a strength reduction and an increase in ductility in all cases. This phenomenon is the result of higher level martensite tempering and corresponds with hardness values as well (Tab. 3). Higher partitioning temperatures also contributed to the stabilization of a higher fraction (reaching of 22% for the material H1 and the highest PT) of retained austenite. The ultimate strength of material H1 which was 1965MPa at 250°C decreased to 1702MPa at 350°C while the ductility rose from 17 to 25%. Material H2 possesses the highest ultimate strength of 2118MPa with ductility A_{5mm} = 14% at PT = 250°C due to higher amounts of manganese and silicon. The fracture was characterized by a ductile failure with a small fraction of brittle fracture after the tensile test (Fig. 8).

Increasing the isothermic hold temperature also had an impact on the character of the microstructure, changing the initial martensitic structure to a tempered martensitic-bainitic structure with significant ferritic fields (Fig. 9).

Tab. 3: Impact of various partitioning temperatures on mechanical properties

Steel	Treatment	PT [°C]	Hold at PT [s]	RA [%]	HV 10 [-]	R_m [MPa]	A_{5mm} [%]
H0	900°C/100s – 200°C/10s	250	600	17	546	2096	12
		300	600	14	508	1810	20
		350	600	17	501	1703	23
H1	950°C/100s – 200°C/10s	250	600	13	570	1965	17
		300	600	19	577	1757	24
		350	600	22	558	1702	25
H2	950°C/100s – 200°C/10s	250	600	13	644	2118	14
		300	600	13	566	1837	22
		350	600	17	525	1720	26

Conclusion

The influence of the quenching and partitioning temperatures on structure development and mechanical properties was studied for three HSLA steels with the same alloying strategy, but with different contents of manganese and silicon.

Increasing the silicon content from 2 to 2.6% led to a partial segregation of free ferrite in the quenching structure during the Q-P process and further caused a stabilization of a higher fraction of retained austenite. Up to 20% of retained austenite was stabilized in some variants. At the same time, this increase of silicon content caused a strength reduction of ca. 100MPa and an increase of ductility from 12 to 17% when compared to the initial processing strategy for the H0 steel. The increase of manganese content from 0.59 to 1.17% in material H2 resulted in the elimination of free ferrite from the structure, raising the ultimate strength to 2118MPa with ductility of 14%.

After increasing the overcooling temperature from 200 to 250°C the ultimate strength decreased significantly. The ultimate strength of all the materials decreased from about 2000MPa by ca. 300 to 350MPa in favour of the ductility. The largest ductility A_{5mm} = 29% was recorded for the H2 material with higher silicon and manganese contents. It was further discovered that the time interval during the transition between the quenching temperature and the partitioning temperature also plays an important role. Extension of this interval resulted in worse mechanical properties.

The experiment showed that as the isothermic hold temperature increases, the total amount of stabilized retained austenite in the structure also increases. At the same time however the structure is tempered at a higher level, which leads on the one hand to a certain loss of hardness and strength, but on the other hand it leads to a significant increase of ductility.

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