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Influence of chemical composition and parameters of heat treatment on the mechanical properties and microstructure of TRIP steels

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Abstract. Good mechanical properties of steels, in which appropriate heat treatment can produce mixed hardening structures, make them candidates for a broad range of applications, namely in the automotive industry. TRIP steels (in which transformation-induced plasticity operates) with a carbon content of approximately 0.2 % are one of such steels. Heat treatment of these steels comprises two stages. The first involve heating to the intercritical region between the A_1 and A_3. It is followed by cooling to a bainitic transformation temperature and holding. The resulting mixed microstructure consist of ferrite, bainite and retained austenite. Thanks to the presence of ferrite and retained austenite, the ultimate strength and elongation can reach 1500 MPa and 25-40 %, respectively. The experiments presented in this paper were performed on two steels which chemistries were specially adjusted to support formation of TRIP microstructure. The main difference between them was the level of chromium. Intercritical annealing was carried out on both steels. Aspects of interest included mainly the effect of the cooling rate above the bainitic transformation temperature and the holding time on mechanical properties and final microstructure. The heat treatment led to microstructures ferrite, bainite and retained austenite. The strength was under 1100 MPa and elongation reached 28 %.

1 Introduction

Advances in engineering place ever stricter demands on mechanical properties of advanced high-strength steels. The automotive industry in particular requires high strength along with high ductility in structural and safety components of sheet metal. These requirements are met by multiphase steels, in which retained austenite contributes to final mechanical properties [1]. Among them there are TRIP steels, materials which benefit from transformation-induced plasticity. The phenomenon is based on transformation of retained austenite to strain-induced martensite while the steel is subjected to plastic deformation. As a result, these materials are capable of absorbing large amounts of deformation energy [2].

Their heat treatment involves temperatures between the A_1 and A_3, cooling to the isothermal holding temperature, isothermal holding in the area of the bainitic transformation. Their microstructure then consists of polygonal ferrite, bainite and retained austenite (Figure 1). Mechanical properties are governed by chemical compositions and heat treatment procedure. In these steels, ultimate strengths of about 1500 MPa can be achieved in combination with an elongation of 25–40 % [3].

Microstructure plays an important role in the mechanical properties of TRIP steels. Ferrite phase has the strongest effect in this regard. It is also the one which makes up the largest portion of the microstructure. When the amount of bainite grows, yield strength increases as well. Yield strength increases with cooling rate in the intercritical annealing process. Retained austenite is another phase which affects plasticity. Important aspects include the morphology, amount and stability of retained austenite. In TRIP steels, retained austenite forms either granular particles or needles within bainite sheaves [4]. Stability of retained austenite is controlled by factors which include the size of austenite islands. The latest studies show that austenite islands higher than 1 μm are unstable. By contrast, those which size is around 1 μm require appreciable deformation force in order to transform to martensite. Consequently, retained austenite in them remains stable under cold deformation [5].

The primary focus of this paper is the effect of increased chromium levels on mechanical properties and microstructure of TRIP steels. In ordinary TRIP steels, the chromium level is not more than 0.4 wt. %. The chromium level in the experimental steel was increased to 0,64 %.

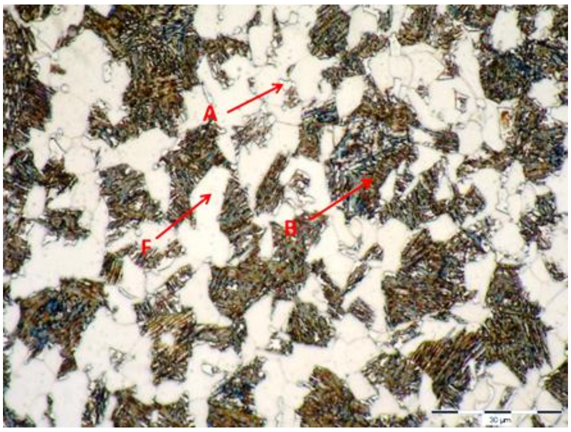

Figure 1. Microstructure of TRIP steel produced by intercritical annealing [6].

