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The Progress of Bainitic Transformation during Austempering in Connection with the Alloying of Unconventional AHS Steels

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It is well known that incomplete bainitic transformation during austempering treatment is mainly caused by the supersaturation of austenite with carbon. Such supersaturated austenite becomes more stable and further stabilization is led by silicon alloying. Stable austenite does not transform and re-mains in the structure as so-called residual austenite. Therefore, carbides, which are desirable in a conventional bainitic structure, cannot be formed and carbide free bainite is formed. The positive effect of silicon and carbon on austenite stabilization in CFB structures has already been demonstrated and described. But chromium is another element that is crucial in the incomplete bainitic trans-formation. The influence of chromium on the development of microstructure in unconventional AHS steels during austempering is discussed in detail in the experiment in this paper.

Keywords: Austempering, AHSS, Chromium, Silicon, RA

1 Introduction

Austempering of higher-silicon steels leads to incomplete bainite transformation [1]. In such a case, the progress of austenite to bainite transformation is rather specific. The addition of silicon suppresses the precipitation of carbides during austenite decomposition into the bainitic structure [2, 3]. Such carbides would absorb a significant portion of carbon atoms that have been rejected from newly-formed regions of bainitic ferrite. Instead of precipitating as carbides, carbon diffuses into bordering austenite. The increasing concentration of carbon in untransformed austenite is the major cause of the suspension of bainite transformation. Once the amount of carbon in the austenite phase approaches a certain level, the transformation stops completely. The resulting microstructure consists of bainitic ferrite, retained austenite and/or fresh martensite in relative proportions governed primarily by the isothermal treatment temperature [4]. The main requirement for the processes described above is sufficient stability of untransformed austenite, which must not decompose during the subsequent isothermal treatment [5]. Its decomposition could be supported by adding silicon to the steel [6]. However, it seems that the presence of other alloying elements – manganese and especially chromium - is crucial for the full exploitation of the benefits of this element. The experimental program aimed to investigate the influence of chromium content on the development of unconventional bainitic structures resulting from the bainitic transformation incompleteness phenomenon. The results of the experimental programme indicated that low chromium content may be the cause of lower stability of untransformed austenite in the isothermal annealing phase, which is likely to result in its gradual decomposition. Consequently, the instability of untransformed austenite may lead to the suppression of the bainitic transformation incompleteness phenomenon, even though the experimental steel contains sufficient silicon to safely suppress carbide precipitation.

2 Experimental programme

Specimens of experimental steels 42SiCr (0.42%C, 0.62%Mn, 2%Si, 1.33%Cr) and 42SiMn (0.42%C, 0.62%Mn, 2%Si, 0.03%Cr) with initial ferritic-pearlitic structure were homogeneously annealed in a furnace with a protective atmosphere of argon at 1200°C for 3 h and then freely cooled in air before the actual experiment [7, 8]. The samples were then subjected to normalization annealing at 950°C for 1 hour with free cooling to room temperature. After machining the partially decarburized surface layers, the samples were subjected to the proposed heat treatment procedures, which consisted of heating to austenitizing temperature of 950°C with a holding time of 600 s and subsequent quenching to bainite isothermal annealing temperatures of 485, 470, 450, 420, 380 and 340°C with a holding time of 2000 s (Fig. 1).

The quenching rate was 50°C/s for 42SiCr steel and 110°C/s for 42SiMn steel. The higher quenching rate for the 42SiMn steel was to minimize the formation of allotriomorphic ferrite during cooling from the austenitization temperature. The isothermal annealing temperatures for bainite were chosen so that the evolution of the bainite structures could be monitored over the entire temperature interval of bainite formation (505 °C to 305°C), which was determined by calculations performed in JMatPro software (Fig. 2 a, b). The heating rate to austenitization temperature was 20°C/s. After isothermal treatment to bainite, samples from both steels were cooled at 50°C/s to room temperature (with three repetitions for each regime). The processed specimens were used to prepare test specimens for metallography by polishing and etching in 3% Nital etchant.

