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Relationship between Mechanical Properties in 42SiCr and 42SiMn Medium-carbon Steels and Austempering Temperatures

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In conventional steels, bainitic microstructure which forms under isothermal conditions consists of bainitic ferrite and carbide precipitates whose distribution and size substantially depend on the parameters of isothermal treatment. In CFB steels (Carbide Free Bainite) however, the main microstructural constituents are bainitic ferrite, retained austenite and, sometimes, the M-A constituent. CFB microstructure may possess better ductility and the same or even higher strength than microstructures of bainitic ferrite and carbide precipitates. This advantage results from the principle of formation of the CFB microstructure and is related to the absence of brittle carbides and their substitution with retained austenite. This paper explores the effect of austempering on mechanical properties of unconventional CFB steels 42SiCr and 42SiMn.

Keywords: Austempering, CFB structure, Silicon, Mechanical properties

1 Introduction

CFB (Carbide Free Bainite) steels are new-generation steels which possess an attractive combination of mechanical properties for technical applications [1]. These properties are dictated by their structure which ideally comprises carbide-free bainitic ferrite and retained austenite. Isothermal treatment in the bainitic transformation region can only produce CFB structure if the steel contains a sufficient amount of silicon or aluminium [2, 3]. When the formation of carbide precipitates during isothermal treatment is suppressed, bainitic transformation remains incomplete. It is a consequence of thermodynamic processes related to the migration of carbon between the newly-formed ferrite and still-untransformed austenite in its vicinity [4,5]. Since carbon has a different solubility in each of the phases, isothermal annealing of CFB steels causes untransformed austenite to become enriched with carbon. With more carbon, untransformed austenite becomes more stable. In other words, the temperature at which bainitic ferrite forms becomes lower. If the amount of carbon in untransformed austenite reaches a critical level during isothermal treatment, the temperature of bainitic transformation drops to or below the current temperature of the material [6]. This substantially hinders the austenite-bainite transformation which can only continue to a very limited extent [7]. The resulting properties depend on the structure of the CFB steel which is, in turn, dictated by its chemical composition and the isothermal treatment temperature.

2 Materials and methods

The materials were medium-carbon low-alloy 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). They were supplied in the form of 60-kg ingots. They were sectioned and homogenized for 6 hours at 1200°C in an argon atmosphere and normalized at 950°C for 2 hours. The annealed material was hot-forged into bars 18 mm in diameter. The forged bars were homogenized at 1200°C for 3 hours in a protective atmosphere and normalized at 950°C for 2 hours. Specimens for processing in a thermomechanical simulator were machined from the bars. TTT and austenitization diagrams for the steels were determined using JMatPro software, as well as approximate temperatures and times for full austenitizing and homogenization, temperature windows for isothermal decomposition of austenite into bainite and approximate Ms temperatures (Fig. 1). Isothermal treatment routes were proposed for exploring the effect of isothermal treatment temperature on mechanical properties in these steels (Fig. 2). Each of the routes was repeated three times. Test pieces for tensile testing and microstructure observation were then prepared from the processed specimens.

The instruments used for microstructure observation included scanning electron microscopes TESCAN VEGA SB Easy Probe, and SEM–FIB Cross Beam Auriga. The etchant was 3 % nital. Heat treatment and tensile testing was carried out in thermomechanical simulator MTS 810 with induction-resistive heating devices and testing grips, respectively [8].

