Enhanced TRIP effect in a lean alloy steel treated by a ‘disturbed’ bainitic austempering process

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ABSTRACT
A novel isothermal bainitic transformation combined with quenching and partitioning (i.e. ‘disturbed’ bainitic austempering) process was employed in an Mn–Si–Cr–C low-alloyed steel to reduce the fraction and size of the blocky martensite/austenite (M/A) islands; the M/A islands that are inevitably formed during the conventional bainitic austempering process are coarse and undesirable for property optimization. Owing to a novel heat treatment, an enhanced combination of strength and ductility was achieved (e.g. ultimate strength, ~1445 MPa; total elongation, ~28%). A pronounced TRIP effect of the refined retained austenite contributes a lot to the overall improvement.

KEYWORDS
Bainite; quenching and partitioning; mechanical properties; retained austenite; TRIP effect

Introduction
The third generation advanced high-strength steels (AHSSs) have been investigated intensively with the aim of saving resources and protecting the environment by decreasing the weight of engineering components [1,2]. To develop new AHSSs with superior properties, great attention has been paid to the bainite-assisted transformation induced plasticity (TRIP) [3,4], low-temperature bainite [5,6] and quenching and partitioning (Q&P) [7,8] steels in recent years. Generally, the multiphase system composed of austenite plus bainite and/or martensite is considered as an attractive microstructure candidate for the third generation AHSSs due to its good combination of strength and ductility [2]. Given that the volume fraction and stability of austenite are controlled properly, the mechanical properties of the multiphase microstructure can be optimized. The austenite stability is determined by its carbon concentration, grain size, morphology and the constraining effect of surrounding phases [9–11].

Essentially, the formation of isothermal bainite enriches two morphologies of austenite: first, the filmy austenite between the subunits of ferrite; second, the blocky austenite between non-parallel sheaves of bainite [12]. The blocky austenite with lower carbon content has relatively low stability and transforms partially to martensite during cooling after isothermal bainite transformation, leading to the formation of blocky martensite and austenite (M/A) island [13]. The blocky M/A islands may degrade ductility and toughness due to the poor stability of the blocky austenite and its less pronounced TRIP effect [14–16]. Therefore, some approaches (by alloy/processing design) have been proposed to reduce the amount of the blocky austenite or ideally merely obtain ultrafine filmy austenite [17,18].

By means of quenching and partitioning (Q&P) treatment, the carbon concentration of austenite can be increased due to the carbon transport from martensite to austenite [7,8]. The higher carbon content in austenite improves the austenite stability and increases the volume fraction of retained austenite. Consequently, the TRIP effect is more effective [19,20]. Based on the Q&P concept, we have developed novel Q&P and quenching–partitioning–tempering (Q-P-T) processes combined with bainite transformation (abbreviated as BQ&P and BQ-P-T) [21,22]. A refined multiphase microstructure (bainite + martensite + submicron/nanometer-sized austenite) can be obtained after the partitioning (P) and tempering (T) steps [23].

In the present work, a novel isothermal bainitic transformation process in conjunction with the Q&P idea will be presented to improve the TRIP effect through reducing the ratio of coarse blocky retained austenite.

Experimental methods
The chemical composition of the steel under investigation is 0.41C-2.05Mn-1.78Si-0.42Cr (wt.%). A 50 kg
ingot was reheated to 1200°C and forged to a 30 mm thick plate (finish-forging temperature ∼950°C). The forged plate was then annealed at 900°C followed by furnace cooling. The CCT and TTT curves of this steel were reported in our previous work [22]. Specimens, 15 × 15 × 70 mm in size, cut from the annealed plate underwent the heat treatments shown in Figure 1. A conventional isothermal bainitic transformation process (i.e. bainitic austempering) was carried out to obtain the BAT sample (Figure 1(a)); after austenitization at 880°C for 45 min, the specimen was cooled down to 360°C at 1°C/s (without bainite transformation during cooling [22]), and austempered for 120 min (to ensure a sufficient long period for isothermal bainite transformation). As a comparison, a novel isothermal bainitic transformation combined with quenching and partitioning (i.e. 'disturbed' bainitic austempering) was conducted to obtain the DBAT sample (Figure 1(b)). The difference between DBAT and BAT lies in the disturbance of the bainitic austempering by a sudden quenching to 100°C (below the Ms temperature of untransformed austenite) after isothermal holding at 360°C for 75 min (the bainitic transformation is extremely sluggish after 75 min as is discussed later), followed by partitioning at 360°C for 45 min (like a Q&P process) after isothermal holding at 360°C for 75 min (the isothermal bainitic transformation is extremely sluggish beyond 75 min). By combining it with the Q&P process, the whole bainitic austempering process seems to be ‘disturbed’.

