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Evolution of Mechanical Properties and Microstructure in Q&P Processed Unconventional Medium-Carbon Silicon Steel and Comparison between Q&P Processing, Quenching and Tempering, and Austemperingfor

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This paper investigates the evolution of microstructure and its related mechanical properties of Q-P processed medium-carbon AHSS steel. The investigated informations were compared to the structures and mechanical properties of quenched and tempered, austempered specimens made of the same steel grade. According to the correlations between observed microstructures after Q-P, quenching and tempering, austempering the presence of bainite in Q-P processed specimens was found. The hypothesis of bainite growth durinq Q-P processing was devoleped. The experimental results show that during Q-P heat treatment the bainite transformation can occur even when the partitioning temperatures are below the temperature Ms of experimental steel.

Keywords: Q&P process, bainite, martensite, mechanical properties

1 Introduction

The underlying principles of Q&P processing include migration of carbon between martensite and austenite, and subsequent austenite stabilization. [1,2,3]. The phenomenon occurs in TRIP steels where austenite enriched with carbon forms as a consequence of bainite transformation. In TRIP steels, carbon which is needed for stabilizing retained austenite is supplied from the newly-forming bainitic sheaves [4]. Thus, austenite is stabilized thanks to the differences between carbon solubility in bainitic ferrite and austenite. However, an intellectual paradox is encountered in Q&P steels where austenite enrichment that is needed for the TRIP effect [5,6] to occur is conditional on carbon diffusion from martensite which, under ideal circumstances, has the same chemical composition as the initial austenite, due to the diffusionless principle of martensite transformation. From this viewpoint, there would be no theoretical driving force for diffusion which is needed for carbon migration between RA and martensite. The theory of Q&P processing of steels is based on diffusion of carbon from super-saturated martensite. The progress of diffusion depends, besides the distribution of alloying elements and other factors, on temperature. The lower the temperature used in Q&P processing of steel, the lower the diffusivity of carbon with time. The quenching step in Q&P processing causes the steel to develop a certain amount of martensite and untransformed austenite [7]. From the physical-metallurgical perspective, the processes that take place in martensite during the partitioning step should be the same as those in tempering of quenched steel [8,9]. This includes the traping of carbon atoms at dislocation nodes of martensite laths or plates, precipitation of transition carbides, and decomposition of austenite between martensite laths into bainite-like microstructure [10]. However, these are competing processes for carbon migration between martensite and untransformed austenite.

2 Experimental programme

The goal of this experimental programme was to assess the effect of the conditions of Q&P processing on the evolution of mechanical properties and microstructure in an unconventional medium-carbon steel containing Fe - 2.03% Si – 0.56% Mn – 1.33% Cr (Tab.1). The martensite start temperature of this experimental material was callculated in the software JMatPro[21] and was 300°C.

Tab. 1 *Chemical composition of the experimental steel (weight %)*

C	Si	Mn	Cr	Mo	Nb	P	S
0.43	2.03	0.56	1.33	0.16	0.03	0.005	0.003

In addition, Q&P processing was compared to conventional quenching and tempering and to austempering. Experimental processing was carried out in an MTS thermomechanical simulator which uses induction-resistance heating [11,20]. Threaded cylindrical test specimens with a gauge length of 15 mm and

8 mm diameter were used. First, they were austenitized at 950°C for 180 s. Following austenitization, they were treated using three different routes (Fig. 1).

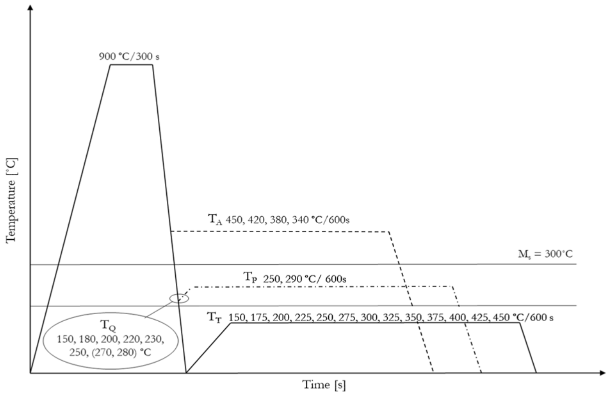

Fig. 1 *Diagram of experimental processing routes*

The first one involved quenching to room temperature at 50°C/s and subsequent holding at defined temperatures for 600 seconds. The second one, Q&P processing, comprised cooling to various quenching temperatures (TQ) at 50°C/s, reheating to one of the partitioning temperatures (TP) of 250, 290 and 340°C, holding for 600 seconds and subsequent quenching to room temperature. In the third one, austempering, the austenitized specimens were quenched to one of the temperatures of 450, 420, 380 and 340°C at the rate of 50°C/s, then held for 600 seconds and quenched to room temperature. Specimens for metallographic examination and miniature tensile testing were then prepared [12]. In case of tensile testing 3 specimens for each experimental heat treatment were used.

3 Results and discussion

Using static tensile test data, the tempering curve for the steel was constructed (Fig. 2). Maximum strengths were obtained in the quenched untempered specimens: ultimate tensile strength (UTS) = 2120 MPa, yield strength (YS) = 1590 MPa, elongation (TE) = 11%. Up to the temperature of 325°C, tempering led to a gradual decrease in UTS. The YS values exhibited no appreciable variance up to the tempering temperature of 325°C. At the tempering temperature of 325°C, UTS and YS began to rise and TE decreased. This represents a typical tempering behaviour in low-alloy medium-carbon steels. It is very likely that it is associated with processes related to decomposition of retained austenite. The lowest values, UTS = 1620 MPa, YS= 1415 MPa, were obtained at the tempering temperature of 450°C when elongation was TE = 19%.

