11 th Scientific / Research Symposium with International Participation
„Metallic and Nonmetallic Materials“ Zenica, B&H, 21-22. April 2016.

MICROSTRUCTURE AND PROPERTIES OF KINETICALLY ACTIVATED BAINITE (KAB) STEELS

Peter Kirbiš, dipl. inž. str., doc. dr. sc. Mihael Brunčko, univ. dipl. inž. str., prof. dr. sc. Ivan Anžel, red. prof.
University of Maribor, Faculty of Mechanical Engineering, Smetanova 17, 2000 Maribor, Slovenia

Key words: Carbide free bainite, nanostructured steel, ultra high strength steel

ABSTRACT
KAB steels are a newly developed grade of advanced ultra high strength steels, which distinguish themselves by the rapid formation of fine nanostructured carbide free lower bainite. The term nanostructured is used with respect to the thickness of the individual bainitic ferrite plates which can vary between 50 nm to as fine as a few nanometers, depending on the temperature at which it was formed. This enables these steels to obtain desirable combinations of mechanical properties due to the presence of finely dispersed retained austenite which has been sufficiently stabilized via the formation of bainite under conditions where the precipitation of cementite is suppressed. Under the influence of stress and strain the retained austenite transforms into martensite and gives rise to microstructural hardening (Transformation induced plasticity effect), enabling such steels reasonable values of predominantly uniform elongation at strength levels of 2800MPa or higher. The aim of the current work is to present the concept of KAB steels, and the relations between their microstructure and mechanical properties. The feasibility of large scale industrial production of the new steel in also discussed.

1. INTRODUCTION
Ever since its discovery by Davenport and Bain in 1933, bainite has been subject to certain controversy, as the shape of bainitic plates suggest a displacive transformation and jet the transformation kinetics resemble those of a diffusion controlled process. Due to this bainitic microstructures were often defined as a non-lamellar aggregate of ferrite and cementite or as an intermediate product between the pearlite and martensite. Later the terminology was adjusted as different types of bainite have been observed in non-ferrous alloy systems like Ti-Cr, Cu-Zn and it is thus defined as.
Within steels different morphologies of bainite can be formed, (i) lath like upper bainite where cementite particles are precipitated at the ferrite lath boundaries, (ii) Plate like lower bainite, which forms in steels with a carbon content above 0.4% whereby particles of epsilon carbide precipitate within the bainitic ferrite plates (iii) carbide free plate like lower bainite, whereby the precipitation of cementite is suppressed by additions of about 1,5% Al and Si, either separate or in combination, alternatively P can be used in lower strength grades [1], causing the carbon to partition into the adjacent austenite stabilizing it down to room temperature. The latter is of particular interest as the interaction between the plates of bainitic ferrite and the thin films of retained austenite can provide additional ductility as it promotes alternative mechanisms of strain hardening. Depending on its stability, the metastable

austenite undergoes a stress/strain induced transformation to martensite, which provides additional local microstructural hardening. If this retained austenite is present in sufficient quantity (about 30%) the resulting transformation induced plasticity effect (TRIP), can delay or even prevent the onset of plastic instability (necking). Carbide free bainitic steels have thus been successfully applied in the automotive industry due to their higher strength combined with sufficiently high formability, and in the production of rails and gears where the retained austenite substantially improve rolling fatigue properties. The formation of this particular morphology is however more time consuming when compared to conventional lower bainite [2], especially when the transformation temperatures are decreased to about 200°C. Low transformation temperatures of about 200°C, are however desirable, as they have shown to result in the formation very thin and slender plates of bainite which approach the nano-scale. Nanostructured bainitic steels transformed at 200°C for 10 days can achieve tensile strengths of 2500 MPa, while maintaining a predominantly uniform elongation of about 10% [3]. The exceptional combination of tensile properties originates from the very fine scale of the carbide free bainitic microstructure. Such a level of refinement where the bainitic ferrite subunits are only about 20 - 50 nm thick is only obtainable by specific alloy design and by transforming at a low temperature. There is in principle no lower limit to the temperatures at which bainite can be formed. But a further decrease, and therefore additional microstructural refinement, has to date been vastly impractical as the required annealing times scale exponentially [4].