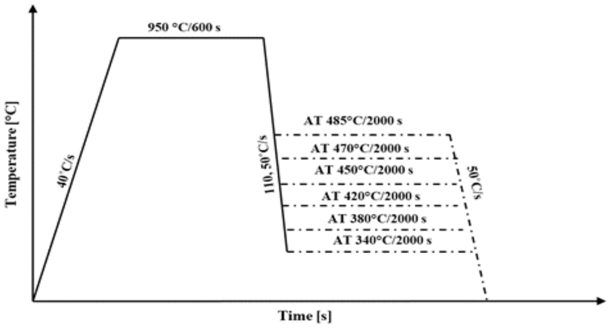

Fig. 1 *Diagram of heat treatment sequences for experimental specimens*

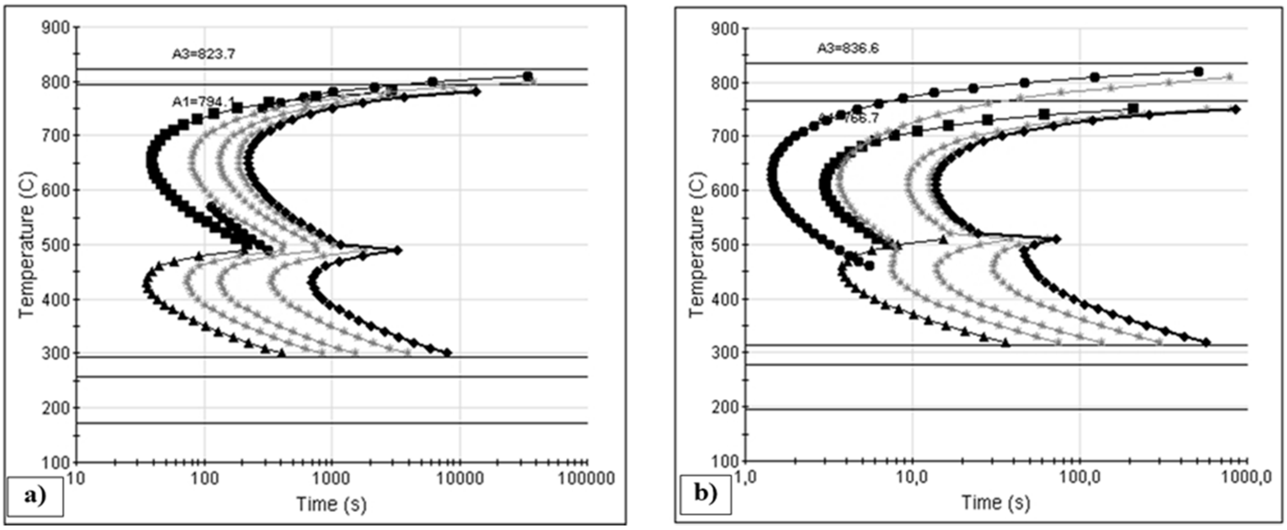

Fig. 2 *TTT diagrams of 42SiCr and 42SiMn steels - a) 42SiCr b) 42SiMn*

Microstructure evaluation was performed using TESCAN VEGA SB Easy Probe, and Zeiss SEM - FIB Cross Beam Auriga. Thermal processing of the samples was carried out on a thermomechanical simulator MTS 810 equipped with induction-resistance heating [9].

3 Results and discussion

The regime at 485°C/2000 s applied to 42SiCr steel led to a microstructure consisting of lath martensite and bainitic ferrite (Fig. 3, 6-a). Sequence AT 485°C/2000 s applied to 42SiMn steel produced a microstructure consisting mostly of bainite, a small amount of allotriomorphic ferrite and martensite (Figs. 3, 8-a). Morphology of the bainite regions was profoundly different from the microstructures in 42SiCr steel. In 42SiCr, bainitic ferrite had a form of separate needles. 42SiMn contained sheaves of bainite plates.

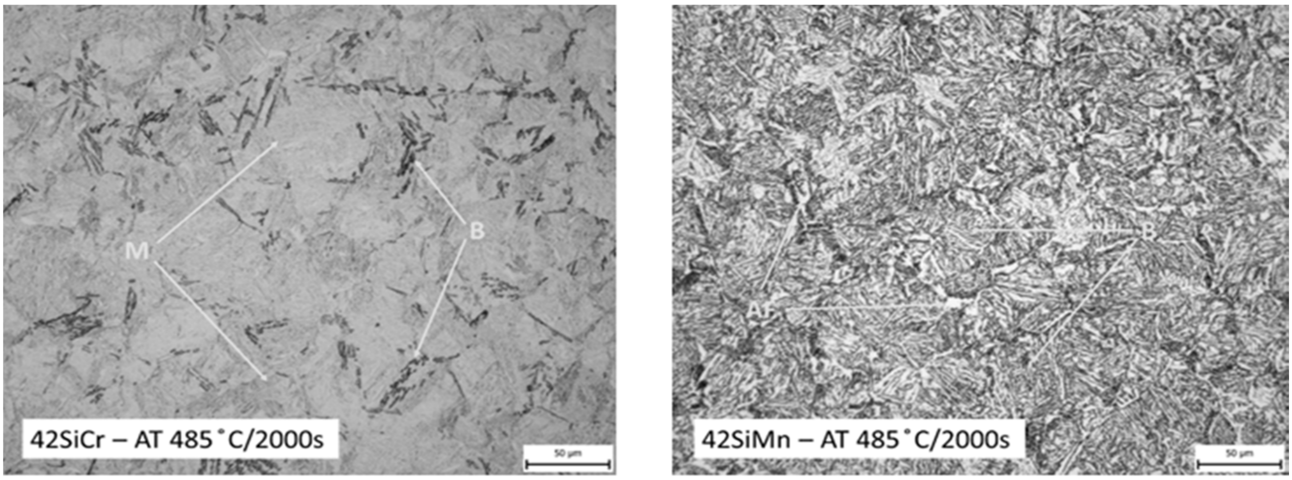

Fig. 3 *Light micrographs of specimens of 42SiCr and 42SiMn steels after austempering sequence AT 485°C/2000 s – 500×; B – bainite, M – martensite, AF – Allotriomorphic ferrite*

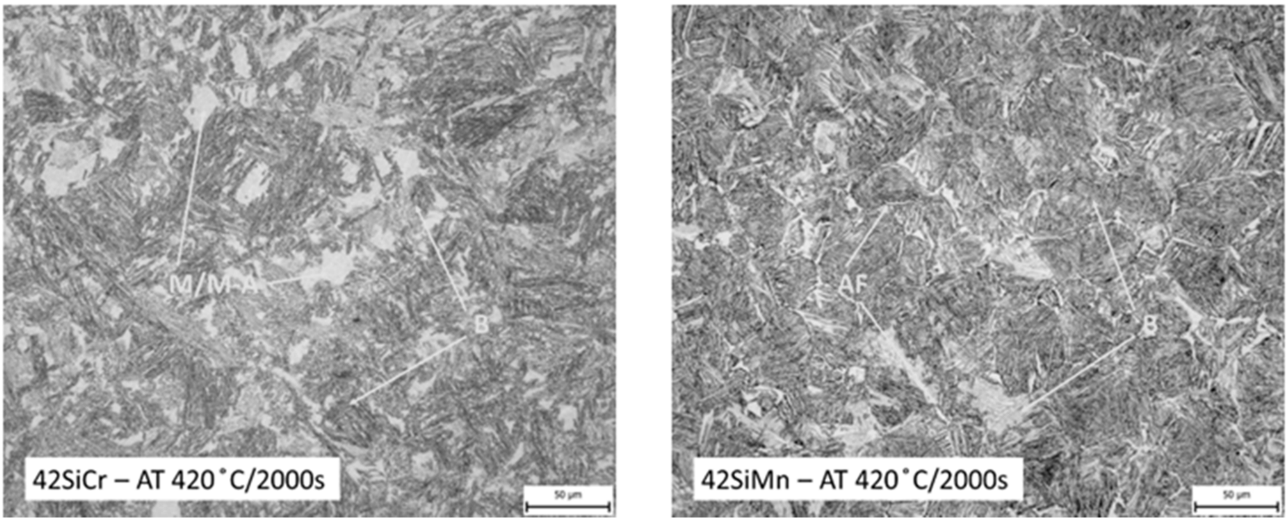

Fig. 4 *Light micrographs of specimens of 42SiCr and 42SiMn steels after austempering sequence AT 420°C/2000 s – 500×; B – bainite, M – martensite, AF – Allotriomorphic ferrite*

