Effect of silicon content on microstructure of low-alloy Q&P-Processed steels

I Vorel, Š Jeniček, J Káňa, K Ibrahim, V Kotěšovec, B Mašek
University of West Bohemia, Regional Technological Institute, Univerzitní 22, Plzeň, Czech Republic
E-mail: frost@rti.zcu.cz

Abstract. Today's requirements for the design of functional parts and components demand low weight and, at the same time, high strength. There are several heat treatment methods which can satisfy such requirements. These include TRIP heat treatment, long-time low-temperature austempering, and Q&P processing. It is the Q&P processing which delivers excellent results in terms of mechanical properties and light weight. It relies on stabilising retained austenite through partitioning of carbon between martensite and austenite. The carbon-enriched austenite then becomes a ductile constituent in the otherwise brittle martensitic matrix. A precondition for successful Q&P processing consists in sufficient silicon content in the steel, which precludes precipitation of undesirable cementite. Cementite would otherwise form as a result of enrichment of retained austenite with carbon. To ascertain the usefulness of higher silicon level in steel for Q&P processing, one can compare Q&P processes in steels with various levels of this element

1 Introduction
Silicon plays an important role in the heat treatment of modern high-strength steels. It is because it affects the precipitation of carbides caused by the state of disequilibrium in steels that had been rapidly undercooled to the region of martensitic or bainitic transformation. The cause of carbide formation is therefore the thermodynamic disequilibrium and the tendency of the material to relieve it. In this context, silicon retards precipitation because the solubility of silicon in cementite is negligible. Ultimately, this should mean that carbon, which would under normal conditions take part in the precipitation of cementite and other carbides, could be able – in steels with higher silicon level – diffuse to the surrounding austenite.

One of the treatment routes that rely on the above-described principle is Q&P processing. The Q&P process is based on the concept of carbon partitioning between martensite and retained austenite so that the latter becomes stabilized [1]. Retained austenite then exists as the ductile constituent in steel, and contributes to considerable ductility of the material on the whole. The Q&P process involves quenching to a temperature below the Ms to produce a certain fraction of martensite. The amount of martensite can be controlled by adjusting the quenching temperature below the Ms. The next step is partitioning, where the steel is reheated to a temperature above the quenching temperature but still lower than the martensite start temperature Ma. During this step, carbon should diffuse between martensite and austenite, and eventually stabilize the austenite [2,3,4]. The necessary condition for this mechanism is that carbon must not form carbides during the partitioning step because it would deplete the surrounding material of carbon. In such case, austenite would not become stabilized by carbon, and the ductility of the Q&P-processed steel would diminish. This necessary condition can
be met by adding more than 1.5 wt. % silicon. Unless the steel contains a sufficient amount of silicon, the effectiveness of the Q&P process can be expected to be affected by this fact [5,6].

Figure 1. Effect of silicon content on the carbon partitioning mechanism during Q&P processing
a) low-silicon steel, b) high-silicon steel.

2 Experimental programme
The objective of this experiment was to compare the effects of silicon content on the microstructures of low-alloy steels with 0.43 % carbon, 1.33 % chromium, and 0.56–0.6 % manganese upon identical treatments involving the Q&P process (Table 1).

| Steel designation | C  | Si   | Mn  | Cr   | Mo  | Nb  | P   | S   | M_s [°C] | M_f [°C] |
|-------------------|----|------|-----|------|-----|-----|-----|-----|----------|----------|
| 42SiCr            | 0.42 | 2.03 | 0.56 | 1.33 | 0.16 | 0.03 | 0.005 | 0.003 | 298      | 178      |
| 42CrMo            | 0.42 | Max 0.4 | 0.6 | 1.2  | 0.15 | -   | 0.03 | 0.04 | 305      | 184      |

Heat treatment routes for Q&P processing were proposed as shown in Fig. 2. The temperatures were chosen so as to obtain approximately 50 % martensite in the microstructure upon quenching and before partitioning. The partitioning temperature was selected to be below and above the M_s temperature that had been calculated by means of the empirical equations used by the JMatPro program.

