



High hardness and retained austenite stability in Si-bearing hypereutectoid steel through new heat treatment design principles

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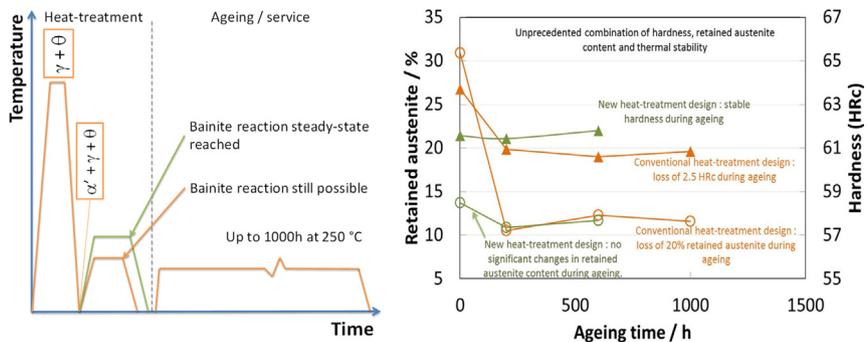
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HIGHLIGHTS

- Quenched-in retained austenite in Si-bearing hypereutectoid steel can transform via a bainitic mechanism at low temperatures ($\geq 200^\circ\text{C}$).
- A new heat-treatment accounting for bainitic reaction leads to unprecedented microstructural stability in a 1C-1.5Cr-1.2Si-1.2Mn wt% steel.

GRAPHICAL ABSTRACT



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ABSTRACT

Austempering, and quenching and tempering heat treatments of high Si hyper-eutectoid steels are investigated using both dilatometry and salt-bath heat treatments. Changes in retained austenite content are measured using X-ray diffraction. Results are compared to the prevailing theory for bainite formation and published data. From the understanding of retained austenite evolution during tempering, a novel heat treatment is designed which is technologically identical to quenching and tempering with the exception that the principles guiding the selection of tempering temperature and duration are different. This heat treatment is shown to lead to a combination of hardness, retained austenite content and thermal stability entirely unprecedented for this category of alloys. In addition, this result is achieved for heat treatment durations that can be considered standard. In comparison, low temperature austempering is shown to require considerably longer holding durations to achieve somewhat lower combinations of hardness and retained austenite content.

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1. Introduction

Hypereutectoid steels such as 100Cr6 (AISI 52100, a 1C-1.5Cr wt% steel) are widely used for the manufacturing of high performance bearings [1] or other components for which high hardness is paramount (e.g. parts for continuously variable transmissions). They are typically given their final properties through a quenching

and tempering heat treatment carried out from a spheroidised microstructure. The latter consists of ferrite and relatively large globular carbides ($\approx 1\ \mu\text{m}$). During the austenitising stage, these carbides are in equilibrium with austenite. Changing the austenitising temperature is therefore a simple mean to control austenite carbon content (see for example calculations in [2]). Depending on austenitising temperature (austenite carbon content), the martensite start temperature can reach relatively low values ($\approx 125^\circ\text{C}$). In turn, this can result in the presence of a significant fraction of retained austenite at room temperature (10–30%).

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On the one hand, retained austenite is often undesirable in standard 100Cr6 steel (1C-1.5Cr wt%) because of its low thermal and mechanical stability. Indeed it is susceptible of rapid decomposition (a few hours) at temperatures as low as 200 °C [2–5]. At lower temperatures, it could presumably decompose over significantly longer durations, which however need to be compared to an expected service lifetime of perhaps thousands of hours. The volume and hardness changes accompanying the decomposition of only a few percents retained austenite are not acceptable in many applications.

On the other hand, 100Cr6 heat-treated to a hardness in excess of 61 HRc exhibits virtually no tensile ductility [1,6]. From the perspective of ductility and damage tolerance, the introduction of a fraction of retained austenite has long been seen as beneficial. In the late 1990s, a modified version of the standard 100Cr6 was developed, which was designed to exhibit higher retained austenite contents [3,7–9] after standard heat treatments. This was achieved through Mn additions (lowering of the martensite start temperature), while Si additions helped further stabilise retained austenite. Indeed, Si additions have been shown to continuously increase the tempering temperature at which full austenite decomposition was achieved, when using fixed tempering durations [2,3]. For example, with an addition of 0.6 wt% Si, full decomposition of the retained austenite present after quenching was found to occur only for tempering temperatures in excess of 250 °C. As mentioned earlier, this temperature is of ≈ 200 °C for a standard Si content of 0.3 wt% in 100Cr6. In parallel, Si additions help reduce hardness loss during tempering [2,3,10].