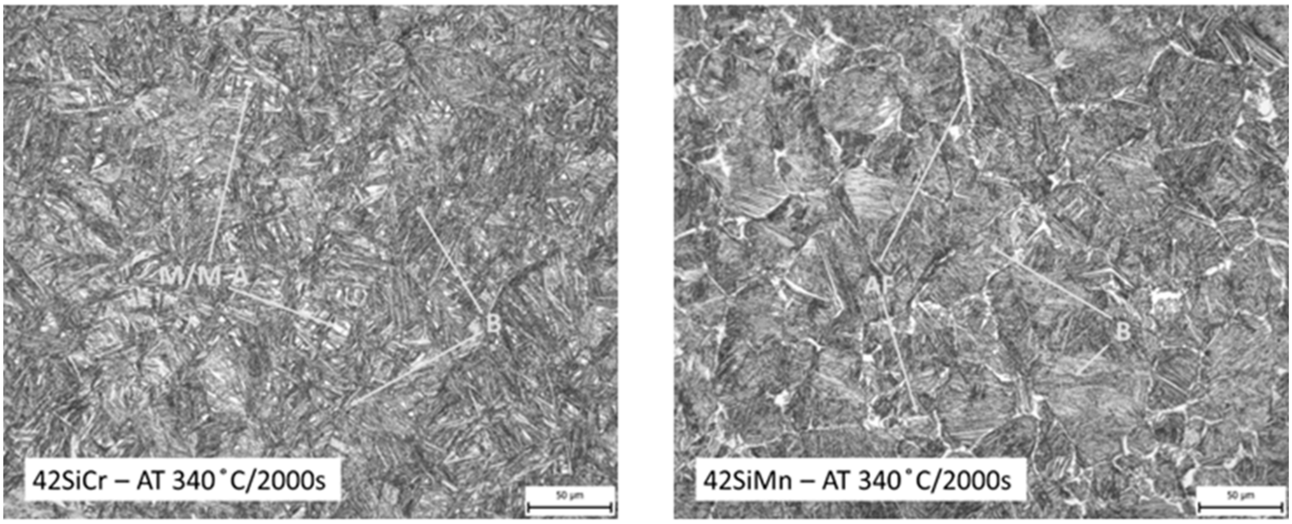

Fig. 5 *Light micrographs of specimens of 42SiCr and 42SiMn steels after austempering sequence AT 340°C/2000 s – 500×; B – bainite, M – martensite, AF – Allotriomorphic ferrite*

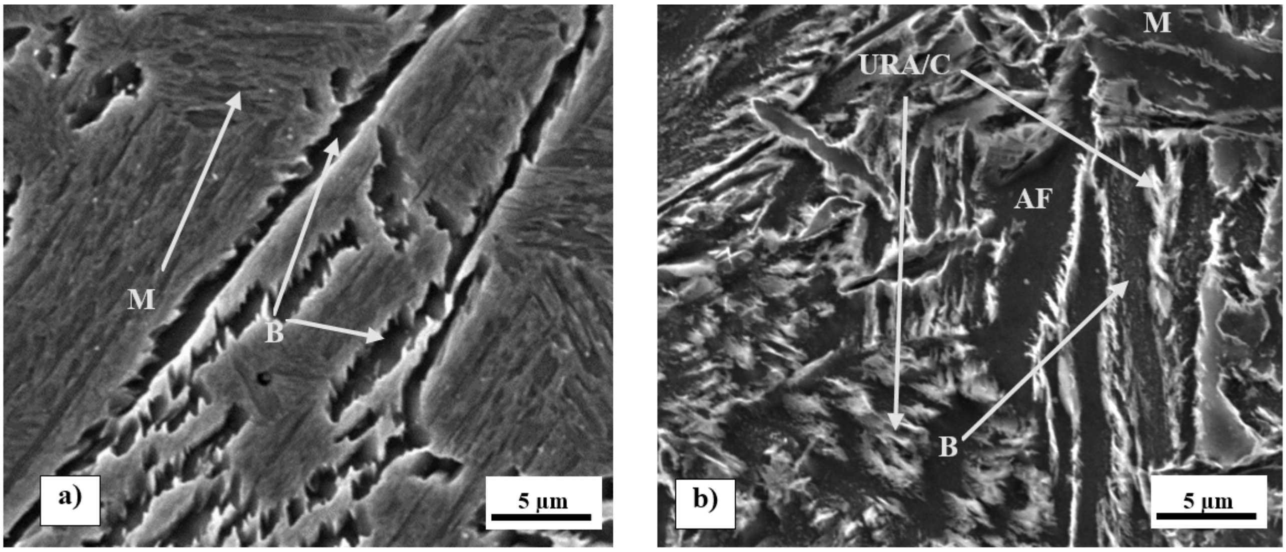

Fig. 6 *Micrographs of specimens of 42SiCr and 42SiMn steels after austempering sequence AT 485°C/2000 s – 5000×; a) 42SiCr, b) 42SiMn; B – bainite, M – martensite, AF – allotriomorphic ferrite, URA – unstable retained austenite, C – carbides*

An important difference between the microstructures of the steels was the volume fraction of bainite. In the 42SiCr steel, bainite was a minor component in contrast to the 42SiMn steel. The bainitic transformation in the 42SiCr steel did not lead to complete decomposition of austenite, but stopped at an early stage of austempering by the incomplete bainitic transformation phenomenon caused by the alloying elements Si, Cr. These alloying elements have a positive effect on the stability of austenite during isothermal heat treatment. The difference between the real structure evolution in 42SiCr steel compared with the evolution with the calculated TTT diagram was probably due to the thermodynamic model of the TTT diagram calculation. This model was based on the pre cipitation of carbide particles during the isothermal formation of bainitic ferrite, which normally leads gradually to the complete decomposition of primary austenite. In the real process, carbide formation was suppressed due to the presence of Si. Therefore, carbon diffusing from the bainitic ferrite into its surroundings caused the gradual stabilization of the residual untransformed austenite. As the carbon content of austenite increased, the B_{start} temperature decreased until it equalled the actual austempering temperature. Thereafter, the bainitic transformation stopped. Thus, the microstructure in the austempering phase consisted of bainite and untransformed austenite. The untransformed austenite was then converted to martensite during the final quenching step.

