

Effect of silicon on stability of austenite during isothermal annealing of low-alloy steel with medium carbon content in the transition region between pearlitic and bainitic transformation

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Abstract. In a vast majority of steels, a prerequisite to successful heat treatment is the phase transformation of initial austenite to the desired type of microstructure which may consist of ferrite, pearlite, bainite, martensite or their combinations. Diffusion plays an important role in this phase transformation. Together with enthalpy and entropy, two thermodynamic quantities, diffusion represents the decisive mechanism for the formation of the particular phase. The basis of diffusion is the thermally-activated movement of ions of alloying and residual elements. It is generally known that austenite becomes more stable during isothermal treatment in the transitional region between pearlitic and bainitic transformation. This is due to thermodynamic processes which arise from the chemical composition of the steel. The transformation of austenite to pearlite or bainite is generally accompanied by formation of cementite. The latter can be suppressed by adding silicon to the steel because this element does not dissolve in cementite, and therefore prevents its formation. The strength of this effect of silicon depends mainly on the temperature of isothermal treatment. If a steel with a sufficient silicon content is annealed at a temperature, at which silicon cannot migrate by diffusion, cementite cannot form and austenite becomes stable for hours.

1 Introduction

Phase transformation from austenite to pearlite that takes place during continuous cooling or during isothermal treatment is controlled by diffusion. It is a reconstructive phase transformation based on thermally activated migration of interstitial atoms, substitutional ions of alloying addition, and iron ions. The control mechanism of this transformation is diffusion. The rate of transformation is mainly dictated by the temperature at which the treatment and the austenite-pearlite transformation are taking place. Bainitic transformation is semi-diffusional in nature, as it is accompanied by diffusion of only the interstitial atoms. The austenite-bainite transformation itself is based on the shear mechanism.

The transition region between pearlitic and bainitic transformations is characterized by increased stability of austenite. This is due to the thermodynamic conditions, which arise from the chemical composition of the steel. The reason is the fact that pearlitic transformation takes place through formation and growth of nuclei which are highly sensitive to the temperature of transformation [1]. At lower temperatures, the nucleation and growth slow down, whereas the free enthalpy of supercooled austenite increases. The amount of supercooling plays a key role in the bainitic transformation [2]. This results in a situation where the amount of supercooling of austenite is sufficient to prevent heterogeneous nucleation of pearlite but at the same time, it is inadequate to



induce the shear mechanism of bainitic transformation [3,4,5]. By this means, and predominantly during isothermal treatment, a region of higher stability of austenite arises, as known from TTT diagrams. Silicon is generally understood to prevent cementite precipitation [6,7,8]. Its effect depends on the temperature of isothermal treatment. When steel is annealed at a temperature, which impedes silicon diffusion, cementite cannot precipitate within a short timeframe [9].

2 Experimental programme

The objective of this experimental programme was to examine the possible effects of the silicon content and the temperature of isothermal treatment in the region between pearlitic and bainitic transformations on austenite stability and on the resulting microstructure in a low-alloy steel with 0.56 weight percent carbon. (Table 1).

Table 1. Chemical composition of experimental steel.

C	Si	Mn	Cr	P	S	M_s [°C]	M_f [°C]
0.56	2.0	0.59	1.33	0.005	0.003	252	126

Thermal treatment sequences were proposed for experimental isothermal annealing in the transition region between pearlitic and bainitic transformations. The specimens were heated to 950 °C for 300 seconds to obtain homogenous austenite, and then cooled to various temperatures in the region between the pearlite and bainite noses of the diagram. These temperatures were chosen so that the various annealing sequences took place in pearlitic transformation and bainitic transformation regions, as well as in the transition region between them, as seen in the TTT diagram of the experimental steel which was constructed using calculations completed in the JMatPro program (Figure. 2)

