



## Two-step austempering of high performance steel with nanoscale microstructure



Behzad Avishan<sup>a,\*</sup>, Majid Tavakolian<sup>b</sup>, Sasan Yazdani<sup>b</sup>

<sup>a</sup> Department of Materials Engineering, Azarbaijan Shahid Madani University, Tabriz, Iran

<sup>b</sup> Faculty of Materials Engineering, Sahand University of Technology, Tabriz, Iran

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### ABSTRACT

It is crucial to eliminate the thermally and mechanically less stable austenite blocks as much as possible if enhanced mechanical properties are demanded in high performance nanostructured bainitic steels. Step-austempering would be an efficient procedure in this regard. This article aims to investigate the strength-ductility- impact toughness combinations in nano-bainite after two-step austempering process comparing with those obtained after conventional isothermal bainite transformation. It has been shown that large austenite blocks further decomposed to bainite after step-austempering process which in turn decreased the average volume fraction of austenite, increased its mechanical stability and generally refined the final microstructure. Step-austempering increased the hardness value and enhanced the yield strength and ultimate tensile strength properties. Additionally, the higher mechanical stability of retained austenite in step-austempered samples increased the elongation level and improved the impact toughness at earlier stages of the second step of transformation. The important point is, it has been found that ductility and toughness properties were influenced by transformation time at the second stage of austempering which approved the idea that not only the mechanical stability and morphology of retained austenite but also its volume fraction must be taken into account when applying a multi-step austempering heat treatment in nanobain steels.

### 1. Introduction

Carbide free bainitic steels can be obtained at very low temperatures and there is no thermodynamic limit for bainite transformation to occur even at room temperature although it would take so long to be completed [1–4]. Accordingly, a new generation of high-performance steels, known as nanostructured low temperature bainite, has been introduced which can be obtained through a single-stage austempering heat treatment of high carbon steel at temperatures lower than 300 °C but above the martensite start temperature ( $M_s$ ) of the bulk material [5–11]. The key point is, the  $M_s$  temperature must be as low as possible to make it probable to conduct the bainite transformation at a very low temperature which consequently refines the microstructural constituents. Therefore, it is essential to use high carbon content to increase the hardenability and to decrease the  $M_s$  temperature. The resultant microstructure contains nanoscale ferrite plates of almost less than 150 nm thicknesses and high carbon retained austenite those of which make it possible to achieve incredible strength and ductility combinations [12–16].

Bainite transformation never goes to completion and stops when

the carbon content of retained austenite reaches to that of predicted by  $T_0$  diagram [4,17,18]. Then, high carbon retained austenite remains stable at room temperature in two filmy and blocky morphologies, later being thermally and mechanically less stable [19,20]. Increasing the transformation temperature results in higher amount of high carbon retained austenite and consequently more austenite blocks within the microstructure [21]. The volume fraction, morphology and stability of the retained austenite not only influence the ductility of nanostructured bainite but also affect the strength properties through the TRIP effect occurrence during straining the sample. Therefore, the preference is to decrease the volume fraction and size of the austenite micro blocks and replace it with austenite films as much as possible to improve the mechanical response of the material [22]. If higher volume fraction of bainite forms within the microstructure, it would then consume more austenite and consequently decrease the volume fraction and size of the austenite blocks which is desirable. This could be applied by conducting the bainite transformation at lower temperatures or decreasing the mean carbon content of the bulk material [4,23] or by refining the primary austenite grain size as it has been demonstrated before [20].

However, there is another approach in which multi-step bainitic

\* Corresponding author.

E-mail address: [avishan@azaruniv.ac.ir](mailto:avishan@azaruniv.ac.ir) (B. Avishan).

transformation can be implemented in order to further decompose the residual austenite to bainite by decreasing the transformation temperature in every next stage of austempering. In a very early work, Papadimitriou and Fournalis [24] studied the crystallographic and microstructural characteristics of bainitic reaction in high carbon silicon rich steel after two-step isothermal heat treatment and it has been shown that conducting the bainitic heat treatment in two consecutive stages resulted in two different generations of bainitic ferrites and those obtained at second heat treatment stage at lower temperature were thinner. From that time, different studies have been conducted to investigate the bainitic reaction after step-austempering heat treatment emphasizing on the microstructural and mechanical properties evaluations, but mostly focusing on low and medium carbon steels. Long et al. [25] conducted a two-stage isothermal cooling on low carbon steel to obtain low-temperature bainite and they have demonstrated that enhanced comprehensive mechanical properties could be acquired compared to that of obtained through a single stage heat treatment due to the thinner bainitic ferrites and different volume fractions of austenite. In another work, Long et al. [26] explored the effect of single and two-step bainite heat treatment, but this time in medium carbon steel, and they concluded that an improved combination of impact toughness and tensile strength could be obtained because of the well-modified microstructure. Soliman et al. [27] showed that two-step austempering of a low carbon steel containing 0.26 wt% carbon resulted in higher amount of bainite and lower volume fraction of retained austenite which was more stable due to its higher carbon content. Moreover they have shown that two-step transformation more refined the final microstructural constituents. In a recent work, Wang et al. [28] carried out the multi-step isothermal bainitic reaction on medium carbon steel to obtain low temperature bainite and they claimed that the mechanical properties were superior comparing to that of attained in conventional single-stage bainitic transformation. They have stated that the better mechanical properties were because of the martensite elimination from the microstructure that formed during the single stage transformation, more uniform and refined microstructure and lower volume fractions of austenite blocks. Care must be taken to the point that, in all above investigations on low and medium carbon steels, a primary partial transformation has been carried out above the  $M_s$  of the bulk materials to consume the certain amount of primary austenite and to further enrich the remained untransformed austenite with carbon in order to further reduce its  $M_s$  temperature comparing to that of primary steel. Subsequently, the next stages of step-austempering implemented at temperatures lower than the  $M_s$  of the bulk material but higher than that of the partially untransformed austenite. This made it possible to conduct the bainitic heat treatment at enough low temperature to obtain very fine bainite. However this is not necessary in high carbon steels since the high amount of carbon reduces the  $M_s$  temperature of the primary material enough to obtain desired microstructure.