A useful approach of rationalizing the formation of bainite in steels is by means of physical modeling. To date several models have been proposed, the majority of which attribute certain common features to the nature of carbide free bainite. To the most widely accepted belongs: (i) the formation of bainite is nucleation controlled, (ii) the nucleation occurs via paraequilibrium partitioning of carbon, (iii) once the first plates have formed the reaction proceeds by means of autocatalysis, (iv) the reaction is incomplete at a given transformation temperature as the carbon partitions from the newly formed bainitic ferrite into the adjacent austenite, (v) lastly due to their comparably slow kinetics, bainitic microstructures tend to be formed using isothermal heat treatments, as summarized Table 1.

Table 1. Different models describing the formation of bainite in steels

MODEL	RREF.	CONTROLLING PROCESS	HEAT TREATMENT	FEATURES
H. Matsuda et al.	[5]	Nucleation controlled	Isothermal/ continuous	Autocatalytic nucleation, incomplete reaction
M. Azuma et al.	[6]	Nucleation controlled	Isothermal	Autocatalytic nucleation, incomplete reaction
M. J. Santofimia et al.	[7]	Nucleation controlled	Isothermal	Autocatalytic nucleation, incomplete reaction
S. M. C. Van Bohemen et al.	[8]	Nucleation controlled	Isothermal	Autocatalytic nucleation,
G. Sidhu et al.	[9]	Nucleation controlled	Isothermal	Autocatalytic nucleation, incomplete reaction
D. Gaude-Fugarolas et al.	[10]	Nucleation controlled	Isothermal	Autocatalytic nucleation, incomplete reaction

Since the formation of bainite nuclei involves the paraequilibrium partitioning of carbon, the rate of nucleation becomes exceedingly sluggish with decreasing temperature. Therefore, nucleation sites would be readily formed at higher temperatures where diffusion of carbon is substantially faster. The essence of the KAB concept lies in the separation of the nucleation and growth stages in the bainite reaction. The potential nucleation sites are formed at higher temperatures in the vicinity of precipitates and upon further cooling below the Bs temperature the carbide free bainitic plates start to grow instantly. In such a way, the rapid formation of carbide free lower bainite is obtained at temperatures which are considered staggeringly low.

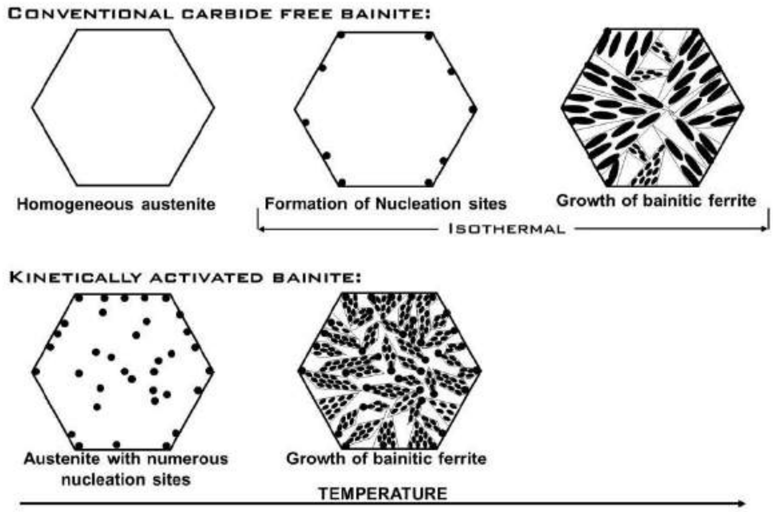

Figure 1. Schematic representation of the concept of bainite formation in kinetically activated bainite (KAB) steels.

The aim of this paper is to present the practical application of this concept to the design of a carbide free nanostructured bainitic steel and characterize the resulting microstructure and mechanical properties.

2. MATERIALS AND METHODS

The steels compositions were determined with the following considerations; C, Cr, Mn, Mo, V and Ni control the transformation temperatures and provide hardenability. Additions were made to the steel KAB 1 as to retard the bainite reaction as little as possible, whereas the formation of martensite was promoted in the second experimental steel by partially suppressing bainite via additions of Mn [11] and has thus been named KAB Hi-Mn. A sufficiently high total amount of Si and Al suppresses the precipitation of cementite in both steel [12,13,1], and ensures that carbide free bainite is formed even at a slow cooling rate. A small addition of Mo prevents temper embrittlement in combination with sufficient C [14,15]. Zr provides better control over the shape of inclusions, and functions together with V, Ti and Al as a grain refining agent [16]. Certain elements have been introduced from the master alloys used or are present as unavoidable impurities. The alloys chemical composition can be seen in Table 1. Critical thermodynamic temperatures such as Bs, $Ms\alpha$ and $Ms\varepsilon$ as well as the temperatures of onset and completion of austenite formation Ac1 and Ac3 respectively, are summarized in Table 2, using equations proposed in [17,18]. The Bs and Ms temperatures were calculated using the software mucg83 [19].