2 Experimental programme

Two steels were designed for these experiments: CMnSiCr and CMnSiNb steels with special alloying for achieving the desired microstructure and mechanical properties (Table 1). Their transformation temperatures, A_1, A_3, M_s and M_f, were calculated from their chemical compositions using JMatPro software (Figure 2, Figure 3). The crucial addition is carbon which substantially governs all transformations, the final microstructure and mechanical properties. Both steels contained about 0.2% carbon. The manganese content was 1.5 %. The element stabilizes austenite, depresses the M_s and M_f, enhances the solubility of carbon in austenite and retards pearlite formation [7]. The purpose of silicon as an alloying addition was to prevent carbides from forming, and promote migration of carbide from super-saturated martensite into austenite. The element also supports formation of proeutectoid ferrite during cooling [8]. Another alloying addition important to TRIP steels is niobium because even a minimum amount substantially alters mechanical properties. Both steels contained 0.06 % Nb. Niobium has a strong impact on austenitizing, recrystallization and enrichment of austenite with carbon. It has effects on the type and amount of retained austenite. Niobium-free steels contain globular retained austenite. Those alloyed with niobium contain retained austenite in lath or interlath form [9]. CMnSiCr grade had a higher level of chromium (0.64 %), the purpose of which was to improve hardenability and provide solid solution strengthening.

As-received materials were 50-kg ingots. Tops and bottoms of the ingots were removed and the ingots were cleaned. Then they were homogenized at 1100 °C/6 hours and cut up. The segments were heated to 1150 °C and forged into bars 20 mm in diameter. They were reheated between individual reductions. The forged bars were normalized at 950 °C/2 hours and left to cool in a furnace. Specimens to be heat treated in a thermomechanical simulator were then made from the bars. Metallographic observation was carried out after heat treatment and tensile testing performed on miniature specimens with a gauge length of 5 mm [10].

Table 1. Chemical compositions of steels [wt. %].

	C	Mn	Si	P	S	Cu	Cr	Ni	Al	Mo	Nb	M_s	M_f
CMnSiCr	0.2	1.5	1.8	0.008	0.003	0.11	0.64	0.098	0.009	0.03	0.06	426	317
CMnSiNb	0.2	1.5	1.8	0.005	0.003	0.06	0.008	0.07	0.006	0.02	0.06	360	246

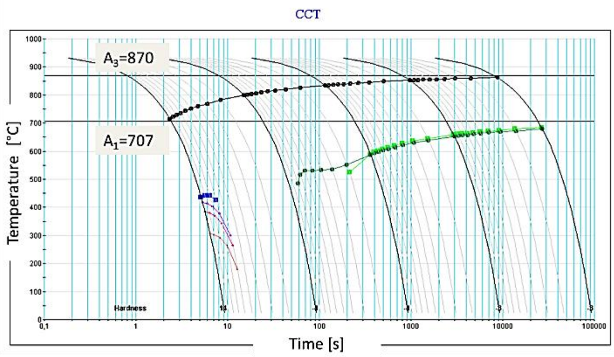

Figure 2. CMnSiCr – CCT diagram.

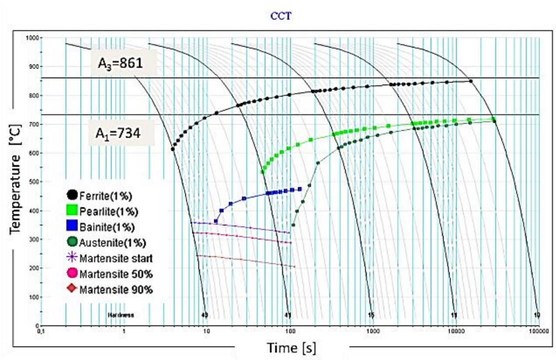

Figure 3. CMnSiNb – CCT diagram.

The first step in designing experimental heat treatment routes was finding a suitable austenitizing temperature for both materials, T6 and T13. To this end, results of calculation with JMatPro and actual heat treatment were compared. Specimens were heated in a furnace to several different temperatures between 800-1200 °C spaced at 50 °C, held for 30 seconds and quenched with water. In the next step, intercritical annealing was designed on the basis of known transformation temperatures. To ensure that the exact temperature profile is maintained, the experiments were carried out in a thermomechanical simulator. Using this machine, real-world heat treatment can be closely replicated on small amounts of material in laboratory conditions [11]. The intercritical annealing sequence comprised five stages (Figure 4), (Table 2). First, the material was heated to a full-austenitization temperature between the A_{c1} and A_{c3}. Based on the experiments, the austenitizing temperature was set at 950°C. The specimens were held at the austenitizing temperature for 100 seconds. The rates of cooling to the bainitic transformation temperature were selected on the basis of CCT diagrams. For CMnSiCr, they were 10 °C/s and 16 °C/s. Since CMnSiNb grade contained no chromium, the pearlite nose shifted to the left. Faster cooling at 30°C/s was used in order to avoid the nose (Figure 3). 425 °C was chosen as the temperature at which bainite would form and retained austenite would become stable. The holding time at this temperature is an important factor governing the amount of bainite and the stability of retained austenite. The holding times were 100 s and 600 s.

