Bainitic Transformation in High-Speed Steels

Julieta KALEICHEVA, Valentin MISHEV

Abstract: The investigation on the structure formation in the bainitic area for high-speed steel HS18-0-1 is performed. The austempering is carried out at 270 °C after austenitizing at 1280 °C following by isothermal retention in the area of high resistance of the undercooled austenite(500÷650 °C). The kinetic of the bainitic transformation, the obtained structure by means of optical metallography (OM), transmission electron microscope (TEM), X-ray analysis and hardness measurement by Rockwell method are studied. The influence of the preliminary destabilisation of the undercooled austenite at 560 °C and 650 °C on the characteristics of the austenite-to-bainite transformation in steel HS18-0-1 is established.

Keywords: α-phase; austempering; bainitic ferrite; bainitic transformation; carbides; high-speed steel; retained austenite

1 INTRODUCTION

The austempering is a type of heat treatment, which is used for hypoeutectoid steels and ductile cast irons [1÷4]. Because of austenite-to-bainite transformation, a bainitic structure with high mechanical characteristics is formed. The bainitic structure combines high strength and hardness with increased toughness and plasticity. The process of austempering with partial transformation of austenite to bainite is used in the practice of processing high-speed steels [5÷8]. The new data received for the austenite-to-bainite transformation in this class of steels expand the possibilities of austempering.

In the present study the transformation of austenite in the bainitic area into high-speed steel HS18-0-1 is investigated. After heating at 1280 °C the isothermal retention of the samples is performed at 560÷650 °C preceding the austempering at temperature 270 °C.

2 METHODOLOGY OF INVESTIGATION

Samples produced from high-speed steel HS18-0-1 of composition 0.73 – 0.83 % C, 3.80 – 4.50 % Cr, 17.20 – 18.70 % W, 1.00 – 1.20 % V, ≤ 0.45 % Si are undergone to austempering.

The microstructure observation is performed by Neofot 2 microscope. The structure is revealed in a solution consisting of 5g $FeCl_3$, 15ml HCl, 50ml H_2O and 2ml HNO_3. Electron microscope analysis by JEOL 100C is used for surface topography investigation on lacquer replicas. X-ray phase analysis on diffractometer TUR M61 is applied for the retained austenite quantity determination and the lattice parameter defining [7]. Rockwell-C test method was used for hardness measurement.

3 EXPERIMENTAL RESULTS AND ANALYSIS

The tools produced from high-speed steels with complicated shapes can be undergone to a step quenching with retention at 400÷600 °C with the aim to reduce the deformations in them. The tools of the same steels with big ratio between length and their diameter are subjected to incomplete austempering at 200÷300 °C, 30÷60 min. As a result, a partial bainitic transformation occurs, and in the structure after quenching, besides martensite, retained austenite and carbides, there is also bainite. The presence of small amounts of bainite in the steel structure reduces the tool deformations and there is the risk of cracking in the tool.

In case of quenching of high-speed steels, including isothermal retention in the temperature range of high resistance of the undercooled austenite (500÷650 °C), it was found that the transformation of austenite to martensite flows to a greater extent (i.e. greater amount of martensite is formed). This is explained by the precipitation of submicroscopic carbide and intermetallic particles from the austenite under isothermal retention at 500÷650 °C, which increases the M_S point in the next austenite-to-martensite transformation. Such a preliminary destabilization of the undercooled austenite at 500÷650 °C could also affect austenite-to-bainite transformation.

In this work the influence of austenite preliminary treatment at temperatures of 560 °C, 240 min (Mode I) и 650 °C, 40 min (Mode II) on the structures formation in the bainitic area of high-speed steel HS18-0-1 is investigated (Tab. 1).

Mode I: 1280 °C (3 min) → 560 °C (240 min) → 270 °C (τ_i min);

Mode II: 1280 °C (3 min) → 650 °C (40 min) → 270 °C (τ_i min).

