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Influence of metastable retained austenite on macro and micromechanical properties of steel processed by the Q&P process

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ABSTRACT

By stabilising metastable austenite with a suitable morphology in a martensitic structure, it is possible to impart to multi-phase steels high ductility combined with tensile strengths exceeding 2000 MPa. One way to achieve such mixed structures consisting of martensite and retained austenite (RA) is the Q&P (quenching and partitioning) process. The resulting structure contains metastable austenite in the form of thin foils located between martensite laths or plates. The stability of austenite under mechanical loading is the essential factor contributing to the extraordinary plasticity of such materials during cold deformation. A steel with 0.43% of carbon, alloyed with manganese, silicon and chromium was chosen for the experiment described in the present paper. Using the Q&P process, a martensitic structure with 20% of retained austenite was obtained. As cold plastic deformation causes the austenite to transform, 10% cold deformation was applied after the Q&P process. This deformation reduced the RA fraction to 11%. Materials prepared by this method were examined using micro-pillar compression experiments. Using the focused ion beam (FIB) method, pillars of 3×3 μm cross-section and 8 μm length were fabricated. These were afterwards mechanically tested in situ in an electron microscope in quasi-static compression at a true strain rate of $3 \times 10^{-4}\,s^{-1}$ to different amounts of plastic strain. The experiment showed that mechanical properties of the two conditions of material differ in terms of yield strength and the strain hardening exponent. An additional metallographic analysis of structures, including the exploration of the influence of decomposition of retained austenite, was performed.

1. Introduction

In medium and high-carbon steels, very high strengths are typically achieved by inducing martensitic transformation, which is at the expense of the material's ductility. The ductility can, however, be improved subsequently, for instance, by tempering the martensitic microstructure. This, on the other hand, leads to a decline in strength. An alternative approach to controlling the properties of the material is to cause an additional microstructural phase to form. One such phase may be the retained austenite which transforms to strain-induced martensite during plastic deformation [1,2]. Its stability is an important factor, as it has a favourable impact on the strain hardening coefficient and on the strength and ductility of the material. Another factor is the austenite's ability to absorb dislocations from adjacent martensite needles, thus improving the deformation capacity of martensite during uniform deformation.

One of the techniques for preparing a microstructure of this type is a heat treatment method known as the Q&P process (Quenching and Partitioning). It is characterized by quenching the material from the austenitizing temperature to a region between M_s and M_f temperatures, where it is held to allow carbon to migrate from the oversaturated martensite to metastable austenite. As a result, the stability of austenite increases [3]. With suitable chemistry and processing parameters, ultimate strengths exceeding 2000 MPa and elongations above 10% can be achieved [4,5].

Mechanical properties of the martensitic–austenitic microstructure depend in part on the stability of its retained austenite (RA) component. Using the Q&P process, such microstructures typically contain between 10% and 15% RA. In most cases, retained austenite takes the form of thin films on the martensite lath boundaries. This sets steels treated by the Q&P process apart from TRIP steels, in which retained austenite is present in a granular form. The film morphology of retained austenite has a stronger influence on the elongation behaviour than the granular type [6]. The stability of RA depends on a number of aspects. In terms of chemical

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composition, it is the content of carbon and other alloying elements, such as manganese and silicon, which depress the M_s temperature below room temperature. The concentration of carbon in retained austenite should be higher than 1 wt.%. Where the carbon level is below 0.5 wt.%, austenite transforms to martensite very rapidly during plastic straining. By contrast, at concentrations above 1.8 wt.% austenite is very stable and survives the cold deformation [7]. Silicon is used to retard carbide precipitation and promote the diffusion of carbon to austenite. In addition to austenite stabilization, manganese improves carbon solubility in austenite and retards pearlite formation. Another suitable alloying element for Q&P steels is chromium [8]. It strengthens the solid solution, retards pearlite and bainite formation and improves the material's hardenability and resistance to tempering.

Austenite stability is also controlled by the size of its particles. The optimum size of austenite particles is in the range of 0.01–1 μm. The stability and strength of RA also depend on the surrounding phases [8,9]. Four transformation temperatures are important for the stability of retained austenite: M_s, M_s^σ and M_{d30} and M_d [8].

The M_s temperature can be determined using both experimental and empirical methods. In calculating the M_s value, a number of phenomenological models can be employed which account for the effects of alloying elements. These include, for instance, the Andrews' model [10] (Eq. (1)) and the model by Mahieu et al. [8] (Eq. (2)). As part of the development of the Q&P process, another empirical formula was constructed, taking into account the effect of the austenite grain volume V_γ [11] (Eq. (3)).