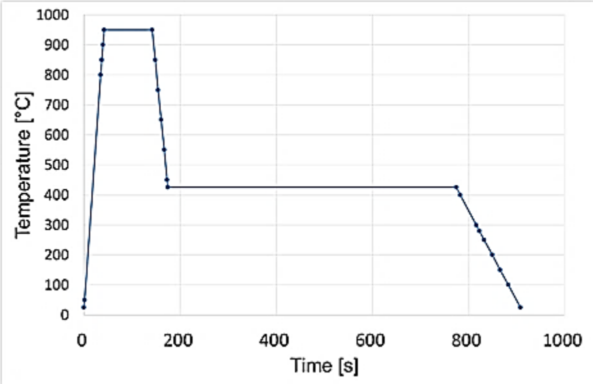

Figure 4. Intercritical annealing diagram.

Table 2. Heat treatment sequences and mechanical properties.

Sequence number/steel	T_A [°C]/t_A [s]	Cooling rate [°C/s]	T_B [°C]	t_B [s]	HV10 [-]	R_m [MPa]	A_{5mm} [%]	RA [%]
1/CMnSiCr	950/100	10	425	100	346	1080	27	12
2/ CMnSiCr	950/100	10	425	600	335	1059	30	13
3/ CMnSiCr	950/100	16	425	100	361	1098	27	12
4/ CMnSiCr	950/100	16	425	600	391	1099	28	12
3/CMnSiNb	950/100	16	425	100	283	905	34	10
4/CMnSiNb	950/100	16	425	600	272	889	39	12
5/CMnSiNb	950/100	30	425	100	301	927	34	10
6/CMnSiNb	950/100	30	425	600	274	873	40	12

3 Results and discussion

First, a suitable heating temperature was required. When the steels were heated to the lowest temperature from the interval, 800 °C, they developed large amounts of ferrite. In line with that, their hardness was low: 301–373 HV10 (Figure 5, Figure 8). Once they were heated to 950 °C ferrite was eliminated, with the resulting microstructure consisting mainly of martensite. Its hardness was 484–503 HV10 (Figure 6, Figure 9). Further increments in the heating temperature, all the way to 1100 °C, brought no additional changes to the microstructure or increase in hardness (Figure 7, Figure 10). Finally, the optimal heating temperature for the experiments was identified as 950 °C.

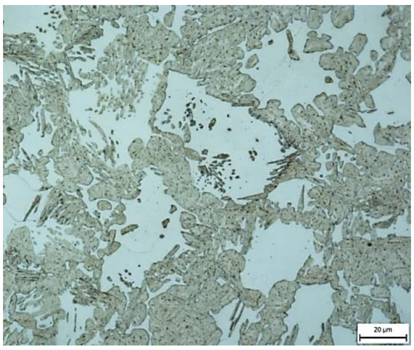

Figure 5. CMnSiCr – heated to 800°C, holding time 30 minutes, 373 HV10.

Figure 6. CMnSiCr – heated to 950°C, holding time 30 minutes, 503 HV10.

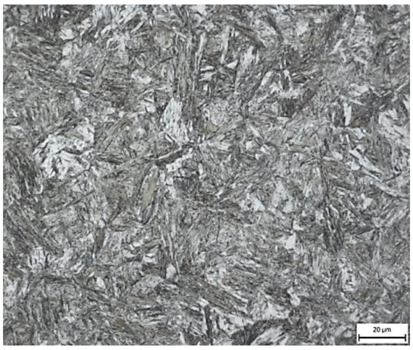

Figure 7. CMnSiCr – heated to 1000°C, holding time 30 minutes, 511 HV10.