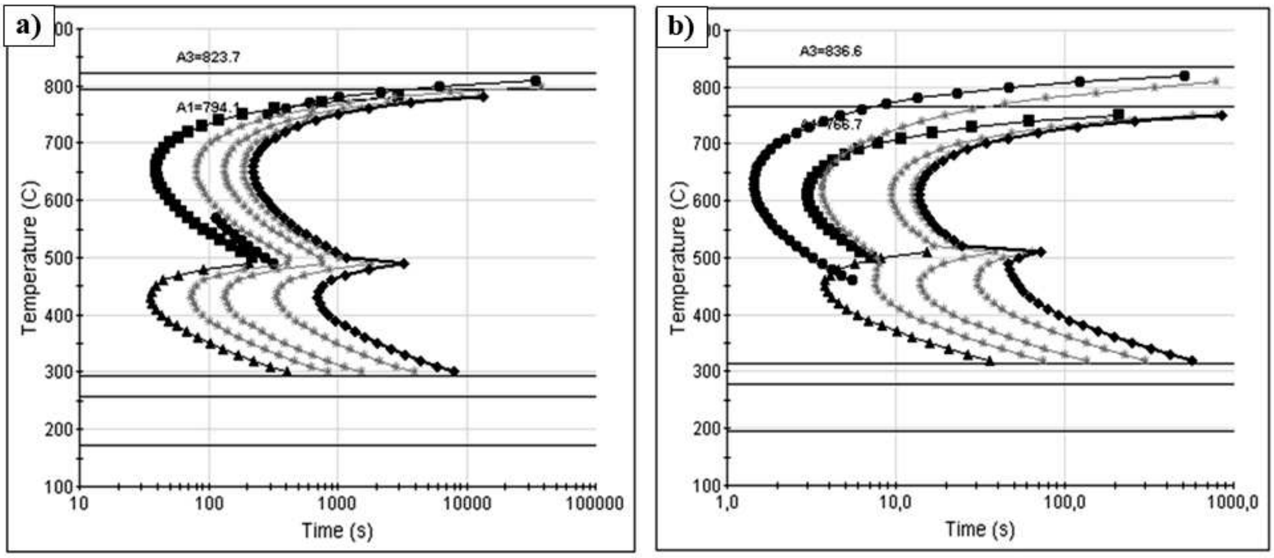

Fig. 1 *TTT diagrams of the steels a) 42SiCr b) 42SiMn*

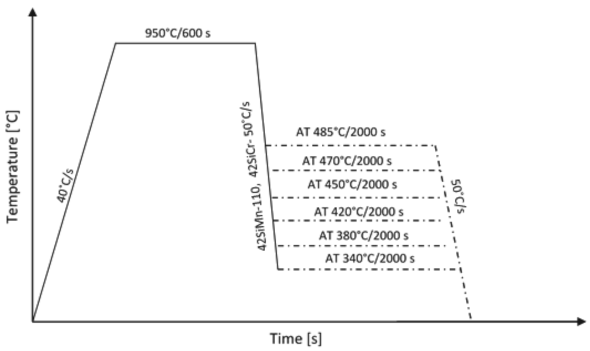

Fig. 2 *Diagram of heat treatment routes*

3 Results and discussion

Ultimate tensile strength (UTS) data led to important conclusions (Fig. 3, Tab. 1). Among the specimens of 42SiMn steel, the ones with the lowest average strength (UTS = 907 ± 16 MPa) were those treated according to AT 485°C/2000s. The highest strength, in turn, was UTS = 1313 ± 18 MPa for AT 340°C/2000s specimens. In all specimens of 42SiMn, the microstructure consisted of a majority of bainitic ferrite, carbide precipitates and possibly unstable retained austenite and a small amount of martensite (Fig. 4). With the isothermal treatment temperatures lowered in each subsequent route, the microstructures became finer which was consistent with increasing strength of the specimens. In 42SiCr, the trend in UTS was different. In 42SiCr, the highest average strength UTS = 2073 ± 36 MPa was obtained with the AT 485°C/2000s route. Interestingly, the same route led to the lowest strength in the other steel, 42SiMn. The cause of this difference in UTS in 42SiCr was the presence of a large fraction of virgin martensite due to incomplete bainitic transformation. As the isothermal treatment temperature was lowered, the amount of virgin martensite decreased, leading to lower strengths, down to UTS = 1363 ± 18 MPa for the AT 380°C/2000s route. The eventual increase to UTS = 1542 ± 14 MPa for the AT 340°C/2000s route was most likely due to the overall refinement of the bainitic structure.