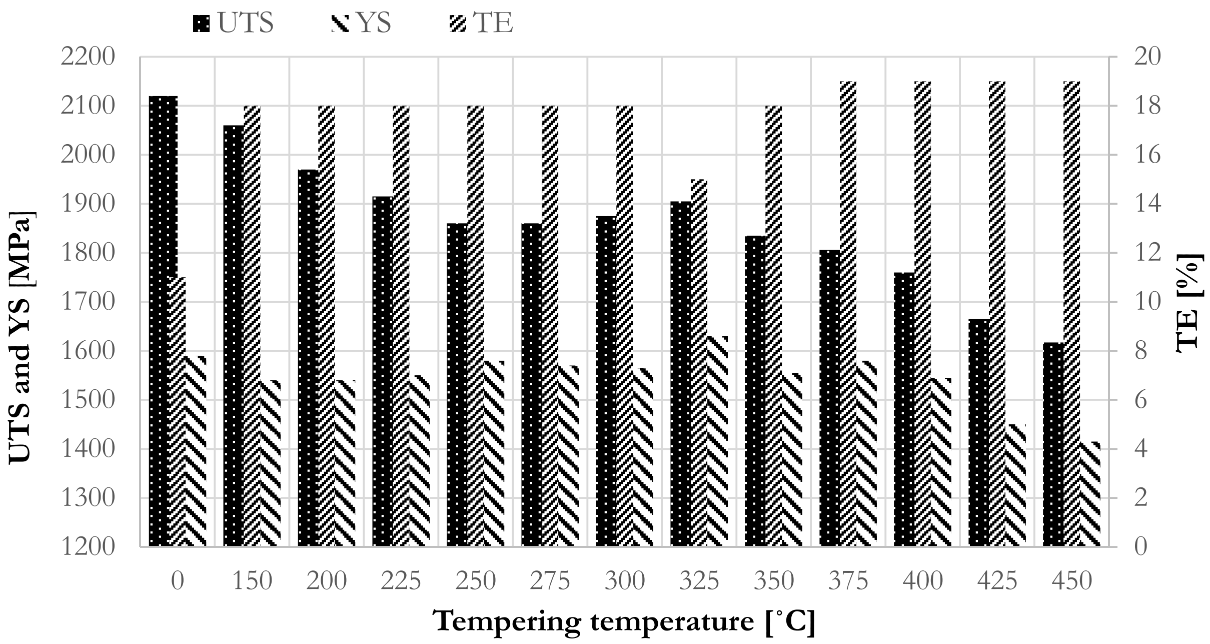

Fig. 2 *Mechanical properties of experimental steel upon quenching and tempering*

The microstructures consisted of typical lath martensite. Tempering at above 250°C produced fine carbide precipitates (Fig. 3).

In the austempered specimens, low values of UTS = 1450 MPa with YS= 785 MPa and UTS = 1430 MPa with YS=955 MPa were obtained in specimens A – 420/600 and A – 380/600, respectively (Fig. 4). Specimens A - 450/600 and A - 340/600 exhibited identical values of UTS = 1610 MPa. However, their YS values were 860 MPa and 1240 MPa, respectively. The highest elongation value TE = 26% was found in specimen A – 380/600. The lowest elongation value TE = 5% was found in specimen A – 450/600. The likely cause was the presence of allotriomorphic ferrite in the microstructure.