M_s^σ is the temperature below which retained austenite transforms to martensite under critical external stress. Above this temperature the transformation is induced by strain. At this temperature, the stress required to induce the transformation is equal to the yield stress of austenite. Above this temperature, the austenite undergoes deformation and the martensitic transformation is facilitated by plastic strain. In the region just above M_s^σ, the level of stress required for inducing the transformation remains constant. If the temperature rises above M_d, austenite remains stable and does not transform to martensite, regardless of plastic deformation. The M_{d30} temperature is the temperature at which 30% tensile strain causes 50% of austenite to transform to martensite. This parameter is widely used to describe the stability of austenite. It can be calculated using empirical formulas based on chemical composition [9] (Eq. (4)).

$$M_s(^\circ C) = 539 - 423C - 30.4Mn - 17.7Ni - 12.1Cr - 11Si - 7Mo \quad (1)$$

$$M_s(K) = 273 + 545.8^* e^{-1.362C} - 30.4Mn - 7.5Si + 30Al - 59.9P \quad (2)$$

$$M_s(^\circ C) = 545 - 423C - 30.4Mn - 60.5V_\gamma^{-1/3} \quad (3)$$

$$M_{d30}(^\circ C) = 413 - 462(C + N) - 9.2Si - 8.1Mn - 13.7Cr - 9.5Ni - 18.5Mo \quad (4)$$

All research efforts to date have focused on the behaviour of such microstructures on a macroscopic scale and on describing their properties. This is why the present investigation is aimed at obtaining new findings and at describing the phenomena which arise from the deformation behaviour of these materials within a microscopic volume. One of the available techniques is micro-compression testing of micro-pillars with dimensions in the order of micrometers. Thanks to the pillar size, plastic straining and fracture propagation within a few martensite needles can be monitored in the test. According to literature sources, the presence of austenite delineating martensite needles can be expected. This is why the boundaries of needles should be observed at high resolution, as they are the locations where localized deformation and failure are expected to occur. Major attention was paid to comparing the deformation behaviour of microstructures formed by Q&P processing with various amounts of strain.

2. Experimental programme

The experimental programme consisted of macroscopic-scale deformation tests and investigation of the behaviour of steels containing martensite with retained austenite using microscopic-volume specimens. The experimental materials were Q&P processed steels. Micro-pillars made from these materials were subjected to compressive deformation. The compressive loading was monitored and the pillar deformation recorded by SEM imaging.

This experiment was performed on 42SiCr steel with 0.42% carbon, alloyed with silicon, manganese and chromium (Table 1). This chemistry was selected with regard to the ability to provide sufficient stability of retained austenite, solid solution strengthening and to retard cementite precipitation and bainite and pearlite formation. The initial microstructure with a hardness of 290 HV10 consisted of pearlite and a very small proportion of ferrite. Miniature tension tests revealed the material's strength of 981 MPa and elongation of A_{5mm} = 30%.

2.1. Thermomechanical treatment

Two groups of specimens were prepared for testing using two treatment procedures in order to compare their properties: the Q&P process and Q&P + cold working. The Q&P process was carried out in a thermomechanical simulator. It consisted of austenitizing at 900 °C for 100 s and of 20-step incremental deformation with the accumulated true strain of $\phi = 5$, applied within a temperature interval of 900–820 °C. The main purpose of the applied deformation was to refine the microstructure. The deformation was followed by cooling to 200 °C, subsequent reheating to the partitioning temperature of 250 °C and holding for 600 s in order to stabilize metastable austenite by absorbing carbon which migrated from martensite. The quenching and partitioning temperatures were chosen with regard to the known M_s temperature (Table 2), which had been determined using dilatometer measurement at a cooling rate of 20 °C/s. In addition, a verification simulation was performed using the JMatPro program (Version 6.2) and an additional verification calculation was carried out with the aid of empirical models (Eqs. (1)–(3)) (Table 2). The M_{d30} temperature was verified for the chemical composition in question using Eq. (4).

The second treatment procedure comprised the same Q&P process and an additional cold working step with 10% tensile strain. The cold working reduced the amount of retained austenite because part of the RA transformed to strain-induced martensite.

Table 1
Chemical composition of the experimental steel 42SiCr.

C	Si	Mn	Cr	Mo	Nb	P	S	Ni	N	UTS R_m (MPa)	Elong A_{5mm} (%)	HV10 (–)
0.43	2	0.59	1.33	0.03	0.03	0.009	0.004	0.07	0.01	981	30	290

Table 2
M_s and M_{d30} temperatures of the 42SiCr steel, as determined by various methods.

JMatPro		Dilatometry −20 °C/s	Andrews	Mahieu et al.	Lee et al.	M_{d30} (°C)
M_s (°C)	M_f (°C)	M_s (°C)	M_s (°C)	M_s (°C)	M_s (°C)	
298	178	289	299	272	322/205	167

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