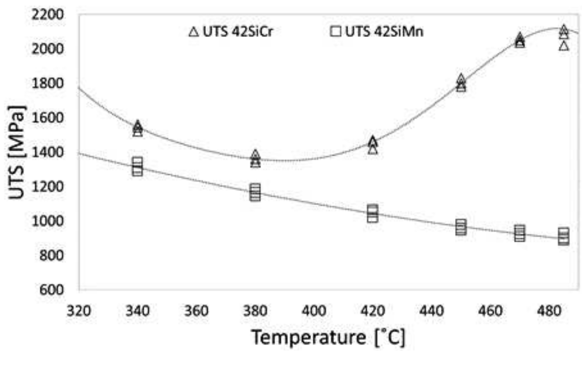

Fig. 3 *Ultimate tensile strength (UTS) in austempered (AT) specimens of 42SiCr and 42SiMn after isothermal treatment*

Tab. 1 *Ultimate tensile strength (UTS) in austempered specimens of 42SiCr and 42SiMn after isothermal treatment*

Treatment route	UTS 42SiCr [MPa]	UTS 42SiMn [MPa]
AT 485°C/2000s	2073 ± 36	907 ± 16
AT 470°C/2000s	2052 ± 12	927 ± 12
AT 450°C/2000s	1803 ± 18	962 ± 12
AT 420°C/2000s	1450 ± 20	1045 ± 17
AT 380°C/2000s	1363 ± 18	1165 ± 13
AT 340°C/2000s	1542 ± 14	1313 ± 18