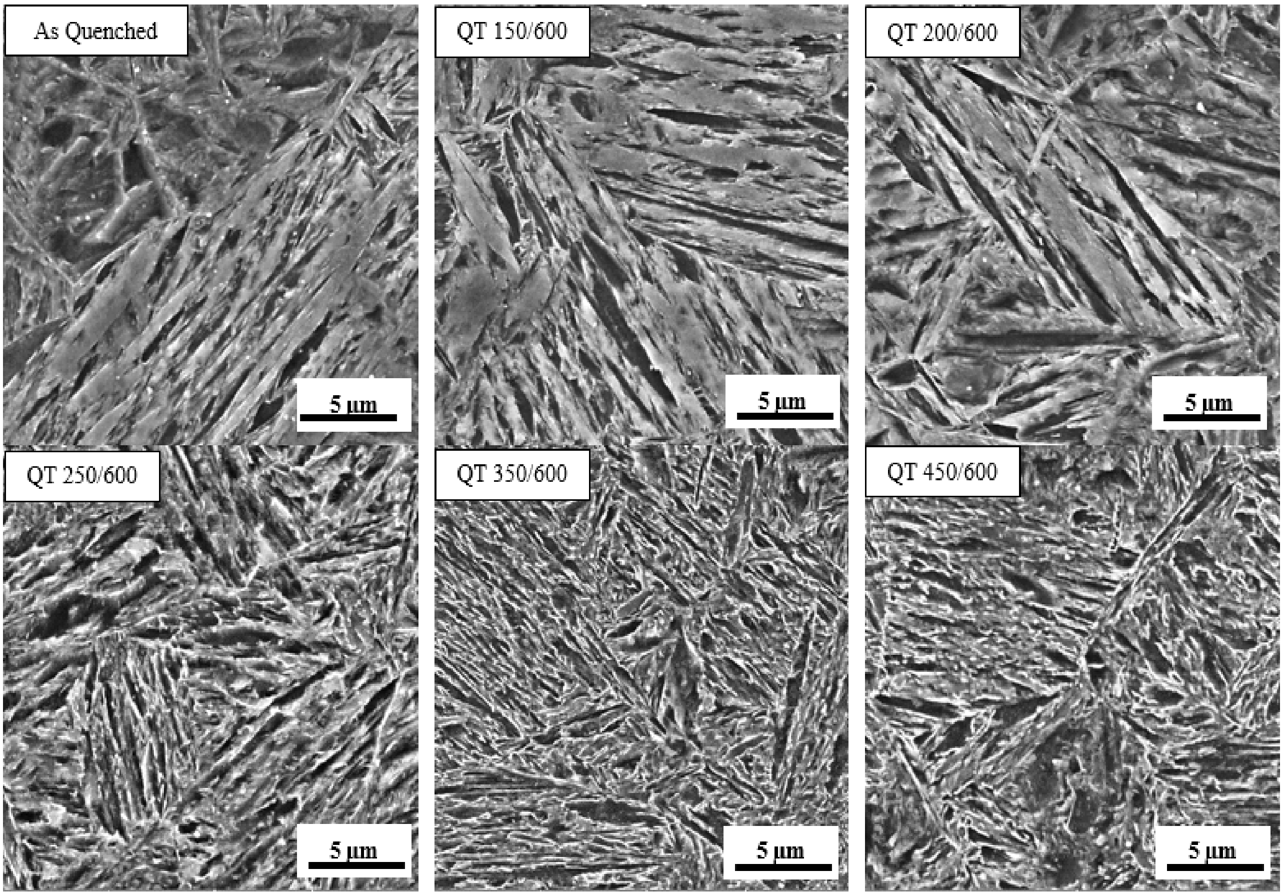

***Fig. 3** Microstructures of experimental specimens after quenching and tempering*

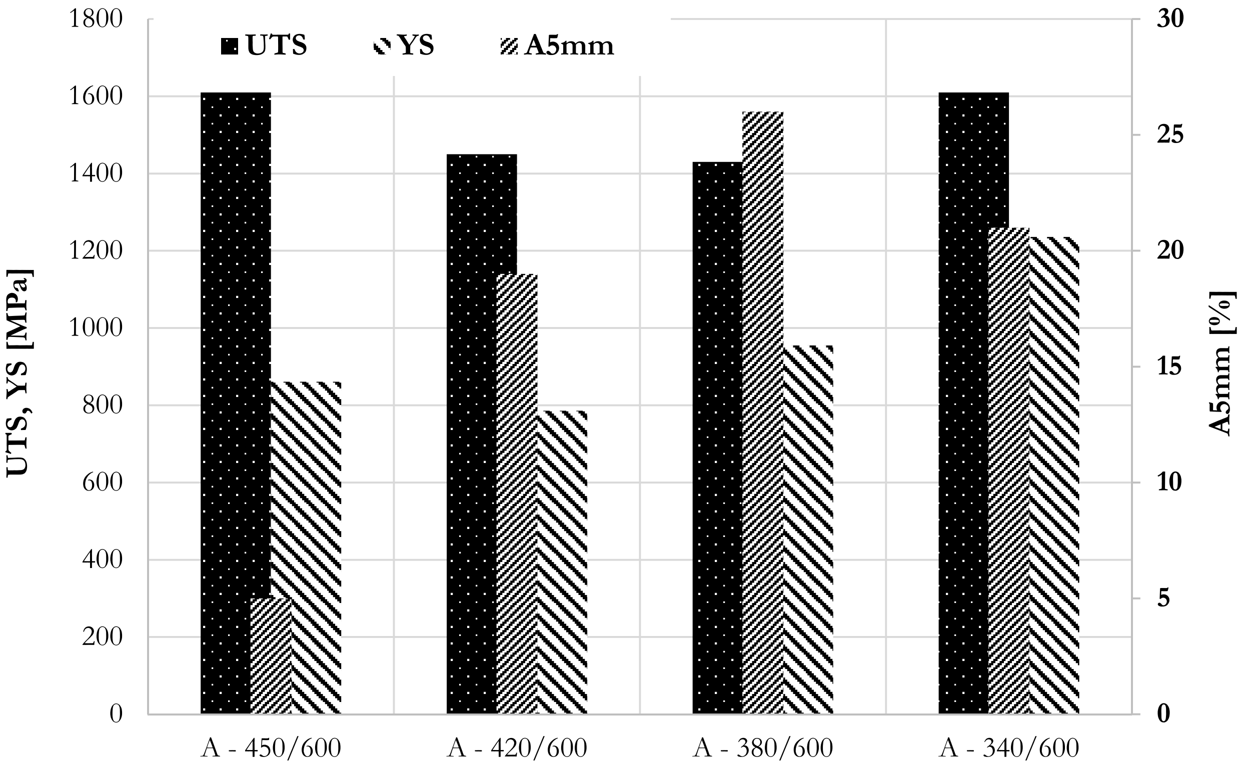

***Fig. 4** Mechanical properties of experimental steel upon austempering*

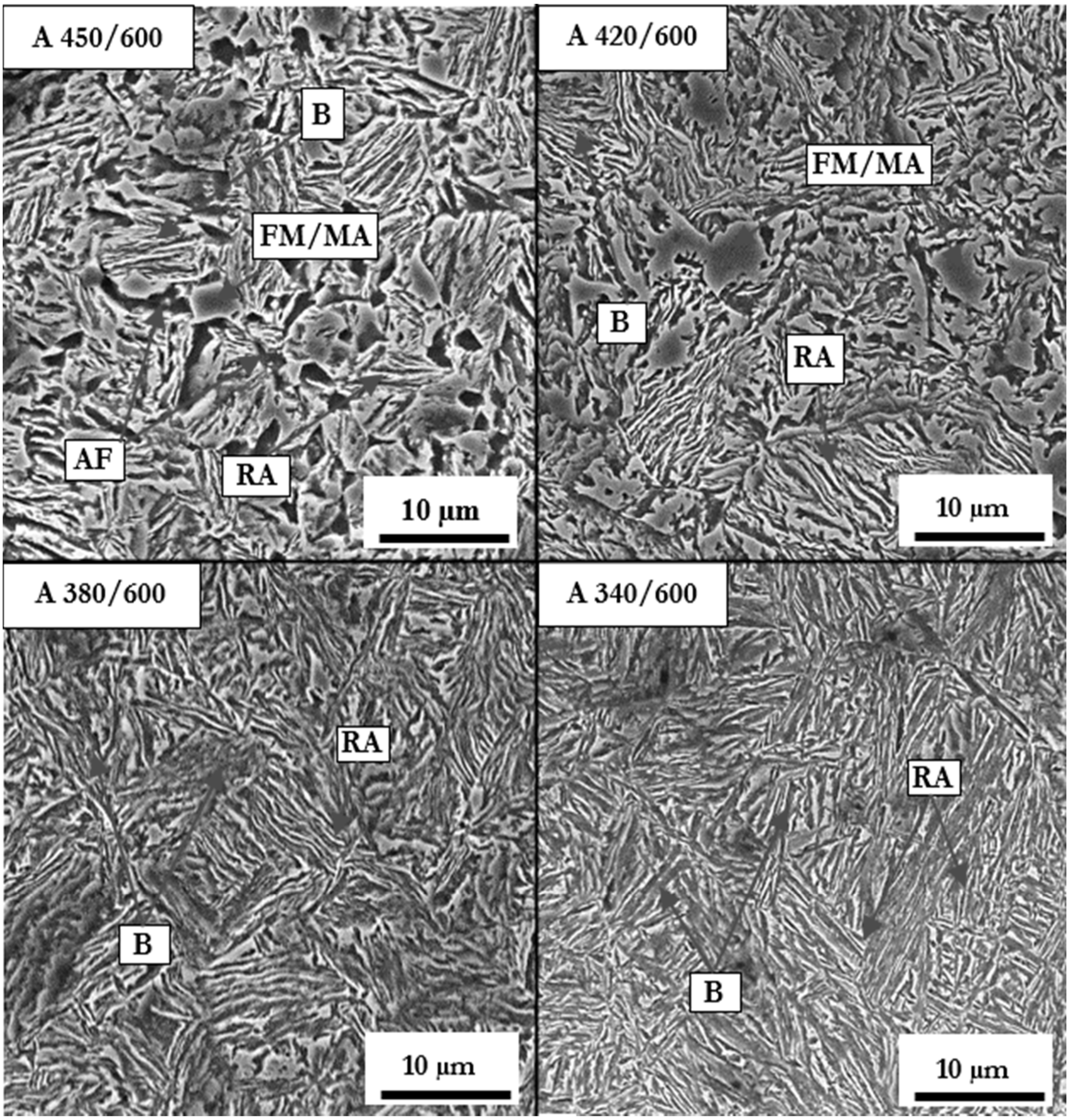

Fig. 5 *Microstructure of experimental specimens upon austempering; B - Bainite, RA - Retained austenite, FM - Fresh martensite, AF – Alotriomorphic ferrite, MA - MA constituent*

The specimen microstructures were a mixture of bainitic ferrite, the M-A constituent/fresh martensite, retained austenite and, in A – 450/600 specimens, a small amount of allotriomorphic ferrite (Fig. 5). The share of the M-A constituent/fresh martensite in the microstructure decreased with decreasing austempering temperatures. By contrast, the fraction of bainite and retained austenite increased at the same time.

The UTS and YS values of specimens from the QP – x/250 ˚C route exhibited no appreciable variance in relation to process parameters (Fig. 6). The maximum UTS = 1840 MPa was obtained in specimens Q-P 250/250. The lowest UTS = 1800 MPa was obtained in specimens Q-P 230/250. The YS values were in the 1210-1120 MPa range and the TE values in the 17-18% range.

The QP – x/290 ˚C route produced similar UTS profiles in relation to process conditions (Fig. 7). The highest UTS = 1755 MPa was found in specimens QP – 280/290˚C, whereas the lowest UTS = 1700 MPa in specimens QP – 180, 230, 260/290˚C. The highest average YS = 1230 MPa was found in specimens QP – 160/290˚C. The lowest average YS = 1020 MPa was found in specimens QP – 230/290˚C. Higher partitioning temperature of TP = 290°C led to higher elongation levels in the range TE = 19-21% [10].