The temperature of 560 °C is in the area of high stability of undercooled austenite for steel HS18-0-1 (Fig. 1). There is no evidence of undercooled austenite transformation during isothermal retention at this temperature for 240 min. However, this may be a reason for austenite destabilisation (as in step quenching) and could alter the kinetics and structure formation in the bainitic area at subsequent isothermal retention at 270 °C (Mode I).

The temperature increase up to 650 °C can accelerate the destabilisation processes of the undercooled austenite and affect the behavior of the bainitic transformation upon subsequent isothermal retention at 270 °C (Mode II).

In the present case, isothermal retention at 650 °C, 40 min causes a partial conversion of the undercooled austenite into perlite area, which will be commented. The 270 °C temperature lies in the HS18-0-1 steel bainitic area (Fig. 1).

In the paper [7], the author investigates the ordinary bainitic transformation of austenite for steel HS18-0-1 in the temperature range of 240÷300 °C and finds that at 270 °C the formation of bainite proceeds at the highest speed.

This determines the selection of the isothermal quenching temperature of 270 °C in Mode I and Mode II.

Fig. 1 shows the TTT – diagram of steel HS 18-0-1. The regimes of heat treatment regarding austempering at temperature 270 °C (Modes I and II) are determined by this diagram. The austenitizing of all of the tested regimes is processed in a salt bath at temperature 1280 °C and time of heating 3 min.
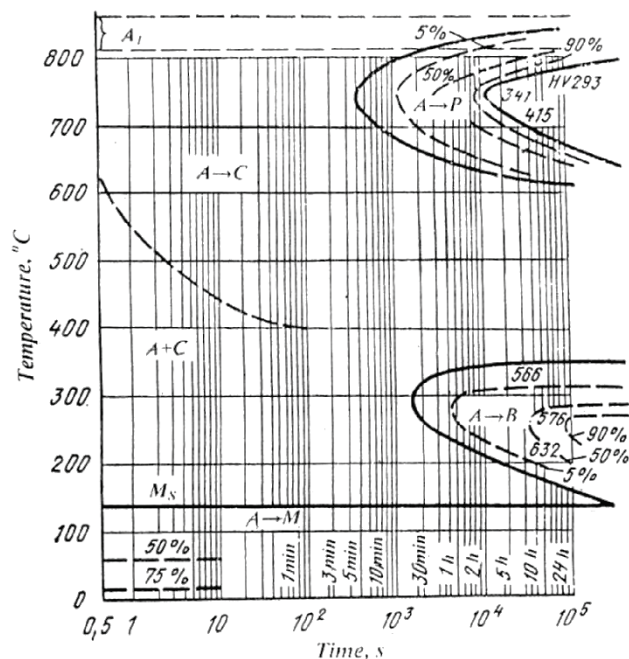

Figure 1 TTT – diagram of steel HS 18-0-1 [7]

Table 1 The regimes of austempering processes

Heating temperature	Isothermal holding regime	Austempering temperature	Austempering time, min
1280 °C	560 °C, 240 min	270 °C	5, 10, 20, 40, 60, 120, 360
	650 °C, 40 min		

The hardness of steel HS18-0-1 after isothermal retention at 560 °C, 240 min (Mode I) and direct cooling to room temperature is 64 HRC. After heat treatment under Mode I, including: 560 °C, 240 min → 270 °C, 40÷120 min the hardness remains constant - 61.5 HRC. After isothermal retention at 270 °C, 6 hours the hardness drops sharply to 56.5 HRC (Fig. 2, Tab. 2).
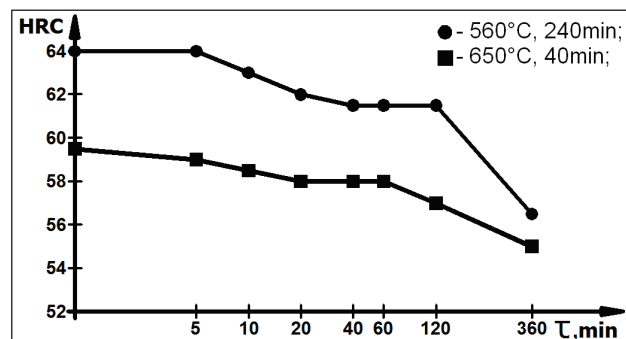