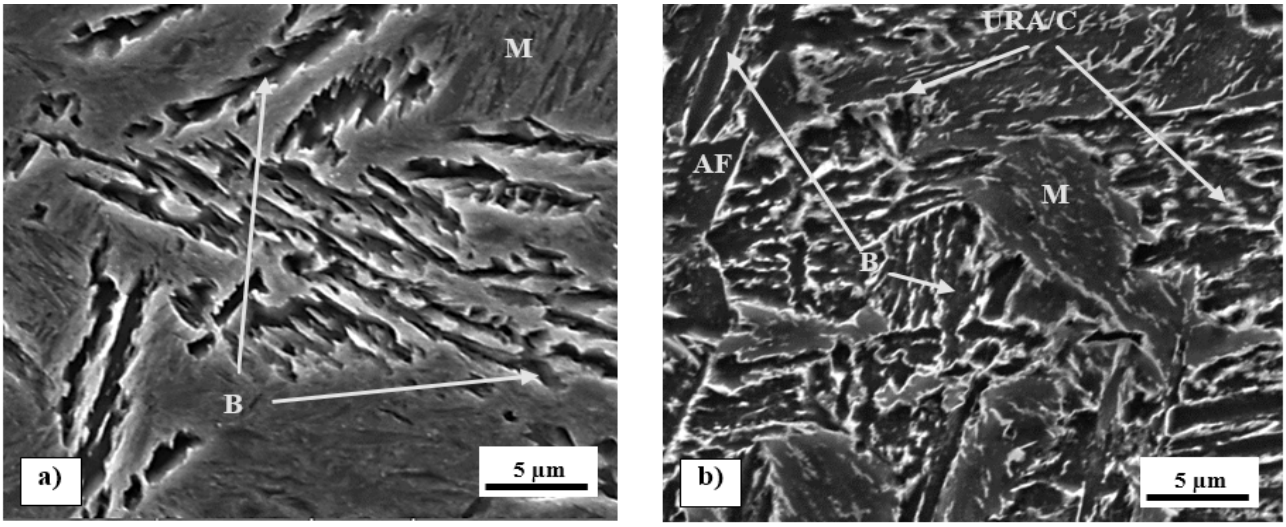

Fig. 7 *Micrographs of specimens of 42SiCr and 42SiMn steels after austempering sequence AT 470°C/2000 s – 5000×; a) 42SiCr, b) 42SiMn; B – bainite, M – martensite, AF – allotriomorphic ferrite, URA – unstable retained austenite, C – carbides*

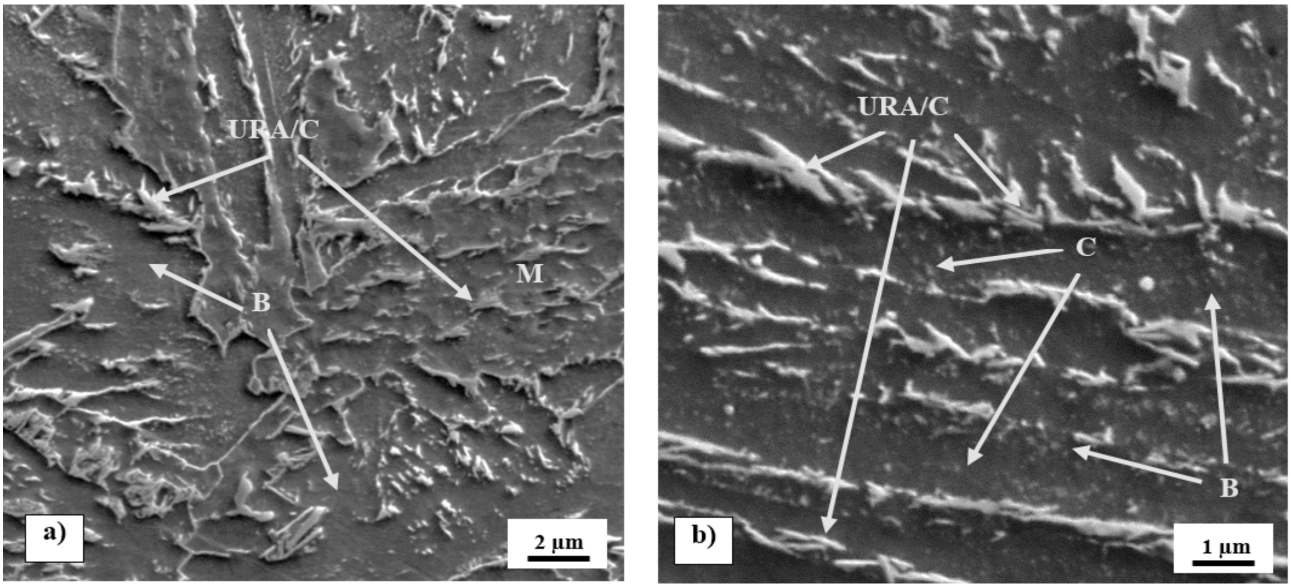

Fig. 8 *a) 42SiMn steel – detail micrograph – sequence AT 485°C/2000 s; B – bainite, M – martensite, URA – unstable retained austenite, C– carbides; b) 42SiMn steel – detail micrograph – sequence AT 470°C/2000 s; B – bainite, URA – un-stable retained austenite, C – carbides*

The structure of 42SiCr steel after sequence AT 470°C/2000 s is a mixture of martensite and bainite (Fig. 7-a). Like in sequence AT 485 °C/2000s, transformation of austenite to bainite was incomplete, with a majority of austenite still being present at the end of the isothermal hold. Austenite then transformed to lath martensite upon the final quench. In 42SiMn, sequence AT 470°C/2000s produced a microstructure in which bainite was the dominant phase, with what was assumed to be unstable retained austenite, and carbide precipitates, martensite grains, and a small amount of allotriomorphic ferrite (Fig. 7-b, 8-b).