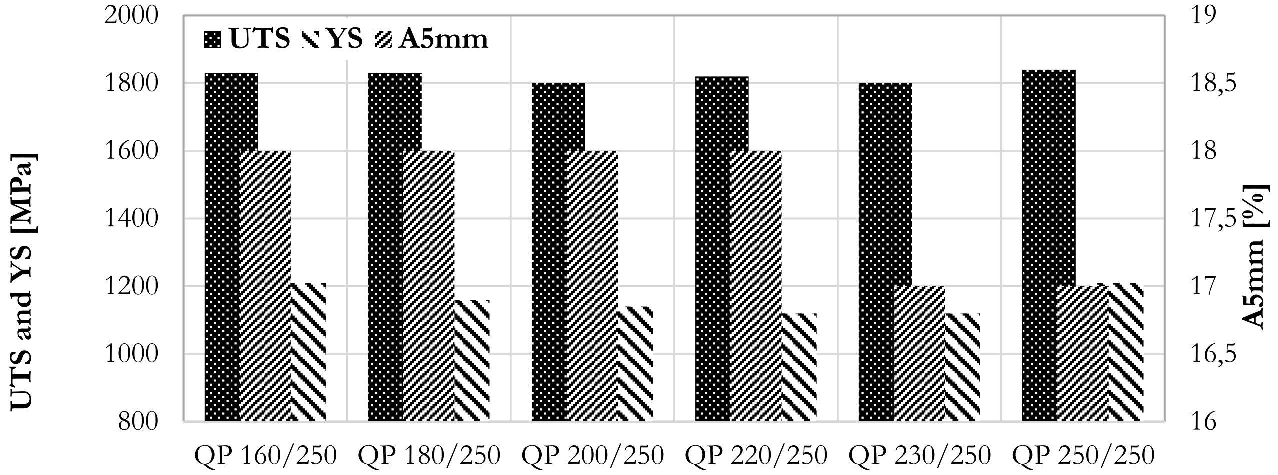

Fig. 6 *Mechanical properties of experimental steel upon the QP- x/250 route*

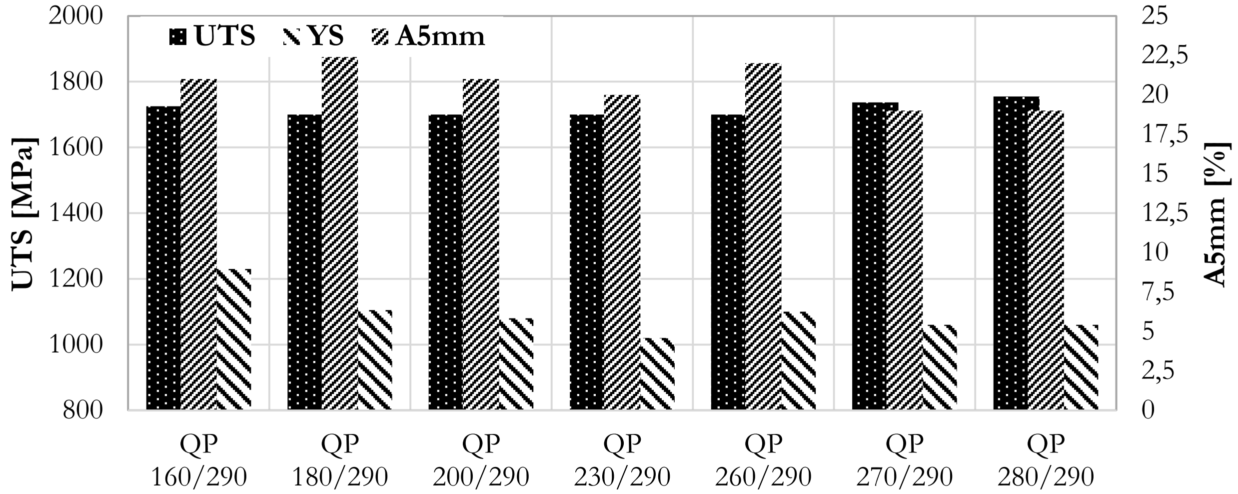

Fig. 7 *Mechanical properties of experimental steel upon the QP- x/290 route*

Upon the QP – x/340°C route, the highest UTS=1590 MPa was found in specimens QP – 290/340, and the lowest UTS=1460 MPa in specimens QP – 200/340 (Fig. 8). YS in all specimens was in the range of 1200-1250 MPa. The lowest TE = 23% was obtained in specimens QP – 180/340, whereas the highest TE = 31% in specimens QP – 280/340.

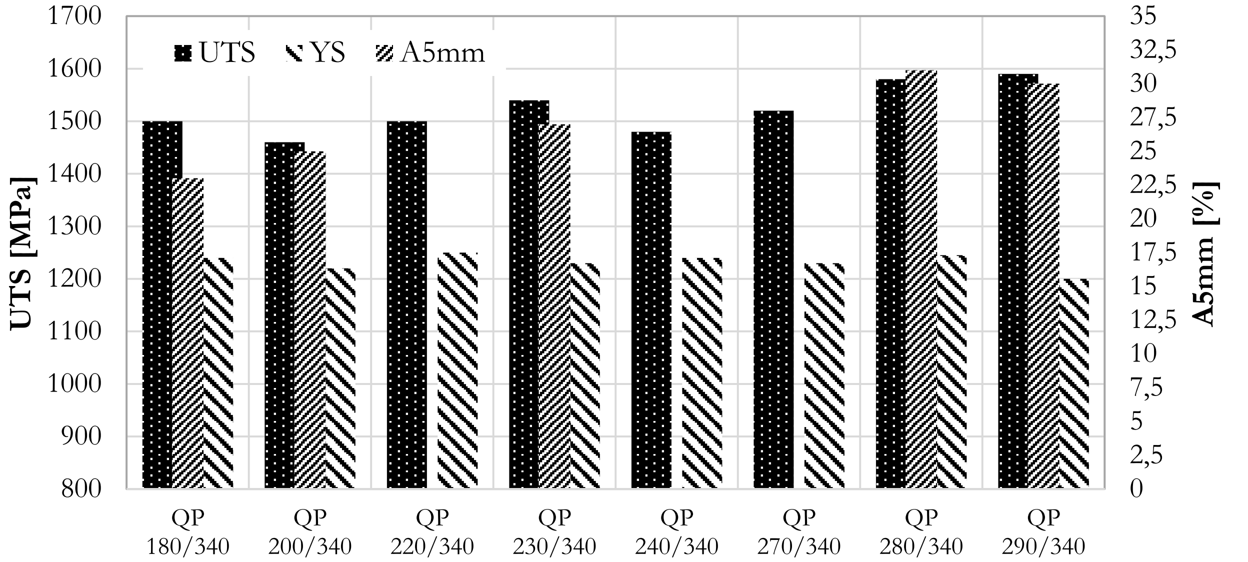

Fig. 8 *Mechanical properties of experimental steel upon the QP – x/340 route*

The values of UTS_{QP} in the experimental steel exhibited minimum variance [13], the value of which increased with the partitioning temperature T_P. They also showed no dependence on the quenching temperature T_Q and even on the partitioning temperature T_P.