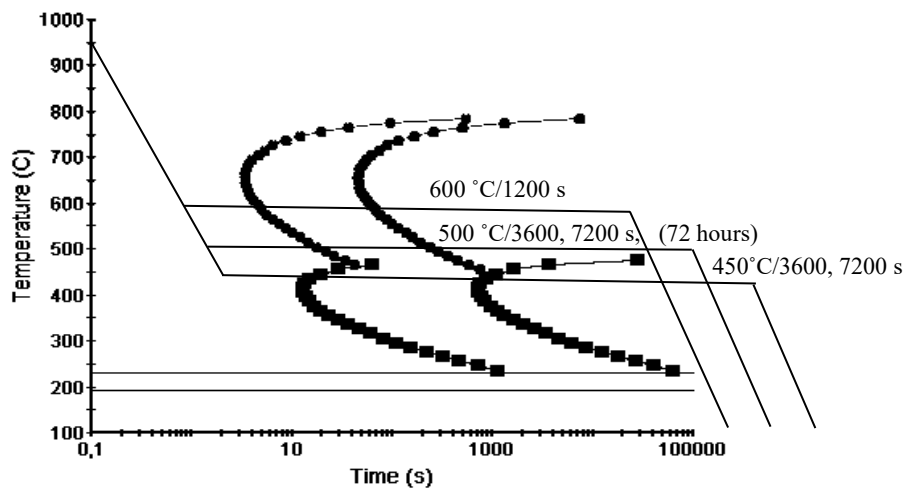


Figure 2. Experimental isothermal annealing sequences in the transition region between pearlitic and bainitic transformations.

The isothermal holding times were 1200, 3600, and 7200 seconds. After the annealing, the specimens were quenched in water. The specimens were threaded round bars with a diameter of 8 mm. Prior to this experiment, they had been annealed at 1050 °C for 15 minutes. The heating and cooling was carried out in a thermomechanical simulator with a induction-resistance heating capability.

3 Results and discussion

Microstructures of the specimens were examined using scanning electron microscopy. The etchant was 3 % nital. For reference, hardness was measured on the metallographic sections.

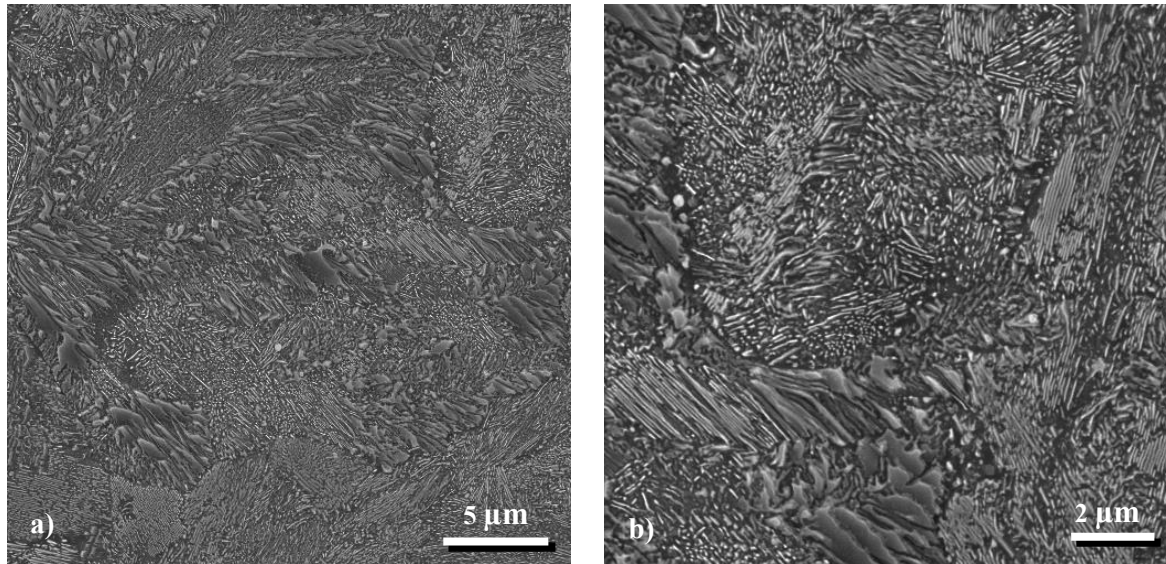


Figure 3. Micrograph of the specimen annealed at 600 °C for 1200 s
a) pearlite – 5000×, SEM, b) pearlite – 10000×, SEM.