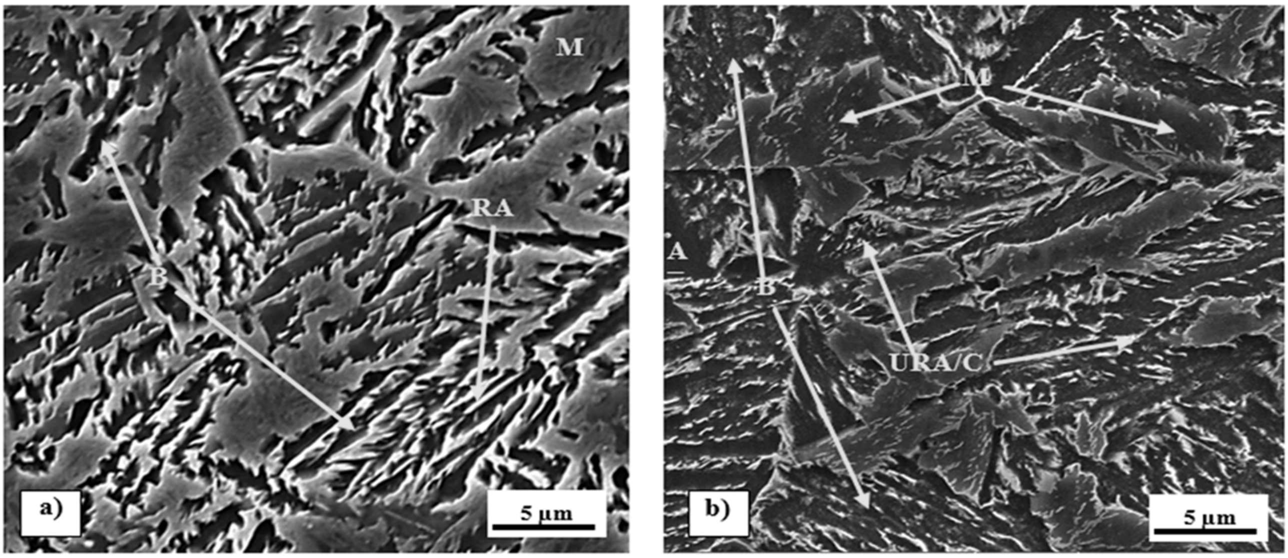

Fig. 9 *Micrographs of austempered specimens of 42SiCr and 42SiMn steels after sequence AT 450°C/2000s – 5000×; a) 42SiCr, b) 42SiMn; B – bainite, M – martensite, AF – allotriomorphic ferrite, RA – retained austenite, URA – unstable retained austenite, C – carbides*

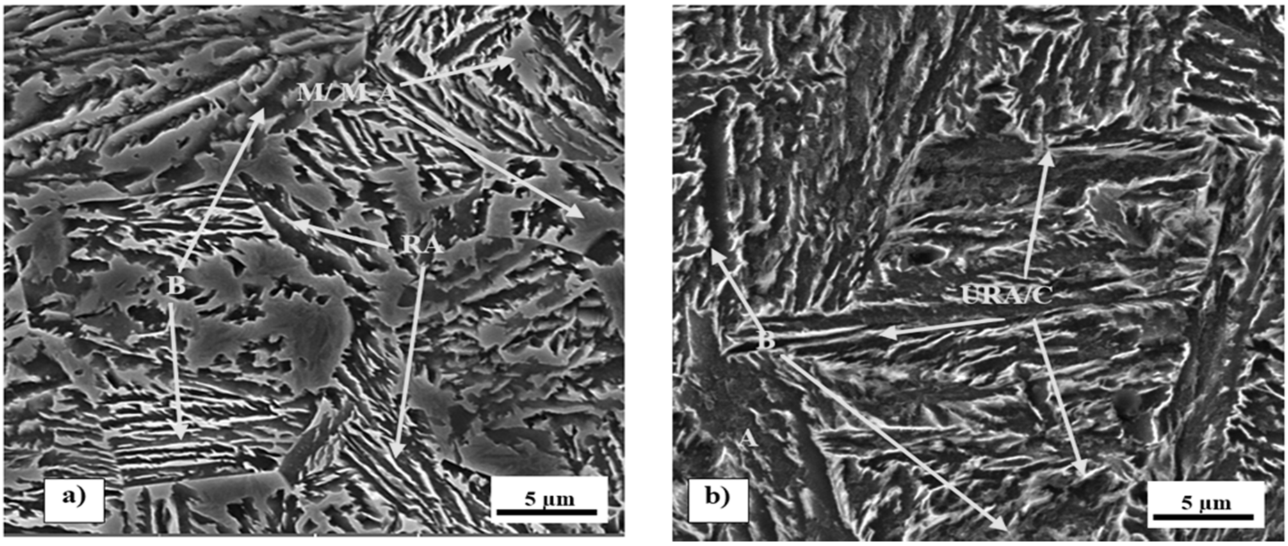

Fig. 10 *Micrographs of austempered specimens of 42SiCr and 42SiMn steels after sequence AT 420°C/2000 s – 5000×; a) 42SiCr, b) 42SiMn; B – bainite, M-A – M-A constituent, AF – allotriomorphic ferrite, RA – retained austenite, URA – unstable retained austenite, C – carbides*

In the case of isothermal annealing, partial decomposition of austenite into bainite took place in 42SiCr steel. In 42SiMn steel, annealing led to an extensive austenite-bainite transformation. The actual extent of the austenite-bainite transformation was much larger than the extent which had been expected based on the amount of silicon – 2 wt % of Si.

The regime of AT 450°C/2000 s produced martensite and bainite and what was presumed to be retained austenite in 42SiCr steel (Figs. 9-a, 11-a). The isothermal treatment temperature was lower than in sequences AT 485°C/2000 s and 470°C/2000 s. As a result, the volume of the bainite fraction was larger. Despite that, a significant volume of retained austenite occurs in the structure up to the quenching phase. During quenching, the RA transformed to martensite. In 42SiMn, regime AT 450°C/2000 s led to a microstructure consisted of bainite, which dominated in the microstructure, a portion of allotriomorphic ferrite and martensite and areas of presumed retained austenite and/or carbides were also present in the structure (Figs. 9-b, 12-a).