Microstructures were characterized on a scanning electron microscope (ZEISS EVO18, 20 kV) after conducting mechanical polishing and etching in a 2% nital solution. The ultrafine retained austenite was identified by a transmission electron microscope (JEOL 2010F, 200 kV) using thin foil samples electropolished at −40°C in 4% perchloric acid solution. The volume fraction of retained austenite (RA vol.%) was measured by X-ray diffractometer (Rigaku Smartlab, Copper Kα radiation) at a step of 0.01° and a counting time of 2s/step using Ø10 × 2 mm cylindrical specimens. The Rietveld analysis with MAUD software was used for calculation based on diffraction data. The RA vol.% was estimated using the peak intensities of (200)γ, (220)γ, (311)γ, (200)α and (211)α. The austenite lattice aγ was obtained by Nelson–Riley extrapolation method. The carbon concentration xγ of retained austenite can be estimated according to the relationship between aγ and xγ as reported elsewhere [11].

In order to capture the microstructure evolution during BAT and DBAT treatments, dilatometric measurements were carried out using 4 mm diameter × 10 mm cylindrical specimens on a Bähr D805L quenching device installed with quartz push-rods. The temperature was monitored by a type-S thermocouple spot welded on the specimen surface. Nitrogen (N2) was used as a quenching medium.

Results and discussions

Figure 2 shows the SEM images of the BAT and DBAT microstructures (as abbreviated in Figure 1). The conventional BAT microstructure is composed of lath-shaped bainite and blocky M/A islands (Figure 2(a)). The lath-shaped bainite that is formed during austempering at 360°C contains bainitic ferrite and filmy austenite [22]. Hence, the untransformed austenite during bainitic austempering (i.e. isothermal bainite transformation) exhibits two morphologies: blocky and filmy. During quenching after austempering, the blocky austenite with lower carbon content transforms partially to martensite and leads to the formation of M/A islands. On the other hand, the lath-shaped bainite formed during austempering is also observed in the DBAT variant. However, the volume fraction and size of blocky M/A islands are greatly reduced (Figure 2(b)). The prior blocky M/A islands (e.g. ∼5 μm, as indicated by the red circle in Figure 2(c)) are mostly divided into filmy retained austenite (RA) ∼0.2 μm wide and carbon-depleted martensite (Mf) plates. The TEM image of the DBAT variant further confirms that some newly formed martensite lathes (∼50 nm width) are located between thin filmy austenite.