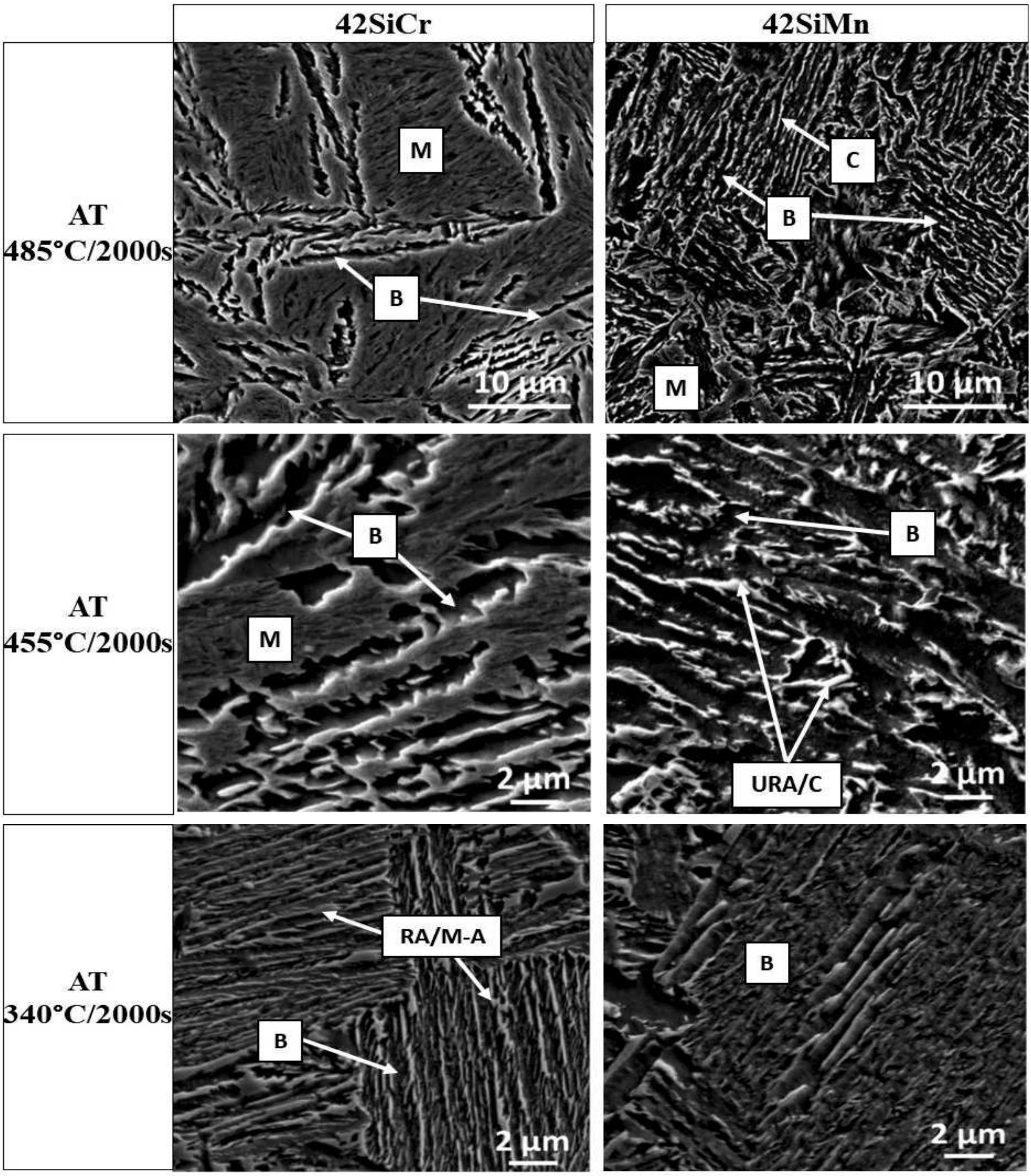

Fig. 4 *Microstructures of 42SiCr and 42SiMn steels after isothermal treatment at different temperatures – B – bainite, C – carbides, RA – retained austenite, URA – unstable retained austenite, M-A – M-A constituent*

The trend of yield strength (YS) was similar to that of the UTS (Fig. 5, Tab. 2). In 42SiMn, the lowest yield strength YS =642 ± 21 MPa was found after the route AT 485°C/2000s. The highest YS = 1030 ± 13 MPa was obtained with AT 340°C/2000s. In 42SiCr, the highest average yield strength YS = 1542 ± 21MPa was found after AT 485°C/2000s. Analysis of the material suggests that this YS value was, again, a consequence of a majority of virgin martensite in the microstructure. YS decreased with isothermal treatment temperatures. The minimum was reached after AT 420°C/2000s route where the microstructure consisted mainly of bainitic ferrite and probably retained austenite or the M-A constituent. After treatment below 420°C, the YS values were higher again. It was most likely due to higher strength of the structure consisting of bainite and retained austenite – owing to finer bainitic ferrite needles and chemical and strain-induced stabilisation of retained austenite.

***Tab. 2** Yield strength (YS) in austempered specimens of 42SiCr and 42SiMn after isothermal treatment*

Treatment sequence	YS 42SiCr [MPa]	YS 42SiMn [MPa]
AT 485°C/2000s	1542 ± 21	642 ± 21
AT 470°C/2000s	1245 ± 17	680 ± 20
AT 450°C/2000s	918 ± 12	707 ± 24
AT 420°C/2000s	727 ± 18	810 ± 17
AT 380°C/2000s	1053 ± 16	923 ± 14
AT 340°C/2000s	1197 ± 12	1030 ± 13

In specimens of 42SiMn, the average total elongation TE_{5mm} values remained very close after routes with temperatures down to 420˚C: 22–24% (Fig. 6, Tab. 3). In 42SiCr, the presence of virgin martensite in specimens AT 485, 470 and 450°C/2000s was the likely cause of the difference in the TE_{5mm} profile from the trend seen in 42SiMn. Another possible reason of the decrease of total elongation with the treatment temperature in specimens AT 485, 470 and 450°C/2000s was the coarseness of bainitic ferrite. When a predominantly bainitic microstructure was formed, possibly with retained austenite, total elongation was higher. The maximum average TE_{5mm} = 26% was found in the AT 380°C/2000s specimen.

***Tab. 3** Total elongation TE_{5mm} in austempered specimens of 42SiCr and 42SiMn after isothermal treatment*

Treatment route	TE_{5mm} 42SiCr [%]	TE_{5mm} 42SiMn [%]
AT 485°C/2000s	10 ± 1	22 ± 1
AT 470°C/2000s	7 ± 1	22 ± 1
AT 450°C/2000s	4 ± 1	23 ± 1
AT 420°C/2000s	18 ± 1	24 ± 1
AT 380°C/2000s	26 ± 1	20 ± 1
AT 340°C/2000s	21 ± 2	14 ± 1