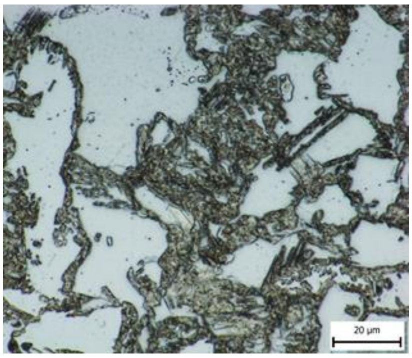

Figure 8. CMnSiNb – heated to 800°C, holding time 30 minutes, 301 HV10.

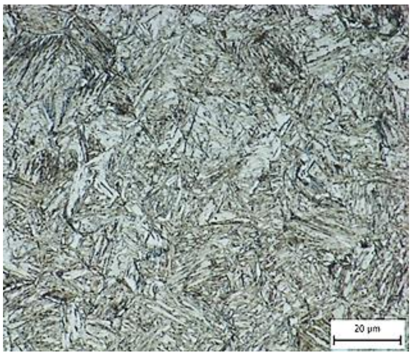

Figure 9. CMnSiNb – heated to 950°C, holding time 30 minutes, 484 HV10.

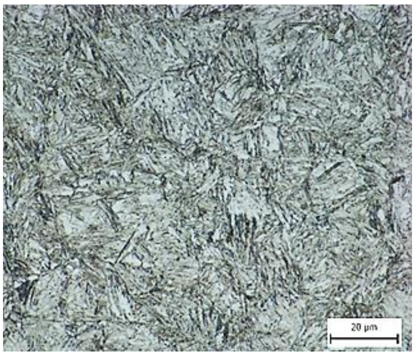

Figure 10. CMnSiNb – heated to 1000°C, holding time 30 minutes, 489 HV10.

Intercritical annealing sequences produced mixtures of ferrite, bainite and retained austenite in both materials (Figure 11 - Figure 20). The amount of ferrite was dictated by the rate of cooling to the bainitic transformation temperature. The time at this temperature, in turn, dictated the volume fraction of retained austenite. The shorter holding time (100 s) failed to secure adequate saturation of austenite with carbon. In the course of cooling from the bainitic transformation temperature to room temperature, retained austenite decomposed into martensite. It was evidenced by the resulting high hardness, lower elongation and a smaller amount of austenite. The longer hold at the bainitic transformation temperature (600 seconds) led to lower hardness, higher elongation and a larger amount of retained austenite (Table 2).

In CMnSiCr steel, the sequence with cooling at 10 °C/s produced a bainitic microstructure with a small amount of martensite, some grains of free ferrite and 12-13 % of retained austenite (Figure 11, a, b). The range of hardness values was 334-346 HV10. The next sequence, with a longer holding time at 425 °C, i.e. not 100 seconds but 600 seconds, led to a slightly lower ultimate strength, i.e. 1059 MPa instead of 1080 MPa, but improved elongation from 27 % to 30 %. In both sequences (which involved different holding times at the bainitic transformation temperature), higher rate of cooling (16 °C/s) from the heating temperature to the isothermal holding temperature led to a lower amount of proeutectoid ferrite and a higher amount of bainite (Figure 12, a, b). This was reflected in higher hardness: 360 -391 HV10. The ultimate strength and elongation were 1099 MPa and 28 %, respectively. X-ray diffraction analysis found 12 % retained austenite for both holding times at 425 °C. The presence of retained austenite was demonstrated and its distribution studied after special colour etching (Figure 13, a, b).

After cooling at the same rate (16 °C/s) CMnSiNb steel developed a ferritic-bainitic microstructure with 12 % retained austenite. The amount of bainite was considerably smaller than in the chromium-alloyed steel (Figure 14, a, b). After holding for 100 s at 425 °C, hardness was 272 HV10, and ultimate strength and elongation reached 889 MPa and 39 %, respectively. Longer holding time produced coarser bainite blocks and a larger amount of bainite. It was reflected in the slightly higher hardness and ultimate strength than in the previous case: 283 HV10 and 905 MPa, respectively, and an elongation of 34 %. The retained austenite volume fraction rose slightly to 12 % (Table 2). Faster cooling (30 °C/s) from the heating temperature to the isothermal holding temperature resulted in a larger bainite fraction and smaller amount of ferrite (Figure 15, a, b). Retained austenite volume fraction was 10-12 %. After the shorter holding time, 100 s, ultimate strength and elongation were 927 MPa and 34 %, respectively. Longer holding time, 600 s, led to lower strength, 873 MPa, and elongation of 40 %. Owing to the absence of chromium, this steel developed lower hardness and ultimate strength (Table 2).

