

The Effect of Mn and Si on the Properties of Advanced High Strength Steels Processed by Quenching and Partitioning

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Abstract. The concepts new types of materials are, for economic reasons, focused mainly on low alloyed steels with a good combination of strength and ductility. Suitable heat and thermo-mechanical treatments play an important role for the utilization of these materials. Different alloying strategies are used to influence phase transformations. The quenching and partitioning process (Q-P Process) is one of the heat treatment methods which can result in a high ultimate strength as well as a good ductility. However, these good properties can be obtained only if a sufficient amount of retained austenite is stabilized. The influence of different contents of manganese, silicon and chromium on microstructural development and mechanical properties were experimentally tested. Alloying elements were used to stabilize the retained austenite in the final microstructure and also to strengthen the solid solution. Ultimate strengths of over 2000MPa with ductility over 10% were reached after the optimization of the Q-P Process. The microstructures were analyzed using several microscopic methods; mechanical properties were determined by a tensile test and the volume fraction of the retained austenite was established by X-ray diffraction phase analysis.

Introduction

Innovative Q-P process is a progressive heat treatment for steel which is differentiated from standard quenching and tempering by the fact that during low-temperature tempering supersaturated tetragonal martensite transforms to cubic martensite with synchronous precipitation of carbides. This transformation of martensite occurs during Q-P process as well; however, excessive carbon diffuses from the supersaturated martensite into the untransformed austenite. Carbide precipitation is in this case suppressed by using a suitable alloying strategy and heat treatment conditions. Retained austenite saturated with carbon remains stable even at room temperature and the final microstructure is composed of martensite and stabilized retained austenite. The fraction of retained austenite depends on several factors which are closely related. It is mainly the lowest undercooling temperature, the temperature of stabilization of untransformed austenite and also the hold at this temperature. The optimal parameters of the process depend strongly on the chemical composition of the steel [1].

Experimental Procedures

For the Q-P process it is important not only to keep to the exact parameters of the process, but also to choose the most efficient alloying strategy. Alloying elements have to hinder carbide precipitation during martensite tempering, stabilise retained austenite at room temperature and strengthen solid solution so that high ultimate strength with good ductility can be achieved. This is the reason why chromium, manganese and silicon were chosen as the main alloying elements besides carbon.

Manganese and silicon play an important role in transformation kinetics and retained austenite stabilisation. Silicon as an element insoluble in cementite prevents or hinders carbide precipitation and thus enables diffusion of carbon into retained austenite [2]. Manganese as an austenite stabilizer, increases solubility of carbon in austenite and opens cooling area by hindering pearlite formation. Both manganese and silicon also increase the strength of material by solid solution strengthening [3]. Chromium increases stability and slows down pearlitic and bainitic transformation, increases strength and quench-ability of low alloyed steels.

Three melts were designed to establish the influence of silicon and manganese contents on microstructure development and properties (Table 1). The first melt was designated H0 and the next two modifications H1 and H2. Both modifications had a higher silicon content and H2 also had a higher manganese content. The ingots were forged into bar semi products from which specimens for thermo-mechanical processing were made.

Table 1 Chemical composition of experimental materials [wt.%]

Melt	C	Si	Mn	Cr	Mo	Al	Nb	P	S	Ni	Cu	Sn
H0	0.43	2.03	0.59	1.33	0.03	0.008	0.03	0.009	0.004	0.07	0.07	0.01
H1	0.43	2.6	0.59	1.33	0.03	0.008	0.03	0.01	0.01	0.01	0.07	0.01
H2	0.43	2.6	1.17	1.33	0.03	0.008	0.03	0.01	0.011	0.07	0.07	0.01

Determination of phase transformation temperature. In order to design heat and thermomechanical treatment properly it is necessary to know the temperatures of individual phase transformations. For the Q-P process the temperature of the beginning of martensitic transformation, M_s is of the utmost importance. This is why CCT diagrams were calculated for experimental material using JMatPro software.