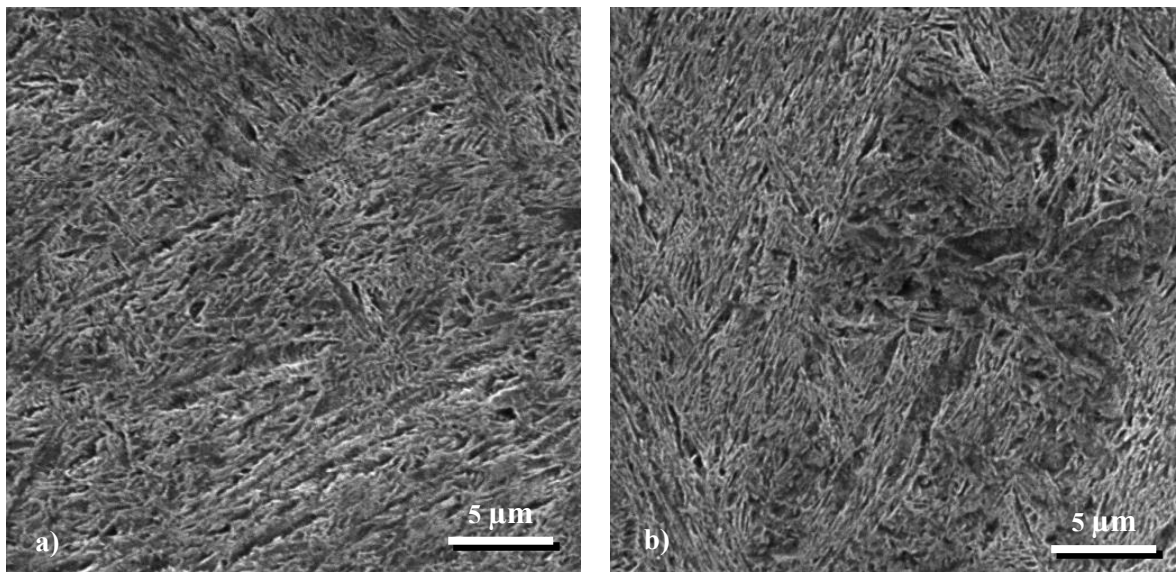


Figure 4. Microstructures of specimens annealed at 500 °C
a) specimen 500 °C/3600 s – martensite – 5000×, SEM, b) specimen 500 °C/7200 s – martensite – 5000×, SEM.

In specimens treated at 600 °C/1200 s, the microstructure consisted entirely of lamellar pearlite with a hardness of 344 HV10 (Figure 3). Specimens 500 °C/3600 s and 500 °C/7200 s contained martensite with a hardness of 720 and 728 HV10, respectively (Figure 4). These findings suggest that the austenite-pearlite transformation has not occurred, although it should have taken place in full, according to the theoretical diagram. For this reason, an additional sequence was carried out: annealing at 500 °C for 72 hours (referred to as 500 °C/72 hrs). It was completed in a salt

bath placed in the heat treatment furnace. Specimen 500 °C/72 hrs contained a mixture of lamellar pearlite and martensite (Figure 5). The hardness of this specimen was 430 HV10.