Figure 2 Influence of the time of austempering τ at 270 °C (Modes I and II) on the samples hardness HRC

The microstructure of Fig. 5a shows that isothermal retention at 650 °C for 40 min leads to a partial conversion of undercooled austenite into the perlite area. The structure of the troostite, which is located along the borders of the

austenitic grains (Fig. 5a), is formed. This is the reason for the decrease of the hardness after a direct cooling from 650 °C, 40 min(59, 5 HRC) compared to the hardness after direct cooling from 560 °C, 240 min (64 HRC) (Fig. 2, Tab. 2). Austenite-to-bainite transformation at temperature of 270 °C from 5 to 360 min results in a gradual reduction in hardness to 56.5 HRC (Mode I) and 55 HRC (Mode II).

Table 2 Quantity of the retained austenite A and hardness HRC

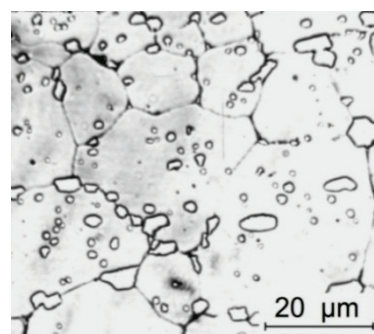| Austempering time, min	560 °C, 240 min		650 °C, 40 min	
	Austempering temperature 270 °C			
	HRC	A, %	HRC	A, %
-	64	12	59,5	5
5	64	16	59	10
10	63	18	58,5	12
20	62	-	58	-
40	61,5	20	58	28
60	61,5	-	58	-
120	61,5	25	57	34
360	56,5	27	55	36

Figure 3 Microstructure of steel HS 18-0-1 after immediately quenching from a temperature of 1280 °C

Fig. 3 shows the microstructure of steel HS 18-0-1 after quenching. The martensite and retained austenite in the structure of the hardened steel do not occur. The boarders of the former austenitic grains, the primary carbides and the undissolved secondary carbides during austenitizing are seen. The optical metallographic analysis shows that as a result of austempering at 270 °C under Mode I and Mode II, a structure of black oriented needles (Figs. 4a and 5a) is formed. This leads to a decrease in hardness with the increasing austempering time. It is determined the amount of retained austenite A and the parameter of its crystal lattice after cooling to a room temperature. An increase in A in the test samples was observed with an increase of austempering time at 270°C (Fig. 6). After the austenite-to-bainite transformation at 270 °C, 360 min an increase of the crystal lattice parameter of A is observed from 0.3638 to 0.3642 nm (Mode I) and from 0.33636 to 0.3648 nm (Mode II) (Tab. 3). Analysis of conversion kinetics data suggests the formation of a low carbon structural component in the process of converting austenite at 270 °C. The oriented structure (Figs. 4b, 4c and 5b, 5c) consists of needles of α – phase (bainitic ferrite). α-phase is formed by a martensitic mechanism from an austenitic region with a low carbon content [1, 2]. At 270 °C, only carbon diffusion [1, 2] occurs, which suggests that increasing amount of bainitic ferrite increases the percentage of carbon in remaining austenite $A_{(c)}$. This lowers the temperature of M_S point of the remaining austenite $A_{(c)}$, which upon subsequent cooling from 270 °C to room temperature is subjected to martensitic conversion.

Part of $A_{(c)}$ turns into martensite, and part of it remains in the structure as retained austenite A. By increasing the carbon content in $A_{(c)}$ the temperature of the point M_S is decreased and the amount of retained austenite A in the structure at room temperature is increased (Fig. 6). The lattice parameter of the retained austenite A is also increased (Tab. 3). The HS 18-0-1 steel structure at room temperature (Mode I) is complex and contains the following components: bainitic ferrite (α-phase); carbides; martensite formed by $A_{(c)}$ under cooling to 20 °C; and retained austenite A (Fig. 4).