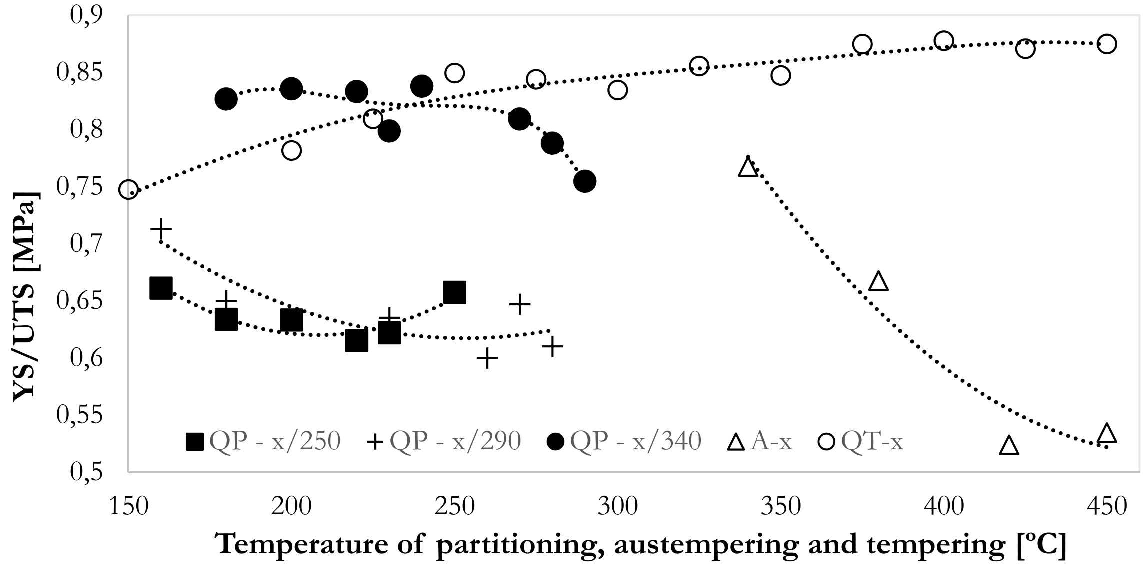

Fig. 9 *Ratios YS/UTS for individual processing routes*

The YS/UTS ratios for individual experimental processing routes are compared in Fig. 9. These results lead to several conclusions. The YS/UTS ratios were similar after both Q&P process routes in which the partitioning temperature was below the Ms. One can thus conclude that in these routes the YS/UTS profiles are very similar, regardless of the partitioning temperature. In the austempered specimens, the YS/UTS ratio increased with decreasing temperature. The likely cause of this increase was an increase in the bainite volume fraction which, in turn, minimized the volume fraction of fresh martensite or the M-A constituent and at the same time raised the amount of retained austenite, see Fig. 5. The YS/UTS ratio in QP – x/340 specimens was much higher than that in the specimens treated in routes with T_P temperatures below the Ms. At the same time, the trends in the UTS/YS evolution were similar to those observed in the austempered specimens. In the quenched and tempered specimens, the YS/UTS ratio increased with the tempering temperature.

Average UTS and YS values were compared for Q&P-processed and quenched and tempered steel. It was found that the UTSQP and YSQP values in the Q&P-processed steel were generally lower than the same parameters in the quenched and tempered steel, UTSQT, i.e. for the same partitioning temperature PT and tempering temperature TT, and comparable to the levels of UTS and YS in the austempered steel (Fig. 10). Average TE levels after Q&P processing increased with the partitioning temperature.

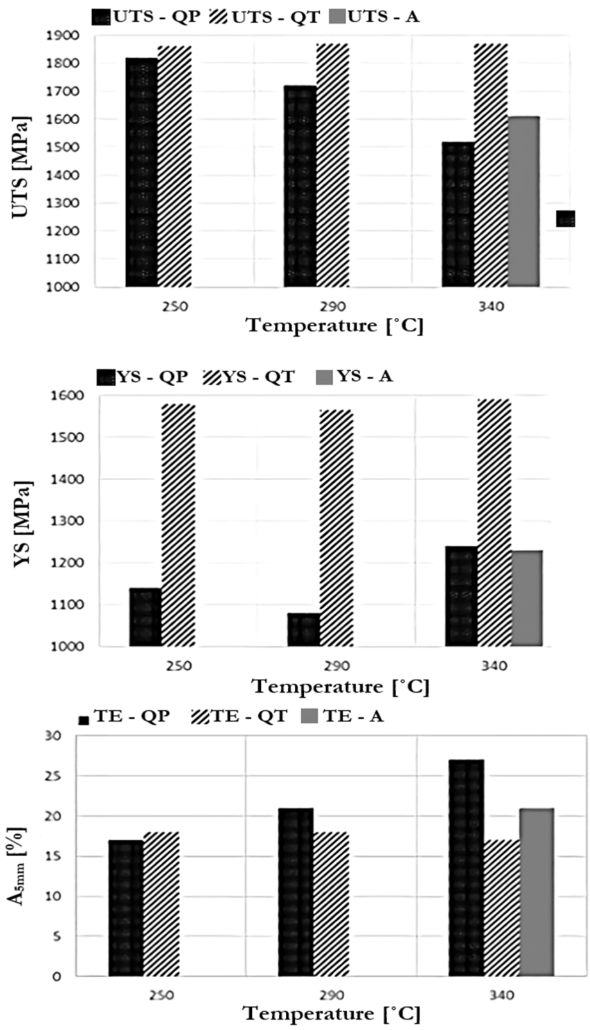

Fig. 10 *Average UTS, YS and TE values in specimens after Q&P processing, quenching and tempering, and austempering*

After Q&P processing, steel should contain a mixture of martensite and retained austenite [14,15,16]. However, the present observation revealed that Q&P processing of the experimental steel was accompanied by austenite to bainite transformation of considerable extent [18,19] (Fig. 11, 12, 13). The QP – x/340 specimens contained a mixture of tempered martensite, bainite and fresh martensite or the M-A constituent. In QP – x/290 specimens, the microstructure contained a mixture of tempered martensite, bainite and fresh martensite or M-A constituent. A similar finding was made with the QP – x/250 specimens.

