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Original Research Article

Development of the low temperature bainite

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ABSTRACT

The possibility of obtaining steels with nano-size plates of bainitic-ferrite by isothermal transformation at low temperature is set forth. These steels have attracted great interest due to their excellent combination of strength, toughness, and ductility. In further investigations, the composition and the processing methods of these steels are adjusted to: (1) Optimize their technological properties with regard to mechanical behavior, weldability and formability. (2) Accelerate their transformation kinetics. (3) Minimize/eliminate the need for expensive alloying elements. (4) Lower the martensite start temperature (M_s) either by thermo-mechanical processing or by modifying the bainite transformation stage. Suppressing M_s is of particular importance in steels with relatively low carbon content; that is to allow for bainite formation at low temperature. Furthermore, many reports addressed some technological aspects like fatigue behavior, wear resistance and bake hardenability. This article presents an overview of the so far studied alloying strategies and processing methods adopted for developing the low temperature bainite together with addressing some examined technological themes. The paper is engrafted in relevant sections with new results of the authors that are not published before. One of these results is that the low temperature bainite possesses a very strong bake hardening potential.

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1. From carbide-free bainite to low temperature bainite

Since the discovery of carbide-free bainite microstructures with both high strength and high toughness in the 1980s [1,2], carbide-free bainitic steels have been widely manufactured and applied in many industrial fields, such as car, gear, railway, and many others [3–6]. The production of carbide-free bainite microstructure is realized by the suppression of cementite precipitation during the bainite transformation

through adequate addition of elements like silicon and aluminum. These elements have very low solubility in cementite. Simultaneously, the mobility of these substitutional atoms at the temperature of bainite formation is limited. The atoms of cementite suppressing elements must then become trapped in the untransformed austenite during the para-equilibrium formation of bainitic ferrite. Ultimately, the cementite formation is suppressed.

The absence of cementite ensures that the carbon enriches the austenite rather than forming cementite plates. This results in lowering the martensite start temperature (M_s).

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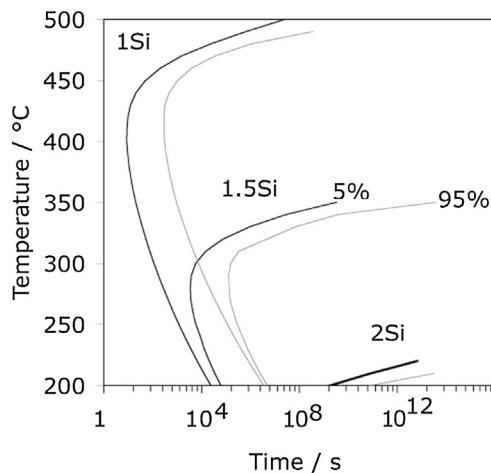


Fig. 1 – Predicted time–temperature–precipitation diagram for para-equilibrium cementite in system Fe–Si–Mn–C with base composition Fe–1.2C–1.5Mn–1.5Si (percentages represent the portion of cementite precipitations being completed) [7].

Therefore, after the course of bainite transformation, a certain amount of austenite can be stabilized to room temperature (RT); this austenite is known as retained austenite. Thus, the final microstructure consists of bainitic ferrite and high carbon retained austenite. However, the calculations of Kozeschnik and Bhadeshia demonstrated that silicon is ineffective in retarding the precipitation of cementite if the parent phase is highly supersaturated with carbon. This is because the driving force for the reaction is large even for para-equilibrium precipitation [7]. Fig. 1 illustrates the predicted time–temperature–precipitation (TTP) diagram for the precipitation of cementite from austenite saturated with 1.2 wt% C at different Si contents.

Reliant on the conception of carbide-free bainite, in combination with allowing for high carbon content and performing the bainitic transformation at low temperature, Sandvik and Nevalainen [1] were the first to obtain ultra-fine bainite with high strength and ductility. They obtained this novel structure through isothermal transformation of austenite at low-temperature conditions in some high-carbon high-silicon steels [1]. Bhadeshia and collaborators set forth investigation on low-temperature bainite (LTB) by modifying the steel composition, addressing the fundamental mechanisms behind its nanostructure along with studying factors determining its mechanical behavior and detailed characterization of its microstructure development [8–13]. Their study attracted great interest due to the excellent combination of strength, toughness, and ductility. The evolution of the mechanical properties evaluations of the novel bainitic steels has revealed ultimate tensile strength (UTS) of about 2.2 GPa, hardness values in the range of 600–670 HV, a noticeable uniform elongation in the range of 5–30% as well as fracture toughness up to $130 \text{ MPa m}^{1/2}$.

These steels satisfy the ever-increasing demands for advanced materials fulfilling the demands for both high strength and high toughness in application fields such as

Table 1 – Typical chemical compositions of the previous novel bainitic steels (wt%) [9,11].

C	Si	Mn	Al	Cr	Mo	Co	Balance
0.8	1.6	2.0	–	1.0	0.25	1.5	Fe
0.8	1.5	2.0	1.0	1.0	0.25	1.5	Fe

automotive and railway industries. The material is now commercially available and the manufacturing process established to a point where hundreds of tons have been produced successfully [14].

2. The first generation of low temperature bainite

The key to the excellent properties of LTB is a fine-scale microstructure consisting of nanoscale bainitic-ferrite and thin films of retained austenite. To obtain these microstructures, it is necessary to carry out the bainitic transformation at low temperatures. Table 1 shows a first generation of LTB with each elemental addition having a specific intended role [9,11]. High carbon content is considered as a key requirement, which suppresses the M_s to allow carrying out the bainite transformation at low temperature. In addition, a high Si content is needed to suppress cementite precipitation. Cementite is a crack initiation phase that should be avoided in high strength steels. Hardenability is increased via Mn and Cr additions [8–11]. Al and Co are added to accelerate the kinetics of the bainite transformation; that is because at low reaction temperatures the rate of transformation is very slow, sometimes taking days to achieve the maximum fraction of bainitic ferrite [9]. The addition of these two elements is the difference between the early alloys studied by Bhadeshia and the earlier ones of Sandvik and Nevalainen.

3. Newly designed alloys of low temperature bainite

Subsequently, much research in the area has focused on experimentally varying the chemistry, transformation time and temperature to achieve certain levels of strength and ductility. Examples of the investigated chemistries are given in Table 2.

Yoozbashi and Yazdani [15] designed a new nanostructured bainitic steel (alloy A) by decreasing the Co and C content and modifying the contents of Mn and Cr in order to reduce the alloy costs. The authors used the electro-slag remelting (ESR) process to improve the cleanness of the steel. Yang et al. [16] added Al instead of Co (alloy B) to accelerate the bainitic transformation and avoid carbides precipitation and added W instead of Mo to prevent temper embrittlement. Temper embrittlement is caused by the presence of specific impurities in the steel, which segregate to prior austenite grain boundaries during heat treatment. The W atom is very large relative to other alloying elements and impurities. It effectively impedes the migration of those elements and thereby provides resistance to temper embrittlement.

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