Table 2. Steel compositions (in w %)

	C	Si	Mn	Mo	Cr	V	Al	Ni	Ti	Zr	P	S	N
KAB 1	0.82	1.2	2.5	0.6	1.8	0.22	1.5	1	0.05	0.05	0.02	0.013	0.002

Table 3: Calculated critical thermodynamic temperatures of the newly developed steels (in °C)

	Ac_1	Ac_3	$\mathbf{B_s}$	$\mathbf{M_s}$
KAB 1	703	879	240	48

The steels were produced using master alloys and pure components, induction melted in vacuum and mold cast under a protective atmosphere of pure argon. The ingots were then homogenized at 1200°C for 2 days. After homogenization heat treatment the KAB steel was hot rolled at 1050°C and reduced from 18 mm to a final thickness of 6 mm, followed by air cooling. Samples were then taken and soft annealed using the slow divorced pearlite reaction heat treatment [20,21].

3. RESULTS AND DISCUSSION

The microstructure of the steel after homogenization annealing and hot rolling can be seen in Fig. 2. a) and b) respectively. Although the scale of the sheaves is significantly refined via the hot rolling, it can be deduced from the etching response (blue) that bainite is the only phase that has formed, there is also a significant amount of retained austenite present which etches white.

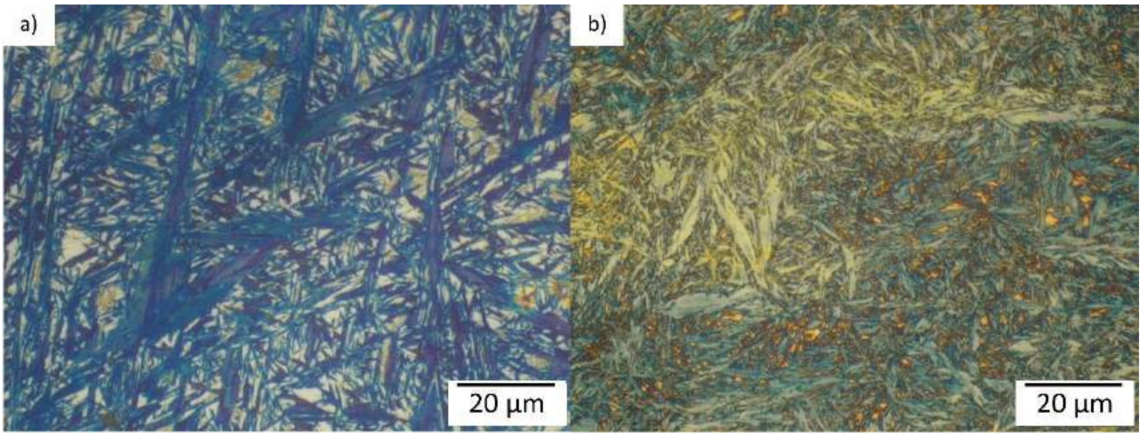

Figure 2. Optical micrographs of the microstructures formed in KAB steels with different grain sizes; a) coarse-grained KAB steel after air cooling showing bainite (blue) and retained austenite (white). b) KAB steel after hot rolling at 1050°C and air cooling, bainite (blue) and retained austenite (white).

As can be seen from the higher magnification image in Fig. 3. the sheaves in the hot rolled sample of KAB steel are very fine and reach even submicron sizes, consequently the individual subunits are very short. The microstructure of this rapidly formed continuously cooled bainite is therefore in sharp contrast with isothermally formed low temperature bainite. The microstructure of the latter is characterized by very long and thin individual subunits [22]. The rapid nucleation rate of the sheaves during continuous cooling favors the formation of new sheaves, rather than the growth of existing ones. Sheave lengthening is favored during isothermal heat treatments, and proceeds via autocatalytic nucleation of individual subunits.