Contrary to all those reports on step-austempering of low and medium carbon steels, Duong et al. [29] demonstrated that multi-step austempering is unnecessary in low carbon steels and it doesn't always lead to enhanced mechanical properties. They showed that two-step heat treatment even worsened the ductility. According to their work, multi-step heat treatment would be advantageous in high carbon steels rather than low carbon steels because further transformation at second stage could be beneficial for mechanical properties only when large quantities of retained austenite are present within the microstructure at the end of the first stage of the heat treatment [29]. In a work by Hase et al. [30] a two-stage isothermal heat treatment has been adopted on a high carbon steel to obtain nanostructured bainite during which they have austempered samples firstly at 350 °C and immediately after quenched the materials into 250 °C to continue the bainite transformation in second stage. The mechanical properties and microstructural features were compared with those of obtained after single-step heat treatments at different temperatures. It has been shown that

a bimodal size distribution of bainitic ferrite was achieved and bainitic plates which have been obtained at the second stage of the heat treatment were finer [30]. Furthermore, it has been illustrated that two-step heat treatment ended up in greater ductility comparing to any single-step heat treatment. They have related the enhanced ductility to lower amount of austenite blocks and therefore higher mechanical stability of retained austenite at the end of the two-stage heat treatment but not the volume fraction of austenite [30]. The point is that they didn't mention exactly the volume fraction of the retained austenite at the end of each single and two-step austempering processes and even they suggested discovering ways to further reduce the quantity of austenite blocks. However, what they suggested awakes the concern of decrease in overall volume fraction of high carbon retained austenite accompanying with reducing the blocky austenite content which consequently may deteriorate the ductility properties. Therefore, besides those valuable results they have reported, it seems to be important to investigate the validity of the idea that, not only the morphology and mechanical stability but also the volume fraction of high carbon retained austenite should be considered during discussing the mechanical properties in multi-step austempering of nanobainite. Moreover, it will be beneficial to assure that second stage of bainite reaction is being adopted after first stage heat treatment being completed rather than conducting a partial bainite transformation at first stage. Completion of bainitic reaction at first stage makes it possible not to have primary martensite within the microstructure before starting the second stage of the bainitic heat treatment. So, this work aims to investigate the effect of a two-step austempering heat treatment on mechanical performance of high carbon nanostructured bainitic steel in more detail after conducting the second stage of the isothermal heat treatment for different heat treatment times when the bainite transformation is being terminated at first stage. This would make it possible to find out not only the effect of mechanical stability of austenite but also its volume fraction effect on the mechanical performance of nanostructured bainite after step-austempering.

## 2. Materials and methods

High carbon steel was cast in an induction furnace under an inert gas atmosphere which subsequently electro slag remelted, homogenized at 1200 °C for 4 h and hot rolled to a sheet of 16 mm thickness. Both sides of hot rolled material were machined and grounded to remove the decarburized layers and to obtain parallel surfaces. The final chemical composition was Fe- 0.83C- 1.43Si- 1.90Mn- 1.16Cr- 1.28Co- 0.32Mo- 0.66Al (all in wt%). The significance of adding each alloying element has been discussed elsewhere [31,32], among all, silicon addition was necessary to prevent the cementite precipitation and high amount of carbon content was used to reduce the  $M_s$  temperature and bainite start temperature ( $B_s$ ) of the bulk material to make it possible to conduct the bainitic heat treatment at low temperature to obtain nanoscale bainite. The  $M_s$  temperature of the primary steel has been approximately determined to be 125 °C using MUCG83 [33] thermodynamic model and accordingly the single and two-step austempering heat treatments were designed as followings. All samples were austenitized at 950 °C for 30 min. For single-step austempering, samples were quenched to 300 °C immediately after austenitizing and kept for enough time for bainite transformation to be terminated (optimum heat treatment time) and then cooled down to room temperature. For two-step heat treatment, samples were quenched to 300 °C immediately after austenitizing and again kept for optimum austempering time identical to that of single-step transformation and then, when the bainite transformation terminated they rapidly transformed to another furnace of 200 °C to continue the second stage of bainite reaction. Samples were austempered for different times of 12, 36 and 72 h in the second stage to obtain different volume fractions and morphologies of microstructural constituents and finally cooled down to room temperature. Both austeni-

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