For the H0 melt $M_s=298^\circ\text{C}$ was established and the temperature of ferrite formation was 822°C . The higher silicon content of the H1 melt resulted in the increase of A_{r3} temperature to 857°C and also in the shift of transformation temperatures to faster cooling rates (Fig. 1). M_s temperature simultaneously increased to 309°C . With regard to the higher manganese content in the H2 melt, A_{r3} temperature decreased slightly to 835°C and transformation temperatures also shifted toward slower cooling rates. In comparison with H0 and H1 melts, M_s temperature dropped more markedly to 276°C .

Original state of material. The original state of the material was documented on forged bars and evaluated by metallographic analysis. The microstructure was pearlitic-ferritic in all three materials with approximately 15% ferrite (Fig. 2).

Thermomechanical simulator. The concept and optimisation of a new type of processing strategy must precisely control temperature and deformation development during processing. The samples were therefore processed by thermo-mechanical simulator. A unique controlling system of the simulator enables to execute very quick changes in temperature and deformation parameters and so simulate very precisely real processing conditions. It is possible to achieve controlled temperature gradients of 100°C/s during heating and 250°C/s during cooling for steels. The deformation member can reach the speeds of up to 3 m/s and

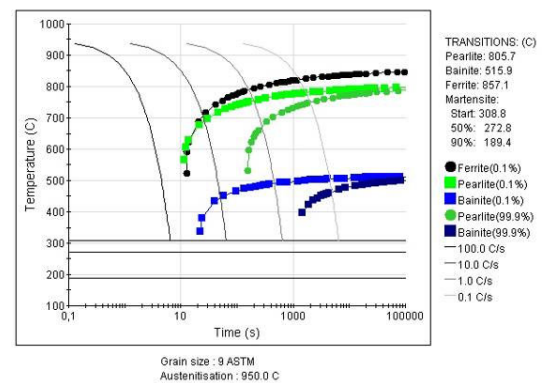


Fig. 1: CCT diagram for experimental material H1

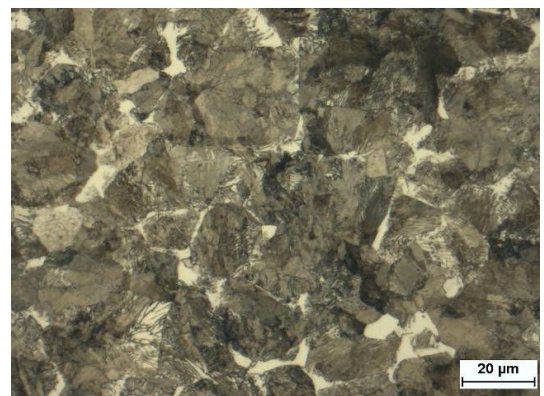


Fig. 2: Steel H0 – pearlitic-ferritic structure of original state

the process is monitored all the time. To obtain desired microstructure and properties it is necessary to optimize many processing parameters. This article focuses on the choice of the most convenient austenitization temperature and the temperature of annealing hold for carbon partitioning.

Results and Discussion

Austenization temperature. To acquire suitable final microstructure and properties, austenization temperature must be chosen so, that full austenization of the microstructure is ensured at the lowest temperature possible.

This is the reason why austenization temperatures of experimental steels were optimized in the first step. The proposed temperatures derived from the results calculated in JMatPro. Six different austenization temperatures were chosen: 885, 900, 915, 930, 940 and 950°C. The specimens were austenized and immediately quenched into the water. Martensitic microstructure without free ferrite was obtained in H0 and H2 steels after all tested temperatures. However the microstructure of H1 steel quenched from 885 and 900°C was martensitic with small fraction of free ferrite (Fig. 3). Quenching from temperature of 950°C and higher resulted in purely martensitic microstructure. Even the highest austenization temperature of 950°C did not cause coarsening of martensitic microstructure.

Q-P Process. Thermo-mechanical treatment strategies were designed for each experimental material on the base of previously mentioned results. Austenization temperature of 900°C/100s was chosen for material H0 and 950°C/100s for materials H1 and H2. After austenitization followed incremental deformation with true strain $\varepsilon = 5$, which was applied in twenty steps in temperature interval of 900-820°C. The samples were then cooled to 200°C where 10s hold took place. In the next step were specimens heated to the isothermal hold temperature of 250°C, 300°C or 350°C. Diffusion partition of carbon and thus stabilisation of retained austenite occurred during this hold.