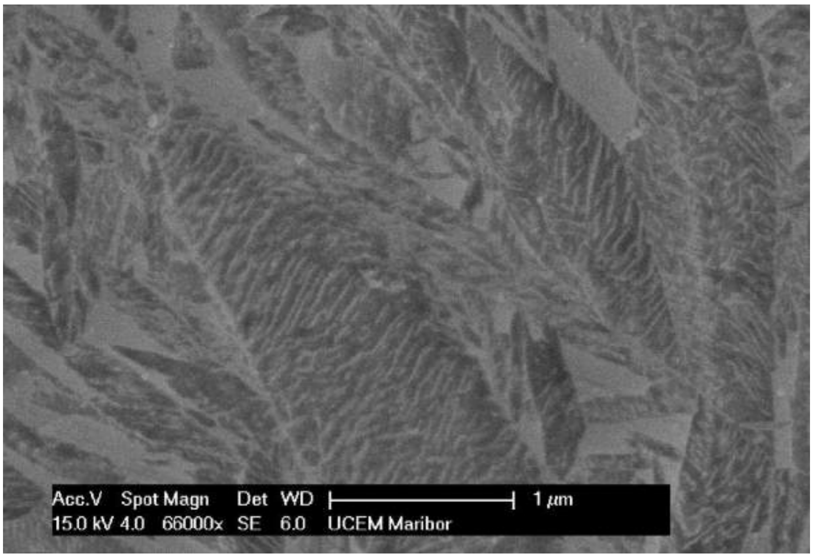

Figure 3. FESEM micrograph of steel KAB 1 after hot rolling.

The bainitic ferrite subunits in the newly developed steel are very fine, the coarsest being about 50 nm thick. From the HRTEM micrograph in Fig.4 a tendency for coagulation of the individual plates can be clearly seen. This is commonly observed when the transformation proceeds with high driving forces [23], aluminum additions also tend to promote this effect. Noteworthy even the thin films of austenite which were the first to form decomposed into an austenite/ferrite mixture at a lower temperature.

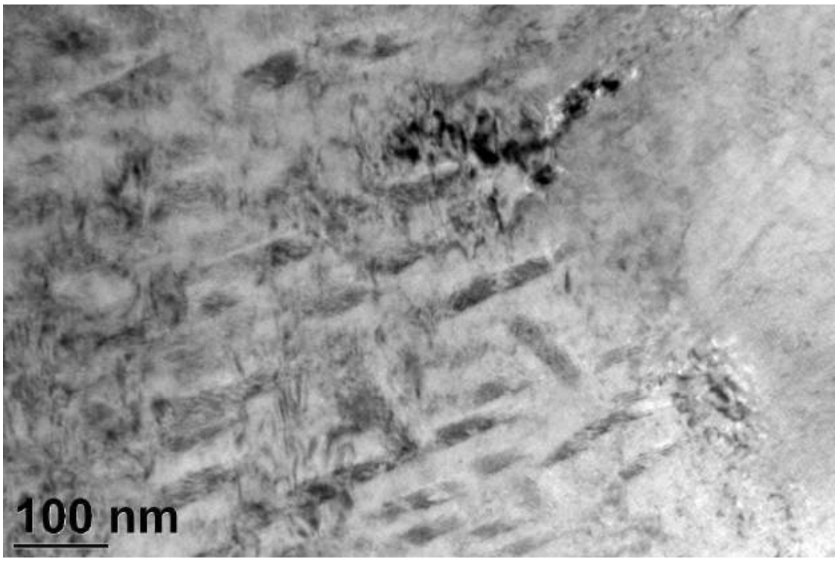

Figure 4. TEM micrograph of steel KAB 1 after hot rolling and air cooling, ferrite is observed dark, austenite light.

Non isothermal heat treatments achieve improvements through a greater geometrical division of the retained austenite, caused by the bimodal size distribution of plates. It is reasonable to assume that an increased number of isothermal holding steps would amplify this effect. A continuous cooling transformation can be thought of as a superposition of several short isothermal steps. The formation of bainite during air cooling therefore introduces a similar effect. In the newly developed steel bainite forms very rapidly at staggeringly low

temperatures, which makes it highly unlikely that carbon would have time to partition into the adjacent austenite after or during the initial formation of bainitic ferrite. The growth rate is known to be significantly slower compared to martensite [24], and some studies suggest the diffusion of carbon occurs during growth of bainitic ferrite plates [25–27]. The latter seems unlikely when bulk diffusion is considered, which strongly supports the view that the bainite forms via a displacive mechanism.
From the tensile curve in Fig. 5., continuous yielding and a predominantly uniform elongation are clearly visible. This indicates a pronounced TRIP effect that enables the steel to retain its work hardening capacity even at such high strength levels. The latter is indicative that the retained austenite has a sufficiently high stability, which originates mostly from its fine size. Analogous to other low temperature bainitic steel grades the strength arises from the very fine microstructure, but there is also thought to be a contribution from the fine scale of the sheaves themselves.