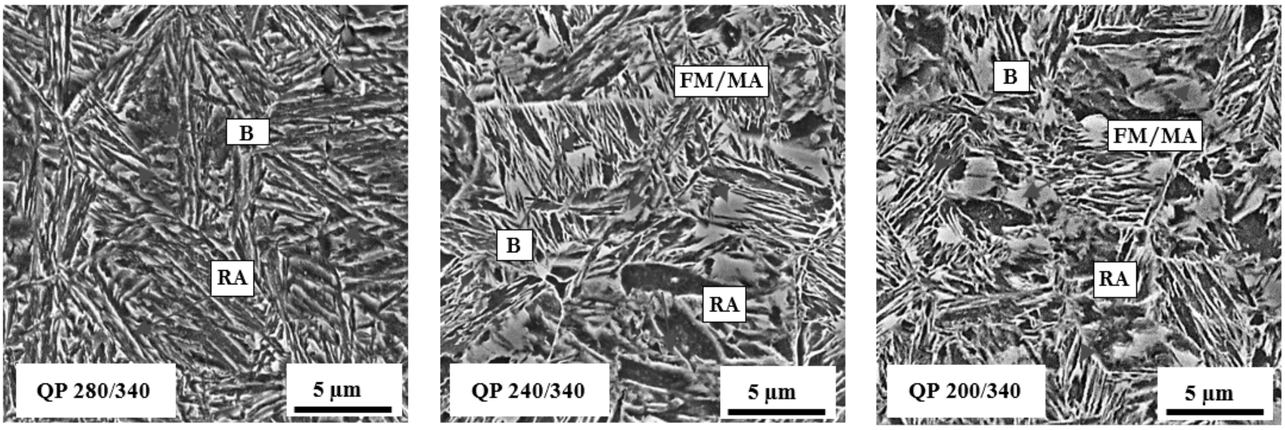

***Fig. 11** Micrographs of Q-P - x/340 specimens processed by Q&P*

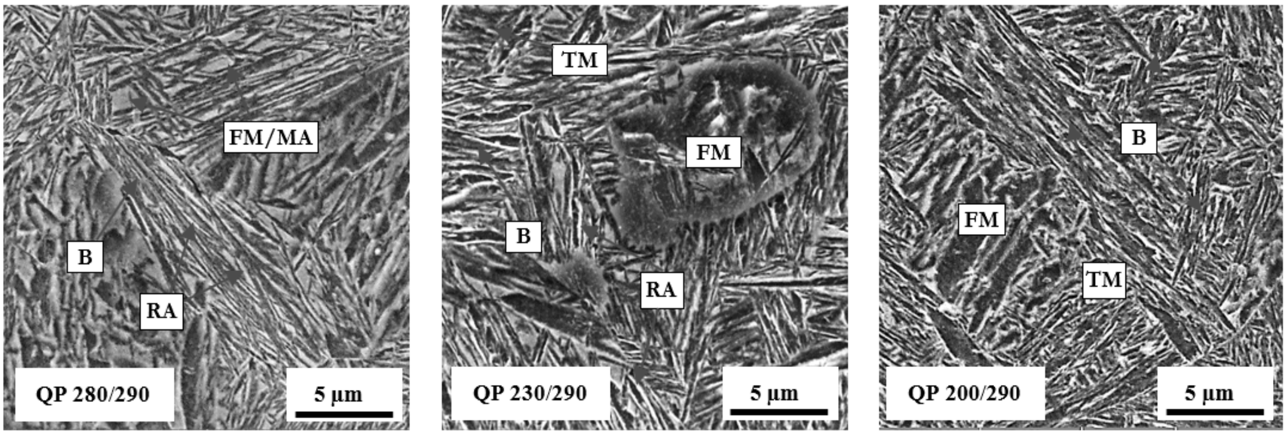

***Fig. 12** Micrographs of Q-P - x/290 specimens processed by Q&P*

B - Bainite, RA - Retained austenite, FM - Fresh martensite, TM - Tempered martensite, MA - MA constituent

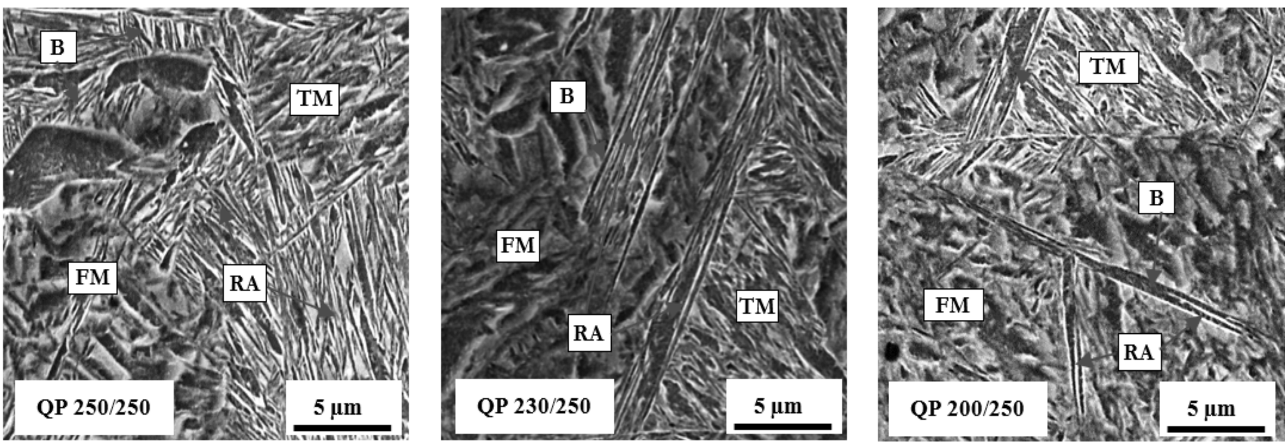

***Fig. 13** Micrographs of Q-P - x/250 specimens processed by Q&P*

B - Bainite, RA - Retained austenite, FM - Fresh martensite, TM - Tempered martensite

The reason for the presence of bainite in the Q&P-processed experimental steel is the probable catalytic effect of martensite and its growth upon an increase in the nucleation potential of bainite. The presence of bainite was linked to locations along austenitic grain boundaries as well as the interior of austenite grains (Fig. 14). The amount of bainite depended on the quenching temperature T_Q and on the partitioning temperature T_P. In general, the volume fraction of bainite decreased with increasing volume fraction of martensite that formed during the stage of quenching.