For Mode II, the structure also contains a little troostite, formed at 650 °C, 40 min and located along the borders of the austenitic grains (Fig. 5a). The hardness of the samples depends on the type of structural components (with different hardness) and on their quantitative ratio.
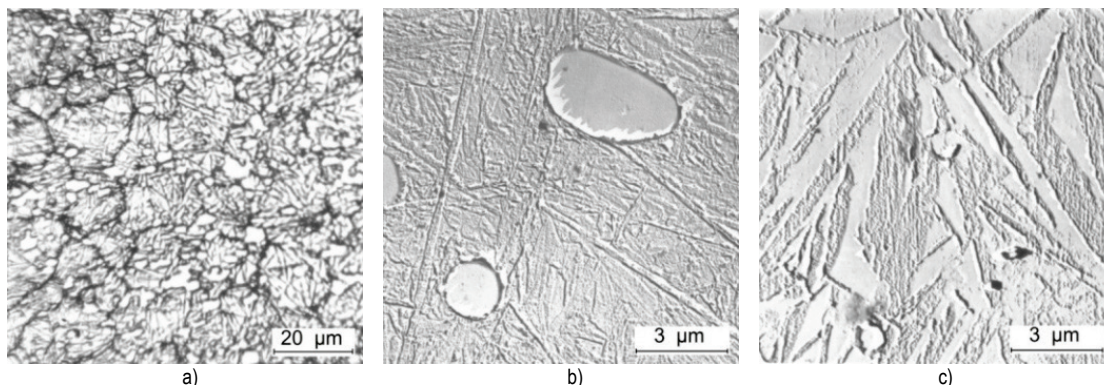

Figure 4 Microstructure of steel HS18-0-1 after heat treatment by Mode I. The austempering time at 270 °C is: 5 min (b) and 360 min (a, c)

During conventional austemepering of steel HS18-0-1 in the bainitic area at Mode: 1280 °C, 3 min → 270 °C, 10÷360 min a structure is formed appearing as oriented needles when the observation with an optical metallographic microscope is performed. The electron microscopic analysis of the structure shows that each needle is a set of alternating a-phase and austenite plates [7]. The hardness decreases from 62 HRC (after quenching from 1280 °C, 3 min) to 53 HRC after isothermal retention for 6 hours at 270 °C. An increase of the retained austenite A by 35% to 58% and its grade parameter from 0.3626 nm to 0.36405 nm is observed [7].
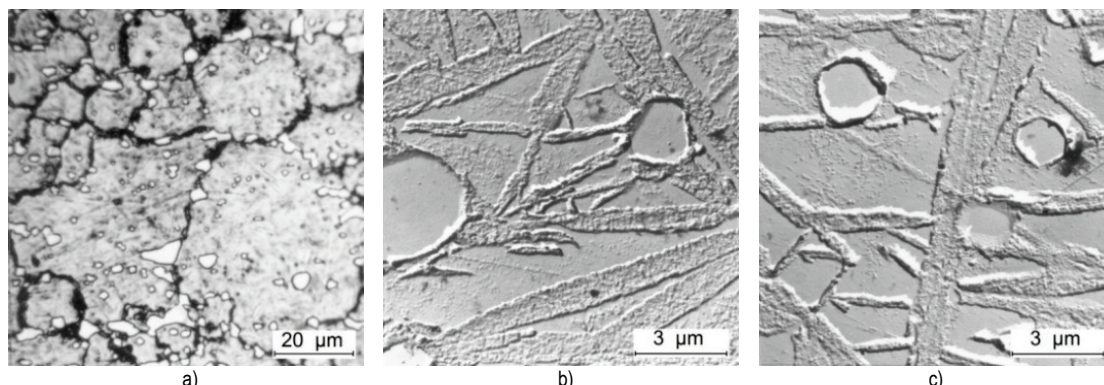

