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Editorial

Advanced High-Strength Steels by Quenching and Partitioning

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1. Introduction and Scope

Quenched and partitioned (Q&P) steels are recently developed materials with carefully selected chemical compositions and multiphase microstructures resulting from precisely controlled heating and cooling processes. The concept of quenching and partitioning process was first proposed in 2003 by Speer et al. [1]. In 2009, they appeared on a production line of Baosteel and were successfully commercialised in 2012 in other steel companies [2]. The key treatment parameters include annealing temperature, quenching temperature, partitioning temperature, and time. The careful control of these parameters, along with the steel chemistry, leads to a variety of multiphase microstructures showing a wide range of properties.

The principles of microstructural design in Q&P steels for improvement of their mechanical strength with no (or very low) reduction of tensile ductility have been understood to a satisfactory level by now. However, the steel performance for a specific industrial application is not governed just by its mechanical strength and ductility under uniaxial tension. Enhanced mechanical properties need to be combined with improved performance properties (such as impact resistance, hydrogen embrittlement resistance, etc.), which have been studied to a lesser extent.

This Special Issue presents a collection of research articles addressing the experimental design of industry-relevant Q&P-based processes, microstructural design in the Q&P treated steels via appropriate alloying strategy and/or varying the Q&P treatment parameters, and the Q&P process–microstructure–properties relationship. Special attention is paid to the stability of retained austenite, which is shown to play a key role in plastic deformation, thus determining the mechanical behaviour of Q&P-treated steels. The contributions to the Special Issue are summarised below.

2. Contributions

Three articles focus on the development of industry-relevant processes consisting of thermo-mechanical rolling, followed by direct quenching and partitioning (DQ&P). The article by Tang et al. [3] presents a process based on asymmetric hot rolling, followed by a DQ&P process. It was applied to a Fe-0.2C-1.5Mn-1.3Si-0.2Al (wt.%) steel, resulting in the formation of an ultrafine-grained microstructure with an excellent combination of the ultimate tensile strength of ~1000 MPa and total elongation of ~35%, and enhanced work-hardening behaviour. This was related to higher volume fraction and the higher stability of film-like retained austenite located between martensite laths. A similar process was applied by Wu et al. [4] to a Fe-0.2C-0.68Si-1.75Mn-0.06Nb (wt.%) steel. It was demonstrated that the DQ&P process refined retained austenite, promoting the TRIP effect and toughness of the grade, in comparison to the alloy without Q&P treatment. The process proposed by Kantanen et al. in [5] was designed for the industrial hot strip production of Fe-0.3C-2.0Mn-0.6Si-1.1Al-2.2Cr and Fe-03C-1.9Mn-1.0Si-1.0Cr (wt.%) steels. The positive effect of DQ&P on the volume fraction of retained austenite, tensile mechanical behaviour, and impact

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toughness was shown. However, it was concluded that the practical implementation of the DQ&P process on a hot strip mill may be challenging due to the sensitivity of the mechanical properties to the quenching temperature.

Other articles focus on the microstructural design in steels via Q&P treatment to improve their mechanical and in-use properties. In the article by Chen et al. [6], the effect of initial microstructure (i.e., before Q&P treatment) on the microstructure and tensile mechanical properties of a Q&P-treated Fe-0.19C-1.26Si-2.82Mn-0.92Ni (wt.%) steel was studied. It was demonstrated that the initial microstructure (ferrite–pearlite, fresh martensite, tempered martensite) affects the prior austenite grain size and Ms temperature, which, in turn, influences the optimum quenching temperature and microstructure developed after Q&P treatment using the same parameters. Therefore, the same Q&P-treated alloy with different initial microstructures can show different tensile mechanical behaviour.

Aoued et al. [7] investigated the microstructural evolution during the Q&P treatment of a model Fe-0.3C-2.5Mn-1.5Si (wt.%) by using in situ high-energy XRD, atom probe tomography, and image analysis together. Carbide-free bainite was formed within a very short range during the reheating and partitioning step, and its transformation rate and kinetics depended on the quenching temperature. A large part of carbon was trapped in martensite in the form of both $Fe_{2.6}C$ iron and segregation on lath boundaries, which was a drag on carbon partitioning from martensite to austenite. It was concluded that the carbon enrichment in austenite is determined by the competition of carbon partitioning from martensite, bainite transformation, and carbon trapping in martensite.

Vercruysse et al. [8] studied the static and dynamic tensile properties of a Q&P-treated Fe-0-2C-1.25Si-2.4Mn-0.023Al (wt.%) steel in the temperature range from −40 °C to 80 °C. The material showed excellent low-temperature tensile properties because of the high thermal stability of retained austenite, which could contribute to the transformation-induced plasticity (TRIP) effect during testing at low temperatures. However, uniform elongation significantly dropped at 80 °C due to less effective use of the TRIP effect at this temperature. Adiabatic heating during dynamic testing at −40 °C also suppressed the TRIP effect, resulting in reduced strength and ductility of the material. The key role of the stability of retained austenite in controlling the mechanical behaviour of Q&P steels was highlighted.

Arribas et al. [9] explored the effect of high partitioning temperature (550–650 °C) on the microstructure and tensile properties of four low carbon steels with different contents of Mn and Ni. The partitioning temperatures of 550 °C and 600 °C were not effective for stabilising austenite, though austenite reverse transformation at 650 °C enabled the stabilisation of a high amount of austenite in the final microstructure of grades with high Mn content alloyed by Ni. The improvement of the tensile properties obtained by the application of high-temperature cycles was not significant. The effect of alloying elements and Q&P parameters on the microstructure and tensile properties of the Q&P-treated alloys was discussed.

Wang and Huang [10] showed that the hydrogen embrittlement resistance of an ultra-high-strength Fe-0.3C-1-57Si-2.94Mn Q&P steel can be improved by applying a higher partitioning temperature (450 °C). Partitioning temperature did not affect the hydrogen trapping properties of the Q&P-treated steel. The relatively lower stability of retained austenite after partitioning at higher temperature ensured a more sufficient TRIP effect before hydrogen-induced fracture. Additionally, dislocation recovery and carbon depletion at the higher partitioning temperature reduced the flow stress of the martensitic matrix, improving its intrinsic toughness and reducing its hydrogen sensitivity.

3. Conclusions and Outlook

The articles published in this Special Issue illustrate potential benefits and challenges for the manufacturing of advanced high-strength steel grades via the Q&P process. They can be summarised in the following general conclusions:

- The Q&P process can be integrated into the manufacturing process directly after hot rolling (DQ&P process). Various steels showing enhanced mechanical properties have already been produced via this approach. Experimental results indicate that the DQ&P-processed steels exhibit better properties, compared to their counterparts without DQ&P treatment. However, the sensitivity of the microstructure and mechanical properties to quenching temperature could be a challenge for the practical implementation of the DQ&P process on industrial hot strip mills.
- Careful control of chemical composition, initial microstructure, and Q&P treatment parameters allows effective microstructural design in the Q&P steels to tune their mechanical and in-use properties. There are numerous microstructural parameters affecting the performance of Q&P steels. These include volume fraction and size of retained austenite, condition of the tempered martensitic matrix, precipitates, and most importantly, the stability of retained austenite. Control of all these microstructural parameters is the right strategy for the further development of Q&P steels for industrial applications.

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