Figure 3 shows the relative length change of the dilatometry specimens (ΔL/L0, where ΔL is the length change, L0 is the initial length). The specimen expansion at 360°C indicates the occurrence of isothermal bainite transformation during austempering (Figure 3(a)). However, the ΔL/L0 change becomes negligible (implying the end of bainitic ferrite transformation) when the austempering time exceeds 75 min. The Ms temperature of the untransformed austenite after austempering for 75 min is ∼225°C (Figure 3(c)), while it is reduced to ∼125°C if the austempering time is prolonged to 120 min (Figure 3(b)). It indicates that carbon diffusion from bainitic ferrite into untransformed austenite and/or carbon homogenization in the austenite still proceeds after the bainitic ferrite formation ceases. During the isothermal bainitic transformation, the carbon concentration gradient may be present in the blocky untransformed austenite [12,24]; the carbon concentration of the blocky austenite near the bainitic ferrite/austenite interface could be higher than that of the block interior. When the carbon concentration of blocky austenite reaches T0 (i.e. the free energy of austenite is equal to that of...
ferrite [25]), the formation of bainitic ferrite stops. At this point, the carbon concentration inside the blocky austenite is relatively low (suggested by the relatively high \( M_t \) after austempering for 75 min). With the increase in holding time, the carbon concentration gradient in the blocky austenite tends to make the carbon near the bainitic ferrite/austenite interface diffuse into the interior of blocky austenite (carbon homogenization in austenite). The average time required for carbon diffusion in ferrite (e.g., from bainitic ferrite to austenite) and austenite (carbon homogenization in austenite) can be estimated by the equation [26]:

\[
\tau = \frac{x^2}{6D}
\]

where \( x \) is the average diffusion distance (here defined as the half-width of bainitic ferrite laths and austenite blocks, namely \( x = 0.5 \mu m \), \( x = 2.5 \mu m \)) and \( D \) is the diffusion coefficient of carbon which equals \( D_0 \exp(-Q/RT) \), where \( D_0 \) is a constant \( (D_{0v} = 0.62 \times 10^{-6} m^2/s, D_{0y} = 0.10 \times 10^{-6} m^2/s \) [26])), \( Q \) is the activation energy of carbon diffusion \( (Q_o = 80.4 kJ/mol, Q_y = 135.7 kJ/mol \) [26]), \( R \) is the gas constant, and \( T \) is the absolute temperature. It is known from the calculation that the carbon diffusion from bainitic ferrite to austenite occurs within 0.3 s, while it takes more than 4 h to accomplish carbon homogenization in the blocky austenite during austempering at 360°C. Therefore, the residual carbon in bainitic ferrite can compensate the carbon loss of the austenite near the bainitic ferrite/austenite interface (caused by the carbon diffusion into the interior of blocky austenite during the above-mentioned carbon homogenization in austenite). Consequently, the carbon concentration of austenite near the interface \( (T_0) \) is maintained and the bainitic ferrite formation is suppressed (also reflected by the negligible \( \Delta L/L_0 \) change during austempering within 75–120 min). In addition, the carbon concentration inside the blocky austenite is relatively low due to the slow carbon diffusion in austenite at 360°C, unless much longer holding periods are applied.

During the DBAT treatment, the interior part of the untransformed blocky austenite after austempering for 75 min at 360°C partially transforms to martensite when quenched to 100°C (lower than the \( M_s \) 225°C). The martensite subunits can divide the blocky austenite (as shown by the \( M_2 \) in Figure 2) and shorten the carbon diffusion path in austenite. Therefore, the carbon homogenization in the blocky austenite is accelerated correspondingly during subsequent partitioning after the ‘disturbed’ quenching. Simultaneously, carbon-depleted martensite and carbon-enriched retained austenite (denoted by \( M_2 \) and RA in Figure 2) are obtained after final quenching [7,8]. It should be noted that martensite formation is not detected during the final quenching step after partitioning (Figure 3(d)). It further indicates that the untransformed austenite after the DBAT treatment is highly enriched with carbon and hence retained to room temperature. Most importantly, the coarse blocky M/A islands are effectively eliminated by the DBAT treatment.

The volume fraction and average carbon concentration of RA in the DBAT sample (25 vol.% and 1.31 ± 0.05 wt.%) are higher, compared to the BAT sample (22 vol.% and 1.19 ± 0.04 wt.%). This indicates that the carbon diffusion from the body-centered cubic phase (bcc: bainitic ferrite and/or martensite) into the face-centered cubic phase (fcc: untransformed austenite) at 360°C is enhanced by the novel DBAT treatment. As a result, the austenite stability is improved.