As an additional information the distribution of alloying elements in the presumed bainitic constituent was studied using chemical analysis (Fig. 14). Given the principles of bainitic transformation, major attention was devoted to carbon and silicon partitioning. As for the changes in carbon levels, it should be noted that the measurement readings do not accurately represent the carbon content in steel but that the variation in concentration between measured locations represents the relative carbon distribution within the microstructure. Results of the analyses suggest an important conclusion. Bainitic transformation, which is very probably catalyzed by preceding martensite transformation of a part of austenite during the quenching stage, is accompanied by carbon partitioning between bainitic ferrite and austenite. Thus, the stabilization of austenite in the microstructure of the experimental is most probably enhanced to a great extent by the bainitic transformation. The presence of stabilized austenite and bainitic ferrite is very likely to have a significant impact on the deformation characteristics of the experimental steel.

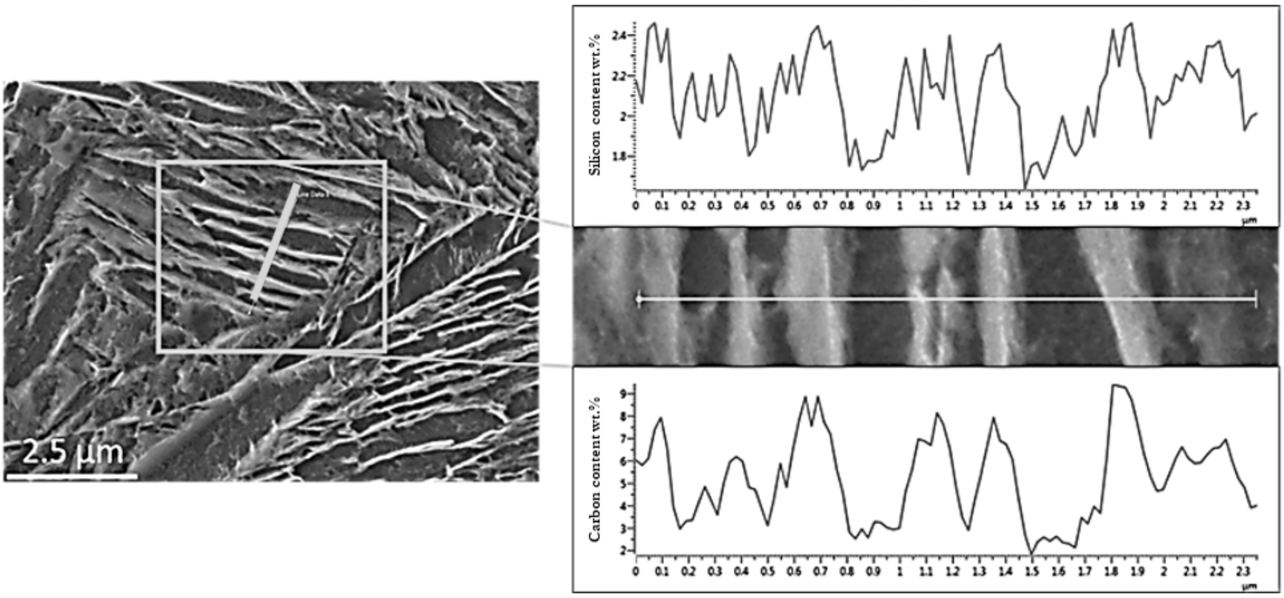

Fig. 14 *Silicon and carbon distribution in weight percents in the presumed bainitic constituent of the microstructure – specimen QP 250/250 (line EDS analysys was used for determination of alloying elements content)*

4 Conclusion

The present paper explores the effect of Q&P process parameters on the microstructural evolution and evolution of mechanical properties in 42SiCr medium-carbon steel. The evolution of mechanical properties and microstructure was studied with respect to Q&P process parameters. Mechanical properties were compared in Q&P-processed, quenched and tempered, and austempered specimens. The experiments led to the following conclusions:

UTS and YS values after Q&P processing represent a transition stage of the UTS and YS values in steel which was quenched and tempered at a temperature corresponding to the partitioning temperature in the Q&P process, and the values of UTS and YS in austempered steel. TE values increase with increasing partitioning temperature TP.

The fact that UTS and YS in Q&P-processed steel are lower than in quenched and tempered steel is related to the presence of bainite in the Q&P specimens. This conclusion was confirmed using the microstructure analysis.

The partitioning stage of Q&P processing of medium-carbon 42SiCr steel is accompanied by austenite to bainite transformation. The extent of the transformation depends on the quenching temperature T_Q and on the partitioning temperature T_P. The quenching temperature T_Q affects the amount of martensite formed during quenching; the presence of martensite most likely increases the nucleation potential of bainite which therefore forms even below the Ms temperature of the experimental steel. The volume fraction of bainite decreases with the T_Q temperature. With increasing partitioning temperature Tp, the amount of bainite increases, with respect to the T_Q temperature.

The presence of bainite is associated with austenitic grain boundaríes but growth of bainite sheaves was observed within austenite grains as well.

Bainitic transformation which occurs during Q&P processing of the experimental steel is accompanied by appreciable partitioning of carbon between bainitic ferrite and retained austenite, even at processing temperatures below the Ms. Because of the nature of bainitic trasnformation, Q-P procesing leads to the migration of carbon in to the surroundings of bainitic ferrite. The partition of carbon between banitic ferrite and retained austenite can be the dominant mechanism of stabilization of retained austenite in the microstructure after the heat treatment process.This effect is very likely to greatly contribute to enhanced ductility of Q&P-processed specimens.

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