Materials Science Forum *Online: 2010-06-30*
ISSN: 1662-9752, Vols. 654-656, pp 29-32
doi:10.4028/www.scientific.net/MSF.654-656.29

Application of Quenching and Partitioning to Improve Ductility of Ultrahigh Strength Low Alloy Steel

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Keywords: Martensitic steel, quenching and partitioning (Q&P), multiphase microstructure, metastable austenite, high strength and high ductility, transformation Induced plasticity (TRIP)

Abstract. In this study Quenching and Partitioning (Q&P) as proposed by Speer was applied to improve the ductility of C-Mn high strength Low Alloy steel (HSLAs). Microstructural observations revealed a multiphase microstructure including first martensite, fresh martensite and retained austenite in the Q&P processed steel. During tensile process, the austenite volume fraction gradually decreased with strain increasing, suggesting the phase transformation induced plasticity for the Q&P processed steel. Ultrahigh strength about 1300-1800MPa and tensile elongation about 20% were obtained after Q&P processing at specific conditions, which is significant higher than that of ~10% of conventional martensitic steel. The the product of tensile strength to total elongation increased from 25 to 35GPa% with increasing carbon content in studied steel. This improved mechanical properties were related to the ductility contribution from TRIP effects of the retained austenite and strength contribution from the hard martensitic matrix. At last it was turned out that the Q&P process is a promising way to produce ultrahigh strength steel with relative high ductility under tailored heat treatment conditions for different micro-alloyed carbon steel.

Introduction

Although sometimes considered as the "old" material, steel remains the most widely used metallic alloy and a subject of intense research. It is well know that the different solid-solid phase transformation of iron from the high-temperature FCC structure to the low-temperature BCC structure results in different microstructure and corresponding desired mechanical properties, and in turn gives materialogists and metallurgists a big window for microstructure control. Amongst these different steels, the martensitic steel is normally the hardest steel at a given chemical composition but assumes worst ductility. Nowadays with the increasing demand of lightweight, energy saving and safety increasing of automobile industry in recent years, there has been an increased emphasis on the development of new advanced high strength sheet steels , namely both high strength (Rm) and high ductility (A), in turn the high value of the product of tensile strength to total elongation (RmxA) [1].

As it is well known, TRIP (transformation-induced plasticity) steel has been studied worldwide since 90s of the last century and it was demonstrated that TRIP steel has an excellent combination of strength and ductility [2]. The strength of conventional TRIP steel is higher than other conventional advanced high strength steels [3], but significantly lower than the martensitic steel. In order to increase the ductility of martensitic steel without losing it strength, quenching and partitioning (Q&P) conception was proposed by Speer in 2003 to produce steels by introducing carbon-enriched retained austenite into martensitic matrix [4]. The Q&P process involves the partially quenching and follows tempering/annealing. The latter was called partitioning, in which carbon atoms were rejected from the developed martensitie phase and were absorbed by retained austenite phase. It was shown that a relative high temperature partitioning with a short time would result in both high strength and high ductility[5].Thus tailoring Q&P heat treatment parameters, such as quenching temperature, partition temperature and time for different steel, is the key to optimise the final mechanical properties. So far, few results of the ductility of Q&P processed steels were demonstrated high than 20% total elongation without significant loss of strength, which may be related to the unreasonable selection of the heat treatment parameters.

In this study, different carbon steels were processed by Q&P process at relative high partitioning temperature with a short time (1 or 2 minutes). Our aim is to develop martensitic steel with ductility up to 20% without significant loss of strength by means of Q&P process. The underlined heat treatment principle to the excellent combination of strength and ductility of different steels would be explained. The strengthening and ductility-enhancing mechanism of Q&P processed steels were concerned in this study.

Experimental Procedures

Different kinds of steels with different carbon contents, 21C(0.21,wt%), 37C(0.37,wt%) and 41C(0.41,wt%), were applied in this study. These steel were melt in arc furnace and then forged into bar with diameter of 16mm. The compositions of these steels are given in Table 1. The Q&P heat treatment parameters for these steel were given in Table 2 designed based on the finding of relative high temperature partitioning with relative short time. All specimen was austenized in a high temperature box furnace, then quenched into a salt bath for partially martensitic transformation, partitioning process was carried on immediately in another salt bath, finally, the samples were water quenched to room temperature.