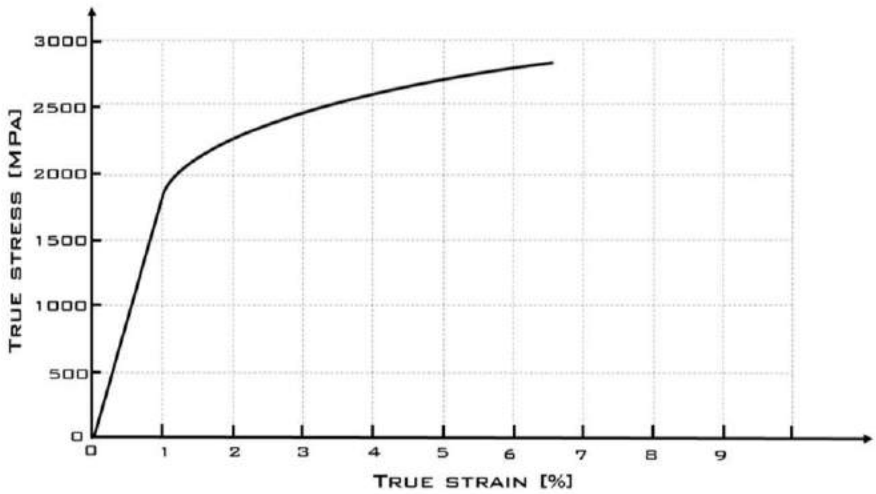

Figure 5. True stress/true strain curve of KAB steel after hot rolling

4. CONCLUSION

The concept of kinetic activation of the bainite reaction - KAB, was successfully applied to the design of an experimental high carbon steel. The microstructure was characterized using different methods which have conclusively confirmed carbide free bainite upon air cooling, with no detectable martensite or carbide precipitation. Observations using HRTEM have shown a very fine scale of the bainitic ferrite plates, which correspond well with the low calculated transformation temperatures. The measured tensile properties are slightly higher when compared to similar steels from the literature, which is most likely due to the continuous character of the transformation, whereby a larger amount of retained austenite has decomposed. Further work should be aimed towards the characterization of deformed microstructures and a detailed analysis of the deformation mechanism of the retained austenite phase. Additionally larger ingots should be casted to assert the repeatability of the current mechanism in an industrial environment.

Acknowledgements

The research work and has been supported by the National Research and Development Programme for long-term research within the framework of the Slovenian Research Agency.

5. REFERENCES

[1] De Cooman, B. C.: Structure-properties relationship in TRIP steels containing carbide-free bainite, Curr. Opin. Solid State Mater. Sci. 8 (2004) 285–303. doi:10.1016/j.cossms.2004.10.002.,

[2] Khare S., Lee K., Bhadeshia H. K. D. H.: Carbide-free bainite: Compromise between rate of transformation and properties, Metall. Mater. Trans. A Phys. Metall. Mater. Sci. 41 (2010) 922–928. doi:10.1007/s11661-009-0164-z.,

[3] Garcia-Mateo C., Caballero F. G., Bhadeshia H. K. D. H.: Development of Hard Bainite, ISIJ Int. 43 (2003) 1238–1243. doi:10.2355/isijinternational.43.1238.,

[4] Bhadeshia, H. K. D. H.:Very Short and Very Long Heat Treatments in the Processing of Steel, Mater. Manuf. Process. 25 (2010) 1–6. doi:10.1080/10426910903143282.,

[5] Matsuda H., Bhadeshia H. K. D. H.: Kinetics of the bainite transformation, Proc. R. Soc. A Math. Phys. Eng. Sci. 460 (2004) 1707–1722. doi:10.1098/rspa.2003.1225.,

[6] Azuma M., Fujita N., Takahashi M., Iung T.: Modelling Upper and Lower Bainite Transformation in Steels, Mater. Sci. Forum. 426-432 (2003) 1405–1412. doi:10.4028/www.scientific.net/MSF.426-432.1405.,

[7] Santofimia M. J., Caballero F. G., Capdevila C., García-Mateo C., De Andrés C. G.: New Model for the Overall Transformation Kinetics of Bainite. Part 1: the Model, Mater. Trans. 47 (2006) 2465–2472. doi:10.2320/matertrans.47.2465.,