The aim of this part of experiment was to determine the impact of isothermal hold temperature on stabilisation of retained austenite. Considering different M_s temperature of each material it was also possible to analyse the influence of different manganese and silicon content on final microstructure.

First of all, processing strategy with isothermal hold of 250°C was carried out. Resulting microstructure for material H0 was martensitic with 17% of retained austenite and hardness of 546 HV10. Ultimate strength was higher than 2000 MPa while maintaining ductility $A_{5mm} = 12\%$ (Table 2). The same type of microstructure was found in material H2, only hardness values reached 644 HV10. Different microstructure was observed in material H1, where larger amount of free ferrite was found in tempered base microstructure.

Elevation of isothermal hold temperature to 300°C produced martensitic microstructures in all three materials. The hardness of material H0 dropped from 546 HV10 to 508 HV10 with small decline in retained austenite fraction. Significant drop in hardness occurred also in material H2, where hardness decreased from 644 HV10 to 566 HV10. Increasing isothermal hold temperature had



Fig. 3 Steel H1 – martensite with free ferrite, austenization temperature 885°C, quenched in water, SEM

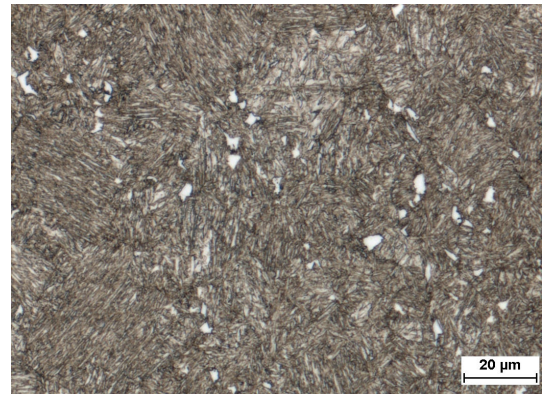


Fig. 4: H1 – martensitic microstructure with 19% of RA after TMT, 950°C/100s – 200°C/10s – 300°C/600 s

small effect on material H1, where the fraction of retained austenite increased but without marked effect on hardness values (Fig. 4).

Further enhancement of isothermal hold temperature means already to exceed M_s for all three researched materials. This temperature caused higher tempering of microstructure and therefore also decline in hardness values. It was found out, that the increase of isothermal hold temperature resulted for material H0 in the drop of ultimate strength by 300MPa with simultaneous increase of ductility by 10% (Table 2). Very surprising was the increase of retained austenite fraction over 20% in material H1, while hardness values decreased only slightly. This interesting phenomenon will undergo further analysis.

Table 2 Results of thermo-mechanical processing

Material	Processing	Isothermal hold temperature [°C]	M_s [°C]	RA [%]	HV 10	$R_{p0.2}$ [MPa]	R_m [MPa]	A_{5mm} [%]
H0	900°C/100s – 200°C/10s	250	298	17	546	2087	2096	12
		300		14	508	1549	1810	20
		350		17	501	1652	1703	23
H1	950°C/100s – 200°C/10s	250	309	13	570	1516	1965	17
		300		19	577	1448	1757	24
		350		22	558	1420	1702	25
H2	– 200°C/10s	250	276	14	644	1656	2118	14
		300		13	566	1557	1837	22
		350		17	525	1221	1720	26

Summary

Optimization of Q-P process on experimental steels with carbon content of 0.43%, manganese content 0.59–1.17% and silicon content 2–2.6% tested the influence of austenization temperature and isothermal hold temperature on final microstructure development. Enhancement of silicon content from 2 to 2.6% caused formation of small portion of ferrite in quenched structure and also stabilisation of higher retained austenite fraction. In some variants up to 20% of austenite was stabilised. Free ferrite formation was suppressed by increased manganese content of steel. Manganese content increased to 1.17% in the case of H2 steel. Experiment further showed that increasing isothermal hold temperature increase overall amount of retained austenite stabilised in microstructure. On the other hand this higher temperature results in more intensive tempering of microstructure and also in significant increase of ductility. Ultimate strength over 2000MPa with ductility $A_{5mm} = 12\%$ was achieved for a low-cost steels with undemanding Mn-Si-Cr alloying concept after application of Q-P process with isothermal hold temperature under M_s .

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