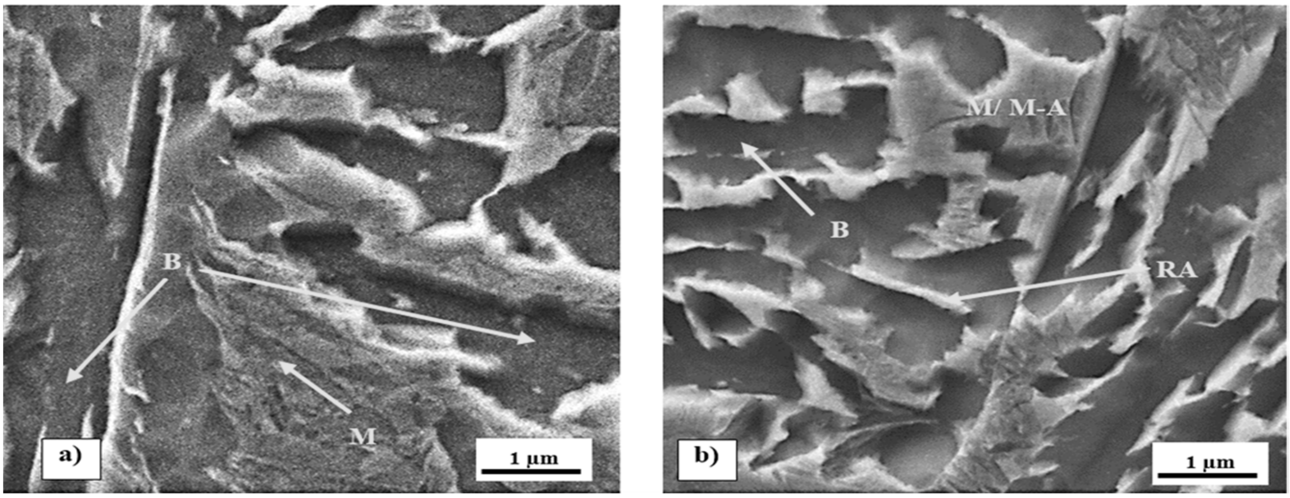

Fig. 11 *a) 42SiCr steel – detail micrograph; sequence AT 450°C/2000 s; b) 42SiCr steel – detail micrograph; sequence AT 420°C/2000 s; B– bainite, M – martensite, M-A – M-A constituent, RA – retained austenite*

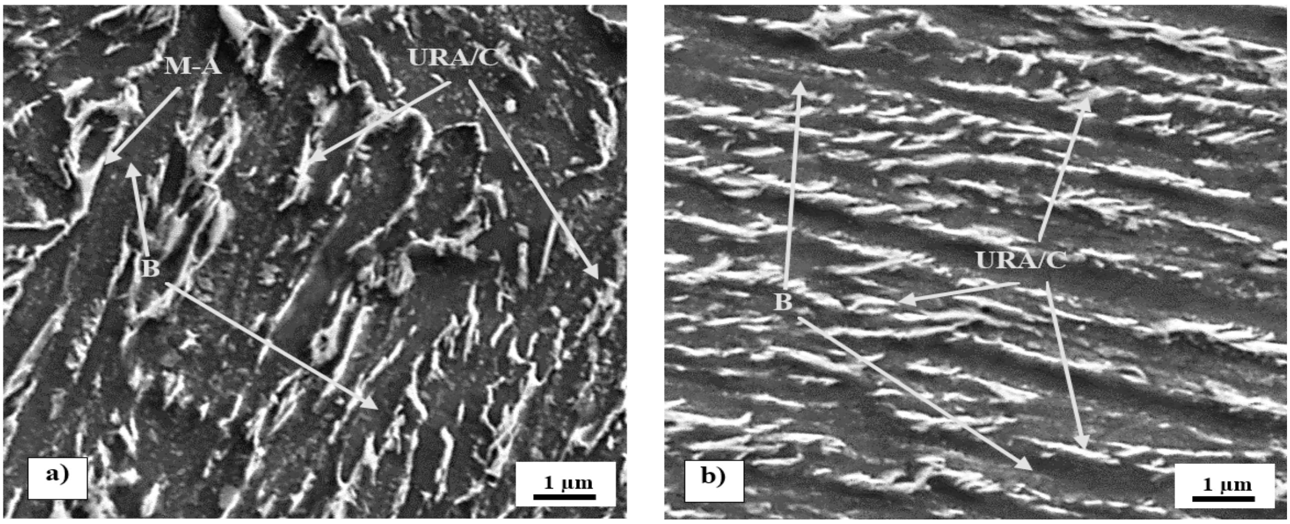

Fig. 12 *a) 42SiMn steel – detail micrograph; sequence AT 450°C/2000, b) 42SiMn steel – detail micrograph – sequence AT 420°C/2000 s; B – bainite, URA – unstable retained austenite, C – carbides*

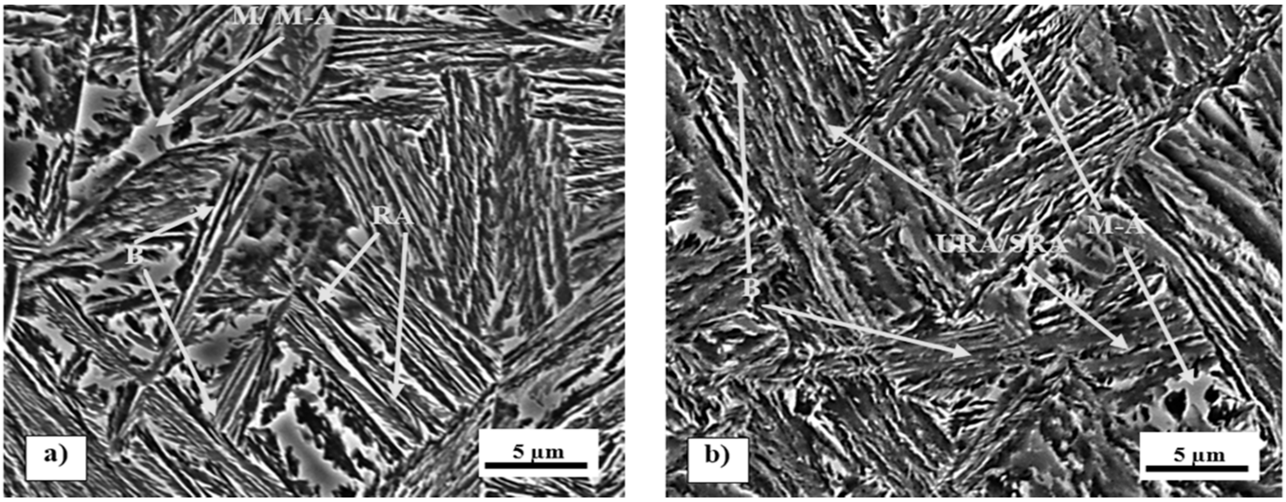

Fig. 13 *Micrographs of austempered specimens of 42SiCr and 42SiMn steels after sequence AT 380°C/2000 s – 5000×; a) 42SiCr, b) 42SiMn; B – bainite, M-A – M-A constituent, RA – retained austenite, M – martensite, URA – unstable retained austenite, SRA – stable retained austenite*

A mixture of bainite, martensite and grains of the M-A constituent and/or retained austenite was made in 42SiCr by sequence AT 420°C/2000 s (Figs. 4, 10-a, 11-b). Specimens of 42SiMn steel contained bainite, a minor amount of allotriomorphic ferrite, unstable retained austenite and/or carbide precipitates, and a small amount of retained austenite. No martensite was found in the microstructure (Figs. 4, 10-b, 12-b).