[8] J. S. S. M. C. van Bohemen: Modeling of isothermal bainiteformation based on the nucleation kinetics, Int. J. Mat. Res. 99 7. (2008).,

[9] Sidhu G., Bhole S. D., Chen D. L., Essadiqi E.: An improved model for bainite formation at isothermal temperatures, Scr. Mater. 65 (2011) 373–375. doi:10.1016/j.scriptamat.2011.05.016.,

[10] Gaude-Fugarolas D., Jacques P. J.: A New Physical Model for the Kinetics of the Bainite Transformation, ISIJ Int. 46 (2006) 712–717. doi:10.2355/isijinternational.46.712.,

[11] Sourmail T., Smanio V.: Low temperature kinetics of bainite formation in high carbon steels, Acta Mater. 61 (2013) 2639–2648. doi:10.1016/j.actamat.2013.01.044.,

[12] Kozeschnik E., Bhadeshia H. K. D. H.: Influence of silicon on cementite precipitation in steels, Mater. Sci. Technol. 24 (2008) 343–347. doi:10.1179/174328408X275973.,

[13] Slycken J., Verleysen P., Degrieck J., Bouquerel J., Cooman B. C.: The effect of silicon, aluminium and phosphor on the dynamic behavior and phenomenological modelling of multiphase TRIP steels, Met. Mater. Int. 13 (2007) 93–101. doi:10.1007/BF03027558.,

[14] Kovalev A. I., Sergeeva T. K., Litvinenko D. A.: Segregation of impurities, temper brittleness , and hydrogen embrittlement of steeL 30KHnma with different concentrations of molybdenum, Met. Sci. Heat Treat. 37 (1996) 196–199.,

[15] V. V. Zabil'skii: Temper embrittlement of structural alloy steels (review), Met. Sci. Heat Treat. Volume 29 (1987) 24–32.,

[16] Baker, T. N.: Processes, microstructure and properties of vanadium microalloyed steels, 25 (2009) 1083–1107. doi:10.1179/174328409X453253.,

[17] Kasatkin O. G., Vinokur B. B., Pilyushenko V. L.: Calculation models for determining the critical points of steel, Met. Sci. Heat Treat. 26 (1984) 27–31. doi:10.1007/BF00712859.,

[18] Yang H. S., Jang J. H., Bhadeshia H. K. D. H., Suh D. W.: Critical assessment: Martensite-

start temperature for the γ → ε transformation, Calphad Comput. Coupling Phase Diagrams Thermochem. 36 (2012) 16–22. doi:10.1016/j.calphad.2011.10.008.,

[19] Bhadeshia, H. K. D. H: Thermodynamic analysis of isothermal transformation diagrams, Met. Sci. 16 (1982) 159–165.,

[20] Luo D., Peet M. J., Ooi S. W., Yan P., Yin Z., Bhadeshia H. K. D. H.: Spheroidisation of hypereutectoid state of nanostructured bainitic steel, Mater. Sci. Technol. 30 (2014) 1282–1286. doi:10.1179/1743284714Y.0000000545.,

[21] Pandit A. S., Bhadeshia H. K. D. H: Divorced pearlite in steels, Proc. R. Soc. A Math. Phys. Eng. Sci. 468 (2012) 2767–2778. doi:10.1098/rspa.2012.0115.,

[22] Bhadeshia, H. K. D. H.: Nanostructured bainite, Proc. R. Soc. A Math. Phys. Eng. Sci. 466 (2010) 3–18. doi:10.1098/rspa.2009.0407.,

[23] Bhadeshia H. K. D. H, Chang L. C.: Microstructure of lower bainite formed at large undercoolings below bainite start temperature, Mater. Sci. Technol. 12 (1996) 233–236.,

[24] Kang M., Zhang M. X., Zhu M.: In situ observation of bainite growth during isothermal holding, Acta Mater. 54 (2006) 2121–2129. doi:10.1016/j.actamat.2005.12.036.,

[25] Hillert, M.: Diffusion in growth of bainite, Metall. Mater. Trans. A. 25 (1994) 1957–1966. doi:10.1007/BF02649044.,

[26] Shiflet G. J., Hackenberg R. E.: Partitioning and the growth of bainite, Scr. Mater. 47 (2002) 163–167. doi:10.1016/S1359-6462(02)00123-9.,

[27] Agren, A. B. M. H. J.: Metallographic evidence of carbon diffusion in the growth of bainite, Acta Mater. Volume 57 (2009).