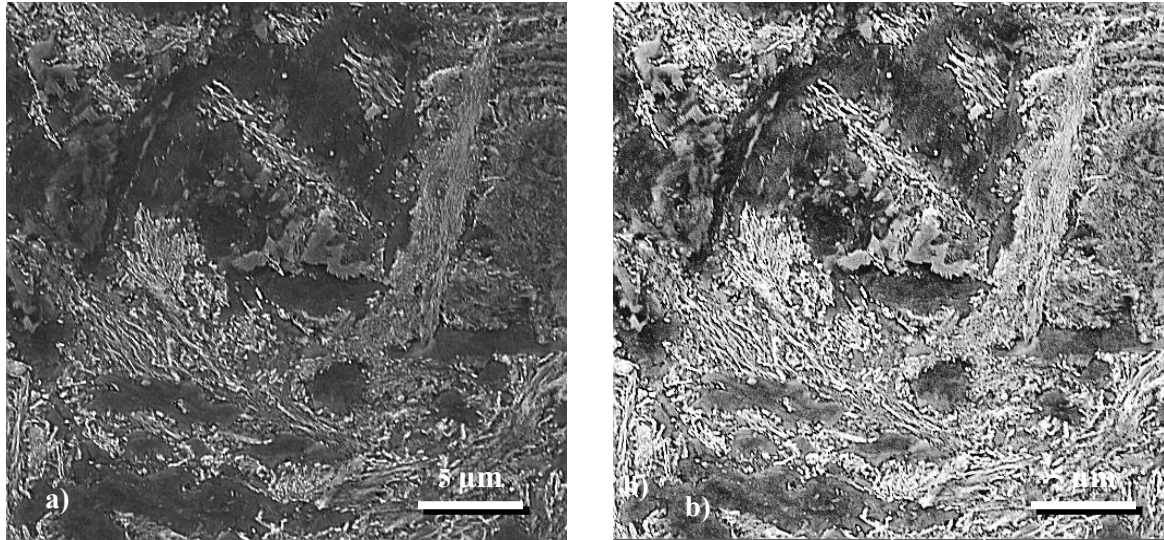


Figure 5. Micrograph of the specimen annealed at 500 °C for 72 hours

a) Pearlite – martensite – 5000×, SEM, b) Pearlite– martensite – phase contrast micrograph – 5000×, SEM.

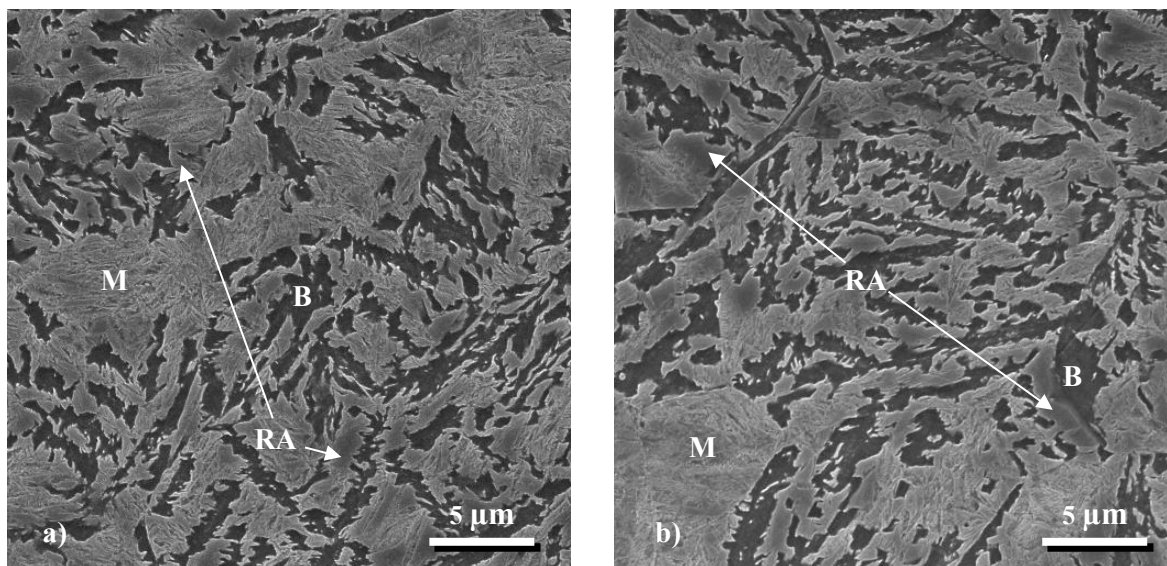


Figure 6. Microstructures of specimens annealed at 450 °C

a) specimen 450 °C/3600 s – bainite – martensite – retained austenite – 5000×, SEM, b) specimen 450 °C/7200 s – bainite – martensite – retained austenite – 5000×, SEM.