In 42SiCr steel, sequence AT 380°C/2000 s led to bainitic ferrite, suspected retained austenite and M-A constituent (Figs. 13-a, 15-a). The suspected retained austenite had a form of thin films along bainitic ferrite needles. The suspected M-A constituent appeared to form small islands, mostly along prior austenite grain boundaries and between bainite needle sheaves. 42SiMn contained bainite and a small amount of allotriomorphic ferrite and suspected M-A constituent (Figs. 13-b, 16-a). The reduced temperature of isothermal treatment resulted in appreciable refinement of the bainitic structure. Analogous conclusions apply to sequence AT 340°C/2000 s. In 42SiCr steel, sequence AT 340°C/2000 s produced bainitic ferrite, what was suspected to be M-A constituent and small grains of retained austenite (Figs. 5, 14-a, 15-b). In 42SiMn steel, sequence AT 340°C/2000 s led to bainitic ferrite and carbide precipitates. (Figs. 5, 14-b, 16-b).

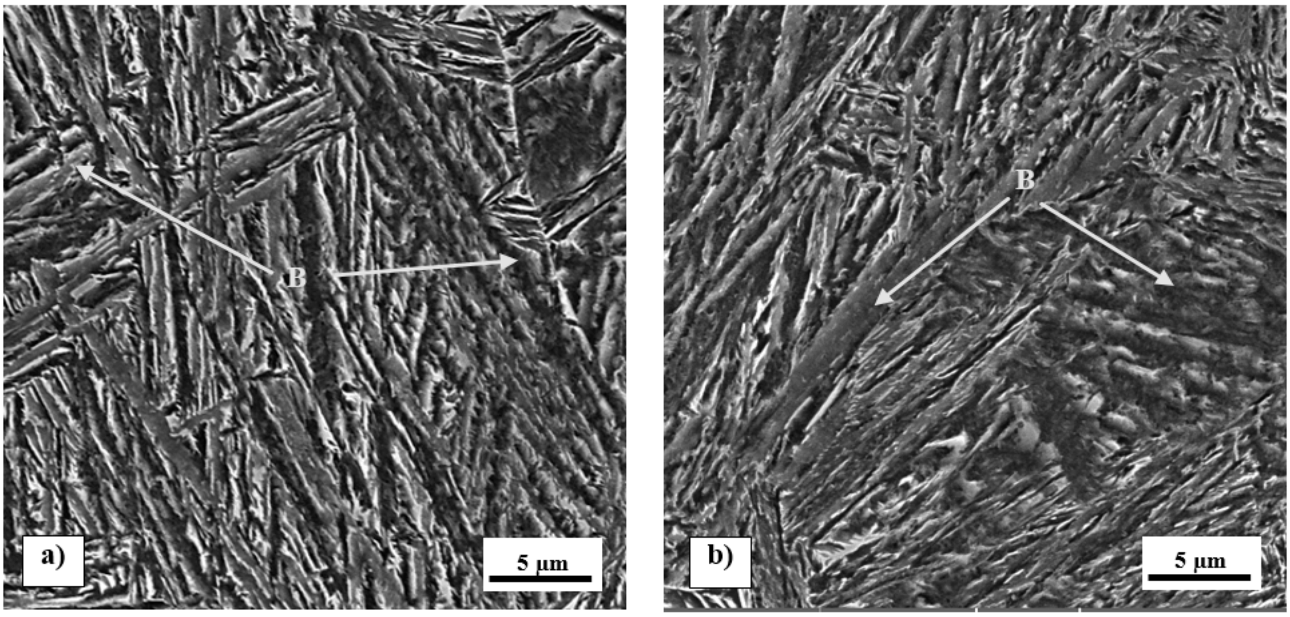

Fig. 14 *Micrographs of specimens of 42SiCr and 42SiMn steels after austempering sequence AT 340°C/2000 s – 5000×; a) 42SiCr, b) 42SiMn; B – bainite*