Figure 2. Experimental heat treatment sequences involving the Q&P process.

The partitioning time was 10 minutes. The experimental specimens were threaded round bars with a diameter of 8 mm. Prior to this experiment, they had been annealed at 1050 °C for 20 minutes.
Heating and cooling was carried out in a thermomechanical simulator with induction-resistance heating (Fig. 3).

Figure 3. Specimen clamped in the jaws of thermomechanical simulator.

3 Results and discussion

Microstructures of the specimens were examined using scanning electron microscopy. They were etched with 4 % picral, and 10 % Na₂S₂O₅ solution. Phase composition was examined using image analysis. For better resolution capability, the micrographs were processed by image transformation.

Figure 4. Micrograph of the 42CrMoS4 steel upon Q&P processing – Q₂₄₀°C–P₂₈₀°C/600 s
a) Mixture of tempered lath martensite (TM), and untempered lath martensite (UM) – 5000× – SEM, b) phase contrast micrograph.
Tempered martensite, untempered martensite, and bainite were identified in the specimens (Figs. 4, 5, 6, and 7) by comparing scanning electron micrographs from the specimens, and micrographs of martensitic structures from literature. In specimen 42CrMoS4-QP240/280, lath morphology was found in both tempered and untempered martensite (Fig. 4). Close examination of the microstructure revealed the presence of fine carbide precipitates. Specimen 42CrMoS4-QP240/340 contained laths of tempered martensite and, most probably, lower bainite as well. The latter, however, was impossible to distinguish from the former due to their close resemblance (Fig. 5). The comparison of specimens 42CrMoS4-QP240/280 and 42CrMoS4-QP240/340 led to an important conclusion that all austenite had transformed during the partitioning stage – most probably to a bainite-type structure due to the low silicon content in the material.
Specimen 42SiCr-QP240/280 contained tempered and untempered lath martensite (Fig. 6). Unlike in specimen 42CrMoS4-QP240/340, the increased partitioning temperature in specimen 42SiCr-QP340 did not cause austenite to decompose into a bainite-type structure. Here, austenite remained present until the last step of the experimental sequence, and eventually transformed to martensite during quenching (Fig. 7). Close examination of the microstructures of specimens 42SiCr-QP240/280 and 42SiCr-QP240/340 did not prove that carbide precipitates were present, unlike in the 42CrMoS4 steel – which can be explained by the above-discussed higher level of silicon in 42SiCr.

![Micrograph of the 42SiCr steel upon Q&P processing-QP240°C-P340°C/600 s](image)

**Figure 7.** Micrograph of the 42SiCr steel upon Q&P processing-QP240°C-P340°C/600 s. a) Mixture of tempered lath martensite (TM), and untempered lath martensite (UM) – 5000× – SEM, b) phase contrast micrograph.

4 Conclusion

The effect of silicon level on microstructural evolution during Q&P processing was examined in low-alloy steels that contained 0.42 % carbon, and very similar levels of manganese and chromium. The steels were quenched to the temperature that should provide approximately 50 % martensite in the resulting microstructure. The subsequent partitioning step took place below and above the Mₐ. In those specimens of the 42CrMoS4 and 42SiCr steels that were subjected to partitioning below the Mₐ, the resulting microstructure contained a mixture of tempered and untempered lath martensite. Fine carbide precipitates were found in the 42CrMoS4 steel which had low silicon level. Partitioning above the Mₐ led to differences in the microstructural evolution in the experimental steels. The microstructure of 42CrMoS4 probably comprised a mixture of tempered martensite and lower bainite formed by the decomposition of untransformed austenite during partitioning. On the other hand, the microstructure of 42SiCr – which had a high silicon level – consisted of tempered and untempered martensite.

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