In specimen 450 °C/3600 s, microstructure consisted of a mixture of martensite, retained austenite, and upper bainite with a hardness of 520 HV10 (Figure 6a). Isothermal annealing for an extended period led to a slight increase in the bainitic phase and retained austenite fractions at the expense of the martensitic phase fraction (Figure 6b). The hardness of specimen 450 °C/7200 s was 525 HV10 (Table 2).

Table 2. Comparison of microstructures and hardness for different isothermal annealing temperatures and holding times.

Isothermal annealing temperature [°C]	Holding time [hours]	Microstructure	Hardness HV10
600	1/3	Pearlite	344
500	1	Martensite	720
500	2	Martensite	728
500	72	Martensite, pearlite	430
450	1	Martensite, bainite, retained austenite	520
450	2	Martensite, bainite, retained austenite	525

The effect of silicon on microstructural evolution in specimens 600 °C/1200 s can be explained with reference to the diffusional nature of the austenite-pearlite transformation. The isothermal annealing temperature was sufficient for the diffusion of substitutional elements including silicon – which therefore could not prevent the formation of cementite. The formation of cementite is one of the preconditions for the pearlitic reaction. The situation in specimens 500 °C/3600 s and 500 °C/7200 s was, in all likelihood, such that the undercooling of austenite was large enough to enable heterogeneous nucleation of pearlite but, at the same time, the intensity of silicon diffusion reached the critical limit for formation of pearlitic cementite. This means that the carbon-enriched lamellae which would at higher temperatures form cementite, contained such an amount of silicon which in fact prevented cementite from forming. The potential for reduction of silicon level in the lamellae which were super-saturated with carbon was, however, severely limited by the low temperature. This hypothesis could explain the long times of phase transformation in the sequences denoted as 500 °C/3600 s, 500 °C/7200 s, and 500 °C/72 hrs because the austenite-pearlite transformation would strongly depend on the diffusion rate of silicon.

In specimens 450 °C/3600 s and 450 °C/7200 s, the effect of silicon was manifested predominantly in the mechanism of bainitic transformation, more precisely in suppressing the carbide precipitation along the boundaries of ferrite laths which had formed by shear.

Given the above, it should be noted that besides the influence of silicon is necessary to take into consideration the effect of manganese and carbon, due to their effect on the stabilization of austenite. This step will be further aim of the research, which will be simultaneously carried out with regard to the distribution of manganese, carbon and silicon between observed phases. Further, detailed analysis will be made of the observed microstructures with respect to carbide precipitation. The comparison of the results with the results of an experiment on steel of similar carbon content and manganese but different silicon content. will be carried out

4 Conclusion

A low-alloy steel containing 0.56 % carbon, 2 % silicon, 0.56 % manganese, and 1.33 % chromium was used for a study of the stability of austenite during isothermal annealing in the transition region between pearlitic and bainitic transformations, in relation to high silicon content in the steel. It was proven that in this steel austenite can remain stable during isothermal annealing at 500 °C for periods of several hours. This finding could be explained by the effect of silicon on the mechanism of pearlite formation in steels. At sufficiently low temperatures which nevertheless still enable heterogeneous nucleation of pearlite on the boundaries of austenite grains and its growth by diffusion, higher silicon level can considerably slow down the austenite-pearlite transformation. It is very likely that this is due to very

low but non-zero diffusivity of silicon which can ultimately result in a very slow austenite-pearlite transformation.

Next stage of the research will be focused on the distribution of manganese, carbon and silicon between the present phases, the influence of these elements on the course of phase transformations of the austenite and detailed microstructure analysis.

Acknowledgements

This paper includes results of the project LO1502 Development of Regional Technological Institute. The project is subsidised by the Ministry of Education of the Czech Republic from specific resources of the state budget for research and development.

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