The tensile properties of the BAT and DBAT samples are listed in Table 1. Compared with the BAT variant, the DBAT sample shows a slightly lower ultimate strength but a much higher elongation. Besides, the average product of strength and elongation is increased to 40.3GPa% (~26% higher than the BAT sample). From the true stress-true strain curves and the corresponding strain hardening rate in Figure 4, we know that the working hardening capacity of the DBAT sample is greatly improved within a wider strain range. This is attributed to the pronounced TRIP effect of RA and microstructure optimization.

Table 1. Tensile properties of the BAT and DBAT samples.

| Sample | Rm, MPa | Rp0.2, MPa | UE, % | TE, % | PSE, GPa% |
|--------|---------|------------|------|-------|-----------|
| BAT    | 1505 ± 7| 1218 ± 9   | 13.5 ± 0.9 | 21.2 ± 0.8 | 31.9 ± 1.2 |
| DBAT   | 1445 ± 10 | 825 ± 15  | 22.5 ± 0.3 | 27.9 ± 0.5 | 40.3 ± 0.8 |

Notes: Rm, ultimate strength; Rp0.2, yield strength; UE, uniform elongation; TE, total elongation; PSE, product of strength and elongation.
(e.g. refinement, ductile phase introduction). Three aspects can be used to explain this phenomenon: (i) due to the more complete carbon enrichment in the untransformed austenite during the partitioning step of DBAT treatment (i.e. the second isothermal holding step), a higher total volume fraction of RA with a higher average carbon content is obtained after the DBAT treatment, which ensures a sufficient TRIP contribution to working hardening capacity at large strains; (ii) the prior coarse blocky M/A islands (∼5 μm) formed together with the isothermal bainitic ferrite formation in the BAT sample are replaced by the submicron-sized filmy retained austenite and carbon-depleted martensite in the DBAT sample (Figure 2). Compared to the blocky austenite, the filmy austenite possesses higher carbon concentration and hence higher stability that not only exhibits TRIP effect at larger strains [27], but also acts as ultrafine microstructure units to suppress crack propagation [22]; (iii) the carbon-depleted martensite formed during the partitioning step of DBAT treatment is more ductile than the martensite constituents of the coarse blocky M/A islands in the BAT sample [10]. The hard martensite may reduce the stability of RA around it due to its constraining effect on the strain distribution [9]. The austenite dispersed in a soft carbon-depleted martensite

![Figure 2](image) SEM images of the (a) BAT and (b) DBAT microstructures, (c) magnified DBAT microstructure, and (d) TEM image of the DBAT microstructure; B: bainite, M/A: martensite/austenite, M2: carbon-depleted martensite, RA: retained austenite.

![Figure 3](image) The relative length change ($\Delta L/L_0$) of dilatometry specimens. (a) $\Delta L/L_0$ versus isothermal holding time showing bainitic ferrite formation at 360°C is finished after a holding period of 75 min; $\Delta L/L_0$ versus temperature during (b) BAT treatment and (c) DBAT treatment; (d) Enlarged window of the dashed rectangle in (c).
matrix may contribute much to work hardening at large strains [28].

Additionally, the DBAT sample exhibits a relatively low yield ratio (R\text{p0.2}/R\text{m}, ∼0.57) that is beneficial for the stamping formability of steel sheets [28–30]. The amount of soft bcc phases is increased due to the introduction of carbon-depleted martensite; the carbon atoms in the bcc phases are more completely released into the fcc austenite phase.

Summary

In summary, a novel ‘disturbed’ bainitic austempering process is presented to yield a pronounced TRIP effect in a lean alloy steel. Due to the combination of isothermal bainitic transformation, quenching and partitioning, the micron-sized blocky austenite has been successfully converted to submicron-sized filmy austenite and carbon-depleted martensite. Hence, the overall microstructure is refined. The refined filmy retained austenite with higher stability (also at a higher volume fraction) and the ductile martensite effectively improve the work hardening capacity of the material.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Figure 4. True strain-true stress curves and corresponding strain hardening rate curves of the BAT and DBAT samples.
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