Table 1 Composition of the studied steels (wt.%)

Steel	C	Si	Mn	Cr	Ni	Mo	V	Nb	Al	S	P
21C	0.21	1.75	0.290	1.03	2.86	0.31	0.08	0.049	0.020	0.0007	0.0060
37C	0.37	1.85	0.200	1.04	1.97	0.30	0.10	—	—	0.007	0.0072
41C	0.41	1.68	0.027	1.05	1.83	0.62	0.14	—	0.014	0.001	0.0050

Tensile test were performed on the dog-bone shape specimens with gauge length of 25mm and diameter of 5mm at a strain rate of 10^{-3}/s in an Instron machine (WE-300) at room temperature. Thin foils for TEM measurements were firstly grinded mechanically down to ~40μm thickness, and then Twin-jet polished in a solution of 5% perchloric acid and 95% alcohol at about -20°C, finally examined by TEM and SEM. Samples for XRD measurements were grinded and polished mechanically, and then electrolytically polished in a solution of 10% chromic acid and distilled water for stress relieving. Volume fraction of retained austenite was estimated by X-ray diffractometry using Cu-Ka radiation. The calculations were based on the integrated intensities of (200)α, (211)α, (200)γ , (220)γ and (311)γ diffraction peaks [6].

Table 2 Q&P heat treatment parameters

Steel	Austenization parameters	Quenching parameters	Partioning parameters
21C-A	900°C ×15min	330°C ×1min	500°C ×1minWQ
21C-B	900°C ×15min	400°C ×20min	500°C ×10minWQ
37C-C	900°C ×15min	250°C ×1min	500°C ×2minWQ
37C-D	900°C ×15min	350°C ×20min	500°C ×1minWQ
41C-E	900°C ×15min	250°C ×1min	500°C ×2minWQ

Results and Discussion

Mechanical properties of studied steels processed according to the heat treatment design as given in Table 2 were summerized in Table 3. The austenite volume fractions measured by XRD were given in Table 3 as well. It can be seen that the tensile strength increases from ~1300MPa to ~1800MPa with increasing carbon content, while their total elongation about 20% doesn't change. As can be seen from Table 3, the uniform elongation increases with carbon content, but the non-uniform elongation decreases with increasing carbon content, indicating the improved ductility is mainly contributed from the uniform elongation. The product of tensile strength to total elongation varies from 25GPa%

to 35GPa%, which is about 2-3 times of that of the conventional martensitic steel. Similarly the retained austenite fraction after given Q&P process also increases from 12% to 27% with increasing carbon content.

The stress/strain curves of the processed steels according to the heat treatment design as given in Table 2 were shown in Figure 1a. It can be seen from the tensile stress/strain curves that the yield behaviors of these steels could be classfied into two groups, one is the high yield stress (>1000MPa) when long time austempering applied (21C-B and 37C-C) and another is the low yield stress (21C-A, 37C-D and 41C-E) when short time austempering applied. The difference between these two yield behaviors may result from the different austempering behaviors at different time. As we know, during this partitioning process, stabilization of retained austenite, precipitation of second particles and the decreasing of dislocation density in the first developed martensite take place simultaneously. The different yield behaviors may be directly resulted from the different amount volume fraction of the second particles. For steels of 21C-A, 37C-D and 41C-E, no or less second particles developed in these steel due to the short time austempering or partioning. However, for 21C-B and 37C-C, long time partioning results in the precipitation of second particles.

Table 3 Mechanical properties of studied steels shown in Fig. 1

Steel	Rm/MPa	Rp0.2/MPa	A/%	Agt/%	$f\gamma$/%	RmxA/GPa%
21C -A	1310	768	20	10	12.01	26.2
21C -B	1390	1025	20.8	10.5	11.98	28.9
37C-C	1570	1235	20.0	10.0	/	31.4
37C-D	1670	788	19.8	12.3	21.09	33.1
41C -E	1835	740	19.0	14.0	27.39	34.9

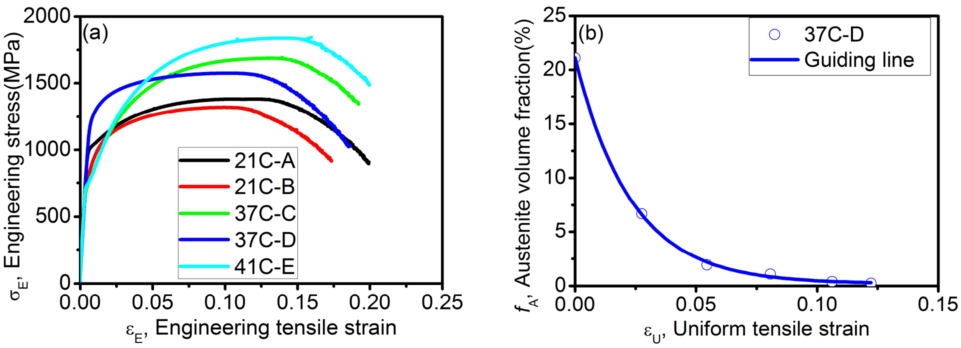

Figure 1 Tensile behaviors of Q&P processed steels. (a) Tensile stress/strain curves and (b) Evolution of austenite volume fraction as a function of tensile strain of 37C-D steel.