Figure 5 Microstructure of steel HS18-0-1 after heat treatment by Mode II. The austempering time at 270 °C is: 5 min (a), 40 min (b) and 360 min (c)

The work performed in [7] and the present work show a similarity in the kinetics of the bainitic transformation under conventional austempering and austempering under mode I and mode II of steel HS 18-0-1. In spite of this similarity in kinetics, the electron microscopic analysis of the structure formed under mode I and mode II has some peculiarities. This structure consists of isolated α-phase needles. As the bainitic transformation develops, each α-phase needle grows on its own without participating in the formation of α-phase and austenitic alternating packs (Figs. 4b, 4c and 5b, 5c). The needles of α-phase have a strong relief, formed because of dispersive precipitates during self-tempering. This process is relieved by the pre-precipitation of submicroscopic carbide and intermetallic particles at temperatures of 560 °C and 650 °C. It is possible that after the formation of the α-phase, the carbon of the border austenitic regions is redistributed again towards the boundary, due to the higher carbon diffusion coefficient in the α-iron. Carbide particles formed on the α-crystals bound by self-tempering of the α-phase or "inheritance" of the pre-prepared structure of the undercooled austenite at temperatures of 560 °C and 650 °C. As a result, α-phase crystals may grow at the expense of impoverished carbon austenitic areas. In this way, self-inducing growing of α-phase is achieved. In the α-phase crystals, there are embossed carbide precipitates located parallel to the boundaries of the growing crystal. This is best seen after preconditioning of the undercooled austenite at 650 °C (Fig. 4b, 4c). The α-phase crystals also grow because of carbon diffusion from the nearby austenite region to the remote one.

Table 3 The retained austenite lattice parameter

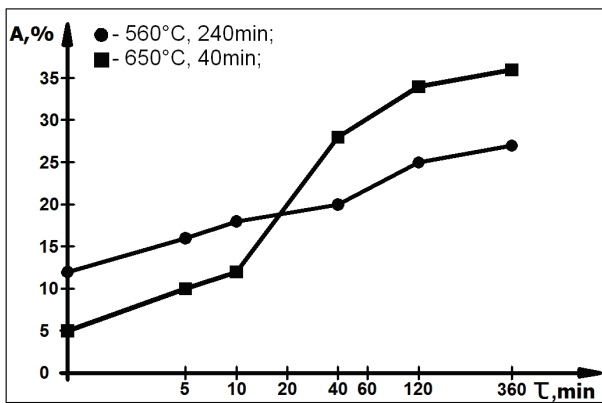| Austempering time, min	560 °C, 240 min	650 °C, 40 min
	Austempering temperature 270 °C	
	Lattice parameter of the retained austenite, nm	
-	0.3638	0.3636
360	0.3642	0.3648

Figure 6 Dependance of the quantity of retained austenite A on the austempering time at 270 °C (Mode I and Mode II).
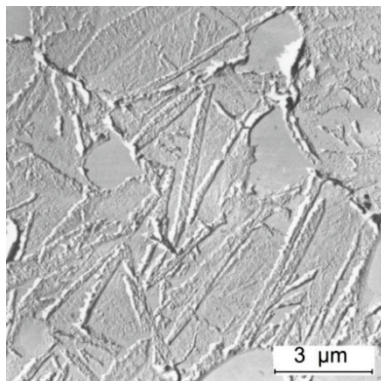

Figure 7 Microstructure of steel HS18-0-1 after thermal treatment by regime: 1280 °C(3 min) → 560 °C(240 min) → cooling to the room temperature with the furnace.