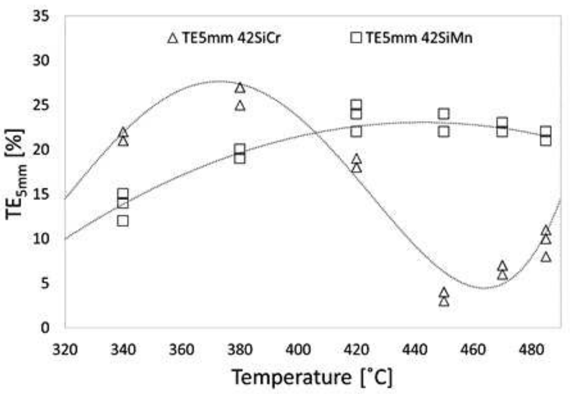

***Fig. 6** Total elongation (TE) in austempered specimens of 42SiCr and 42SiMn after isothermal treatment*

Examination of mechanical properties obtained with routes involving different temperatures revealed that the different chromium addition in 42SiMn (0.03% wt.) led to lower UTS in predominantly bainitic structures, the decrease being 200 to 250 MPa. It also led to lower YS, by more than 100 MPa, and elongation TE_{5mm} by approximately 6%. Besides the different strengthening behaviour of solid solution, the main reason was the difference in the austenite-bainite transformation. In 42SiMn, the bainitic transformation was complete, and therefore retained austenite decomposed – instead of stabilization. This follows from the TTT diagrams of both steels, from which it is clear that the 42SiMn steel always fully transformed due to shorter transformation times, and in the case of using lower tempering temperatures, the microstructure was almost fully bainitic. At the same time, carbides precipitated in the material.

4 Conclusion

The effect of chromium content on mechanical properties and microstructural evolution in medium-carbon steels 42SiCr and 42SiMn during austempering was explored. The specimens were heat-treated in a thermomechanical simulator: heating to austenitizing temperature of 950°C, holding for 600 seconds and then quenching to defined temperature: 485, 470, 450, 420, 380, 340°C and holding for 2000 seconds. Isothermal holding was followed by quenching to ambient temperature.

Austempering was proven to lead to attractive and useful combinations of strength and ductility in these steels. In 42SiMn, the highest ultimate strength was UTS = 1313 ± 18 MPa, with yield strength YS = 1030 ± 13 MPa and total elongation TE5mm 14 ± 1 % in the specimens which were held at 340˚C. Their microstructures consisted of bainitic ferrite and possibly unstable retained austenite which showed signs of decomposition accompanied by precipitation of carbides. Higher temperatures of isothermal treatment led to lower ultimate and yield strength and higher elongation. The highest strength UTS = 907 ± 16 MPa, YS = 642 ± 21 MPa and total elongation TE5mm = 22% were found in specimens which were isothermally treated at 485°C. Their structure comprised predominantly bainitic ferrite and carbide precipitates and possibly unstable retained austenite.

Specimens of 42SiCr underwent incomplete bainitic transformation and the amount of virgin martensite substantially dictated their mechanical properties. As a consequence, the highest UTS = 2073 ± 36 MPa, YS = 1542 ± 21 MPa and total elongation of TE5mm = 10% was found in specimens which had been isothermally held at 485°C. Lower isothermal holding temperatures led to less martensite in the microstructure. This was the cause of the decreasing UTS, YS and TE5mm with lower isothermal treatment temperatures (as opposed to 42SiMn steel). Predominantly bainitic specimens which were isothermally-treated at 380 and 340°C had ultimate strength of UTS = 1363 ± 18 MPa and UTS = 1542 ± 14 MPa, respectively, yield strengths YS = 1053 ± 16 MPa and YS = 1197 ± 12 MPa, respectively, and total elongation of TE5mm = 26 ± 1 and 21 ± 2%, respectively.

The addition of chromium in 42SiCr secured better mechanical properties than in 42SiMn. The likely mechanisms were solid solution strengthening and stabilization of retained austenite without carbide precipitation. In 42SiCr, the microstructure was predominantly bainitic and the bainitic transformation was incomplete; its mechanical properties were approximately 10% higher than in 42SiMn, in which the transformation was complete. he mechanical properties and the resulting microstructures of both steels were closely related to the TTT diagrams, which were calculated for this experiment in the software JMatPro. 42SiCr steel has not undergone a full transformation, its diagram is shifted to significantly longer transformation times compared to the second steel, 42SiMn. On the other hand, 42SiMn steel underwent a full transformation in all cases, and with a lower tempering temperature, the almost fully bainitic structure was obtained in this way.

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