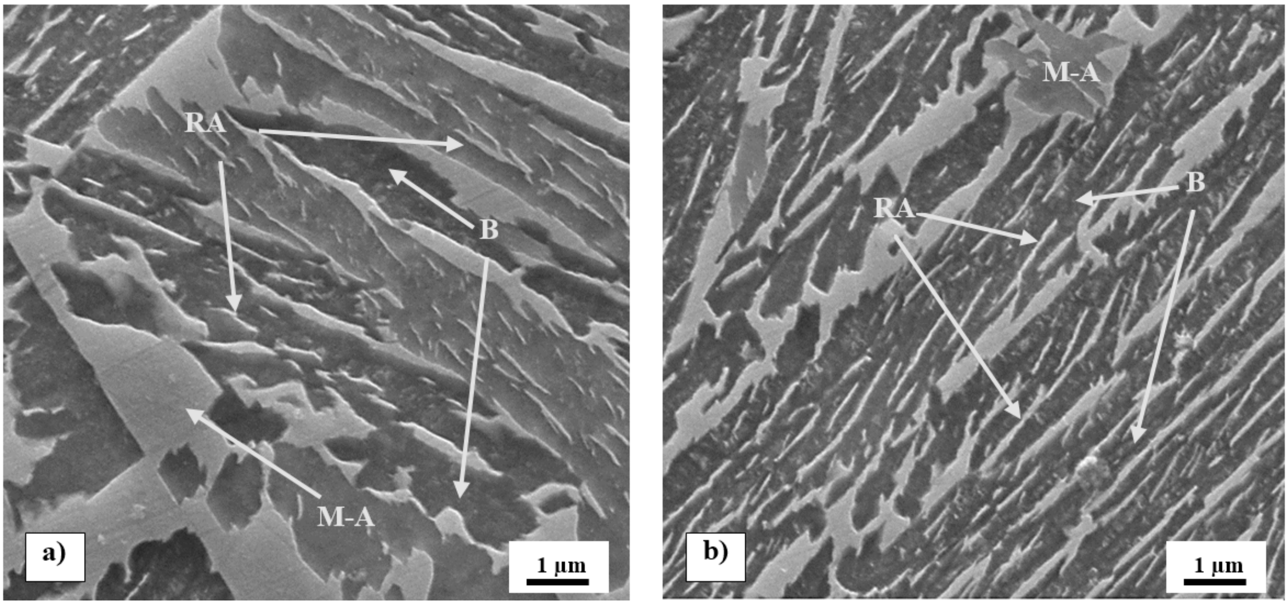

Fig. 15 *a) 42SiCr steel – detail micrograph; sequence AT 380°C/2000 s; B – bainite, M-A – M-A constituent, RA – re-tained austenite; b) 42SiCr steel – detail micrograph; sequence AT 340°C/2000 s; B – bainite, M-A – M-A constituent, RA – retained austenite*

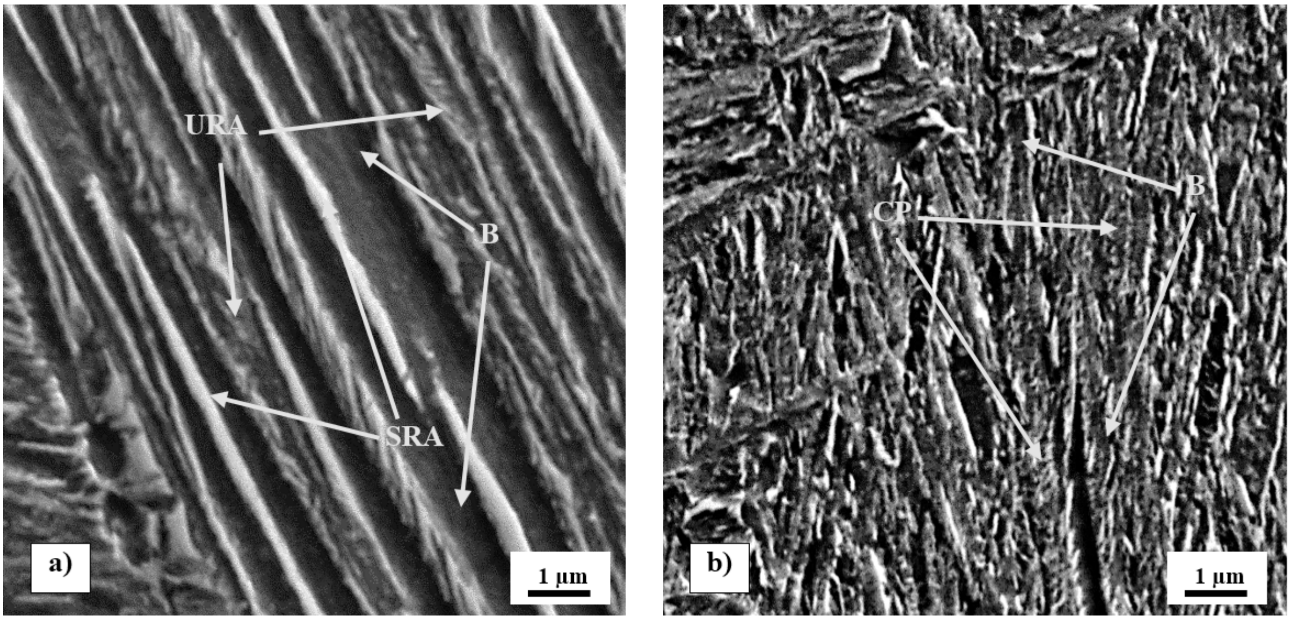

Fig. 16 *a) 42SiMn steel – detail micrograph – sequence AT 380°C/2000 s; B – bainite, URA – unstable retained austenite, SRA – stable retained austenite b) 42SiMn steel – detail micrograph – sequence AT 340°C/2000 s; B – bainite, CP – carbide precipitates*

4 Conclusion

The paper deals with the influence of austempering of chromium alloyed medium carbon steels on the development of their microstructure. The investigated experimental steels were AHSS 42SiCr and 42SiMn. Samples of these steels were heat-treated on a thermomechanical simulator. The heat treatment regimes included austenitization at 950 °C for 600 seconds, followed by cooling to bainitic transformation temperatures of 485, 470, 450, 420, 380 and 340 °C, at which the samples were maintained for 2000 seconds. The isothermal treatment was followed by cooling to room temperature.

During austempering, the bainitic transformation of the 42SiCr steel with 1.33 wt.% chromium stopped before full completion. The rate of progression of the transformation depended on the temperature of isothermal processing. After isothermal processing at 485, 470 and 450 °C, the resulting microstructure consisted mainly of fresh martensite, bainitic ferrite and small grains of untransformed austenite, or M-A component. The proportion of bainitic ferrite increased with decreasing isothermal processing temperature. At even lower processing temperatures, 420, 380 and 340 °C, the presence of martensite gradually minimized while the proportion of bainite increased. A completely different microstructural evolution process was observed for the 42SiMn steel, which contained 0.03 wt.% chromium. Isothermal processing regimes carried out at 485, 470 and 450 °C led to a microstructure dominated by bainitic ferrite accompanied by a small amount of martensite and unstable untransformed austenite, part of which eventually disintegrated in parallel with carbide precipitation. Lowering the isothermal processing temperatures to 420, 380 and 340 °C led to the formation of bainitic structures whose morphology was similar to that of 42SiCr steel. In the 42SiMn steel, extensive austenite to bainite decomposition occurred during all isothermal endurance phases.

The differences in microstructural evolution in austempered 42SiCr and 42SiMn steels suggest that not only sufficient silicon but also chromium was most likely important for the incompleteness of the bainitic transformation. In the case of 42SiMn steel, the absence of chromium manifested itself in the marked instability of the untransformed austenite during isothermal maintenance. In general, the addition of chromium to 42SiCr may have been the cause of the re-decrease in silicon diffusivity. As a consequence, silicon was difficult to precipitate from the untransformed austenite. This phase, therefore, retained sufficient stability, leading to an incomplete bainitic transformation.

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