Since martensite formation proceeds without diffusion, retained austenite composition at the end of quenching is that dictated by the equilibrium with cementite at the austenitising temperature. Its carbon content is thus typically only slightly less than the nominal composition (since austenitising is normally carried out below the carbides dissolution temperature). The tempering of the as-quenched microstructure is therefore entirely analogous to the partitioning step used in the quenching and partitioning heat treatments developed for steel sheets [11–13]. For the purpose of clarity however, the terms quenching and tempering are used throughout, in preference over quenching and partitioning. From a microstructural point of view however, both denominations would be equally valid.

In this context, three main phenomena may be expected to compete during tempering, as illustrated in Fig. 1. These include precipitation of cementite or transition carbides in martensite, carbon partitioning from martensite to the retained austenite, and bainite formation within the retained austenite. The possible formation

of fresh martensite from the austenite during final cooling is not mentioned. Although this is a well-known issue in low carbon steels (0.1–0.3 wt%), formation of fresh martensite during final cooling has not been observed in high carbon, high Si steels [14], even in the context of austempering treatments.

Works on low temperature austempering of high carbon high silicon steels [6,14–23] provide a wealth of information on the kinetics of bainitic decomposition of austenite in the range of temperatures 125–350 °C. In the above cited research, materials not unlike Si-added 100Cr6 are austenitised then rapidly cooled to the transformation temperature. They are then held at this temperature to allow development of a mixture of very fine bainite laths with retained austenite. As indicated in all the above references, the duration to reach steady-state for the bainite reaction is typically greater than 20 h at a temperature of 250 °C. The transformation duration can furthermore exceed 100 h for lower temperatures, although it can be as low as 1 h at 350 °C.

Conventional tempering temperatures for hyper-eutectoid steels heat treated to high hardness are typically within 160–230 °C. Therefore, the bainite reaction taking place in the austenite left after quenching can be expected to occur over extended durations (tens if not hundred of hours). It is possible that pre-existing martensite shortens the required duration for bainitic decomposition [24], although in all likelihood, this will not be sufficient to reach steady-state with conventional tempering durations.

Furthermore, partitioning from pre-existing martensite to retained austenite is known to compete with the bainitic transformation [25]. In a lower carbon material (0.3C-2.5Mn-1.5Si-0.8Cr wt%), recent in-situ investigations have shown that carbon partitioning from martensite was the dominant contributor to retained austenite stabilisation (at 400 °C). In other words, for these conditions, austenite stabilisation was primarily due to carbon partitioning from pre-existing martensite rather than carbon rejected during the bainitic reaction. However, at low temperatures such as those used for tempering of bearing steels, it has been suggested that carbon partitioning from martensite was not as efficient [12]. A similar situation is now well documented for low temperature austempering of high carbon, high silicon steels. For these materials, significant ferrite supersaturation has been reported for transformation temperatures as high as 350 °C. This implies a lesser austenite carbon enrichment for a given fraction of bainitic ferrite [26–28].

In summary, the interplay between bainite transformation and carbon partitioning has been largely investigated for lower carbon steels at somewhat higher temperatures (0.1–0.3 wt%, typically 300 °C and above). There is however a significant lack of data when

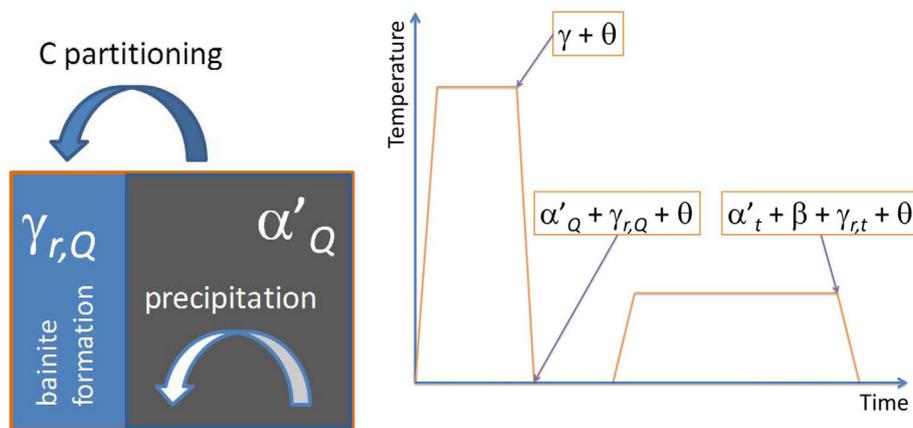


Fig. 1. Schematic illustration of the different phenomena likely to occur during tempering of austenite present at the end of quenching in hypereutectoid steels. The austenite retained at the end of quenching, denoted $\gamma_{r,Q}$ is susceptible of transformation to bainite (β), leading to a lower fraction $\gamma_{r,t}$ after tempering. At the same time, carbon may partition from pre-existing martensite (α'_Q) or precipitate within the latter, so that martensite at the end of tempering (α'_t) must be distinguished from that after quenching.

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