Comparing with the ductility (~10% total elongation) of the conventional martensitic steel, the steels studied in this study developed high ductility (~20% total elongation) by Q&P process as given in Table 3. The reason may be related to the TRIP effects. Fig.1(b) reveals the evolution of austenite volume fraction of 37C-D as a function of uniform tensile strain. It can be seen from this figure that the austenite volume fraction gradually decreases with strain increasing, implying the TRIP contribution to the enhanced ductility. It also can be found that increasing austenite increases the uniform elongation but decreases the non-uniform elongation (necking induced elongation). Further study on the mechanisms austenite volume contribution to uniform elongation. Figure 2(a) shown the microstructure of 21C-B steel characterized by SEM, from which the easily etched part was identified as the initial martensite formed during the partial quenching process, the white blocky phase was identified to be the fresh martensite, the small second particles can be identified in this figure as well due to the long time partioning, which supports the proposed reason to its high yield stress. Figure 2(b) revealed the martensitic phase and austenite phase of 41C-E steel examined by TEM. It can be seen that most of the retained austenite with thin film morphology were kept after partioning. The thickness of these retained austenite varies from 50nm to 100nm, implying the higher stability of thin film-like austenite than that of the large sized austenite, which eventually transformed into fresh martensite after parttioning. After short time partioning treatment, the martensitic structure was still remained in the final microstructure (Figure 2 (b)). Based on above results (Fig.2), it can be concluded here that the high strength is mainly contributed from its large amount of martensitic phase and its high ductility stems from its reatined austenite. Thus Q&P processed steel is a promising way to fabricate high strength and high ductility steel by means of optimizing the heat treatment parameters.

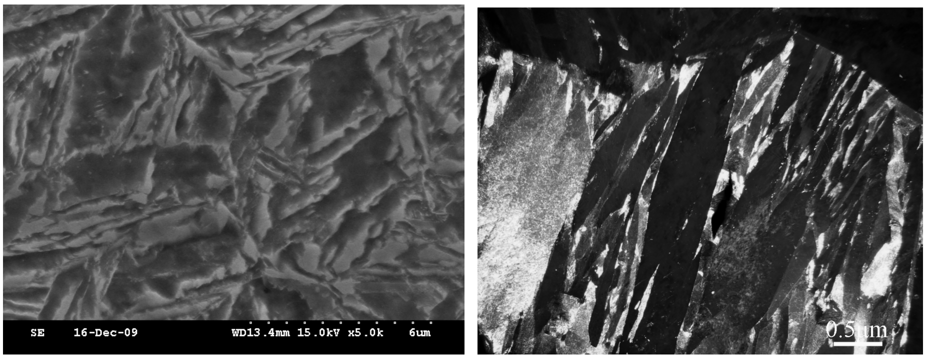

Figure 2 Microstructures of Q&P processed steel examined by SEM and TEM. (a) Multiphase microstructure of 21C-A steel characterized by SEM and (b) Retained austenite dark field morphologies in 41C-E steel characterized by TEM.

Conclusions

Microstructure and mechanical properties of different low alloy carbon steels processed by Q&P were demonstrated in this paper. The main conclusion could be summarized as:

(i) It was found that short time parttionging treat at relative high temperature was useful to produce high strength and high ductility steel. The strength of the Q&P processed steels presented in this paper varied from ~1300MPa to 1800MPa and their ductility was about 20%. The product of tensile strength to total elongation of (RmxA) Q&P processed steels ranged from 25-35GPa%, which is about 2-3 times of that of the conventional martensitic steel. It was evidenced that the short time partioning treatment at relative high temperature during Q&P process benifits not only the strength but the ductility.

(ii) It was shown that the high strength was mainly contributed from the martensitic structure remained in the final structure but the improved ductility of Q&P processed steel was from the retained austenite by means of TRIP effects during deformation.

(iii) Further study on the microstructure evolution concerning the quenching temperature and time, partioning temperature and time is necessary for Q&P application to optimize the heat treatment parameters of the Q&P process.

Acknowledgement

This research is supported by National Basic Research Program of China (973 program) No.2010CB630803 and National High-tech R&D Program (863 program) No.2511.

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