Fig. 7 shows the HS18-0-1 steel microstructure obtained in the following Mode: austenitizing at 1280 °C, 3 min, isothermal retention at 560 °C, 4 hours, and subsequent furnace cooling to room temperature. This mode of the heat treatment involving continuous cooling from 560 °C to room temperature allows austenite-to-bainite transformation to be carried out over the entire temperature range of the bainitic area. The bainitic-ferrite crystals (α-phase) in the microstructure of the steel are formed at different temperatures of the bainitic region, but have the same structure (Fig. 7).

The bainitic transformation in a high-speed steel HS18-0-1, after preconditioning on the undercooled austenite (Modes I and II), results in the formation of a structure consisting of needles α-phase (bainitic ferrite) and carbon-enriched remaining austenite $A_{(c)}$: (α + $A_{(c)}$). The remaining austenite $A_{(c)}$ does not decompose into a biphasic ferrite-carbide mixture (α+carbide) in the bainitic temperature range. This scheme of the bainitic transformation (α+$A_{(c)}$) resembles the formation process of a lower bainite in the low and middle carbon steels.

4 CONCLUSION

The austempering of the HS18-0-1 steel in the bainitic area (200÷350 °C), including pre-cooled isothermal retention (500÷650 °C), does not change the phase composition of the bainitic structure. This structure consists of α-phase and austenite enriched with carbon. The morphology of the structure is changed: bainitic ferrite is formed as a separate needle α-phase with strongly expressed signs of self-tempering. A similar structure is

formed in austempering of constructional steels in the lower temperature range of the bainitic area. The characteristics of the bainitic transformation in HS18-0-1 steel (Modes I and II) are explained by the precipitation of submicroscopic particles (carbides and intermetallic compounds) under isothermal retention at the temperature of 560 °C, 240 min and 650 °C, 40 min, and by the α-phase inheritance of the altered austenitic structure.

5 REFERENCES

[1] Kurdyumov, G. V., Utevskiy, L. M., & Entin, R. I. (1977). *Transformations in Iron and Steel*, Nauka, Moscow.
[2] Bhadeshia, H. K. D. H. (2001). *Bainite in Steels*. 2nd ed., Inst. of Materials, Cambridge, London.
[3] Dorasil, E. (1985). *High-strenght Bainitic Nodular Cast Iron*, Academia, Prague.
[4] Yescas, M. A. (2001). Modelling the Microstructure and Mechanical Properties of Austempered Ductile Irons, *PhD thesis,* University of Cambridge, Department of Materials Science and Metallurgy, Cambridge.
[5] Vatavuk, J., Totten, G. E., Nucci, J. E., Albano, L. L. M. & Canate, I. C. F. (2016). Comparative impact behavior of high-C steel after conventional quenching, tempering, and austempering. *Materials Performance and Characterization*, 5(1), 227-238. https://doi.org/10.1520/MPC20150042
[6] Tananko, I. A., Kaleicheva, Z. A., & Pavluchenko, A. A. (1987). Formation of the Structure and Properties of KH12M-Steel in Partial Bainitic Decomposition of Austenite. *Metal Science and Heat Treatment, 29*(7-8), 550-553. https://doi.org/10.1007/BF01167746
[7] Kaleicheva, J. A. (2007). Structure and Properties of High-Speed Steels after Austempering. *International Journal of Microstructure and Materials Properties, 2*(1), 16-23. https://doi.org/10.1504/IJMMP.2007.012934
[8] Caballero, F. G. & Bhadeshia, H. K. D. H. (2004). Very strong bainite. *Current Opinion in Solid State and Materials Science, 8*, 251-257. https://doi.org/10.1016/j.cossms.2004.09.005

Contact information:

Julieta KALEICHEVA, Full Prof., PhD
Technical University of Sofia,
Faculty of Industrial Technology,
8 Kl. Ohridski blvd., 1000 Sofia, Bulgaria
E-mail: jkaleich@tu-sofia.bg

Valentin MISHEV, Assist. Prof., PhD
Technical University of Sofia,
Faculty of Industrial Technology,
8 Kl. Ohridski blvd., 1000 Sofia, Bulgaria
E-mail: v_mishev@tu-sofia.bg