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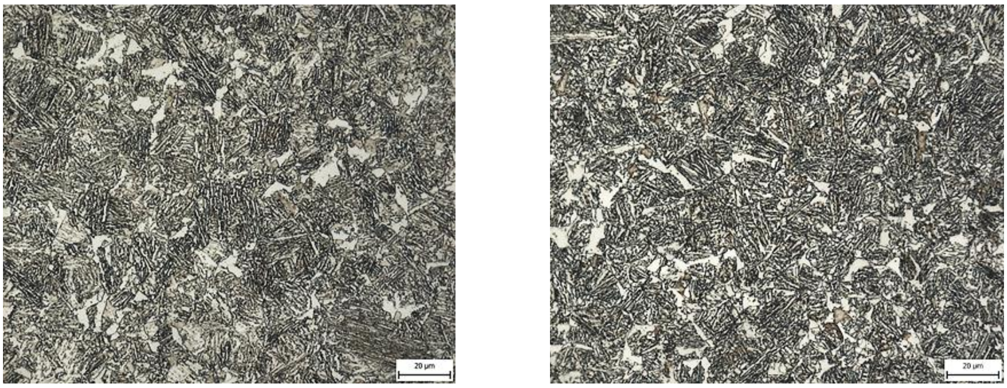
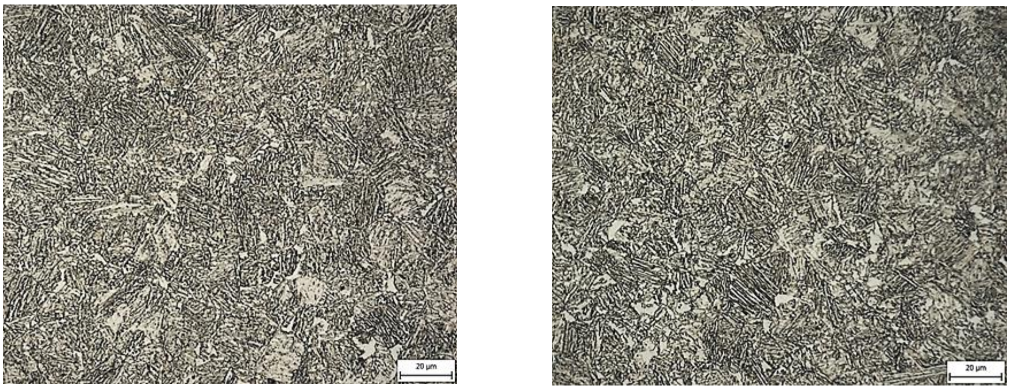


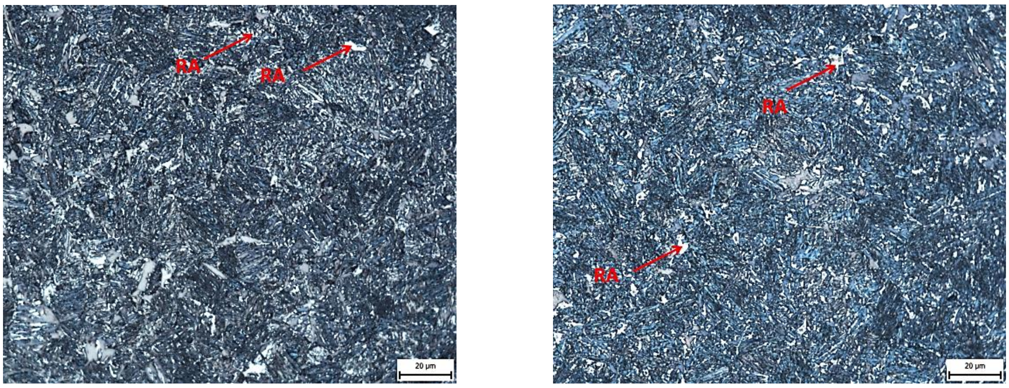
a) sequence 1, 100 s b) sequence 2, 600 s

Figure 11. CMnSiCr, cooling rate 10 °C/s, TB 425 °C, bainitic structure with some amounts of martensite, ferrite and retained austenite.



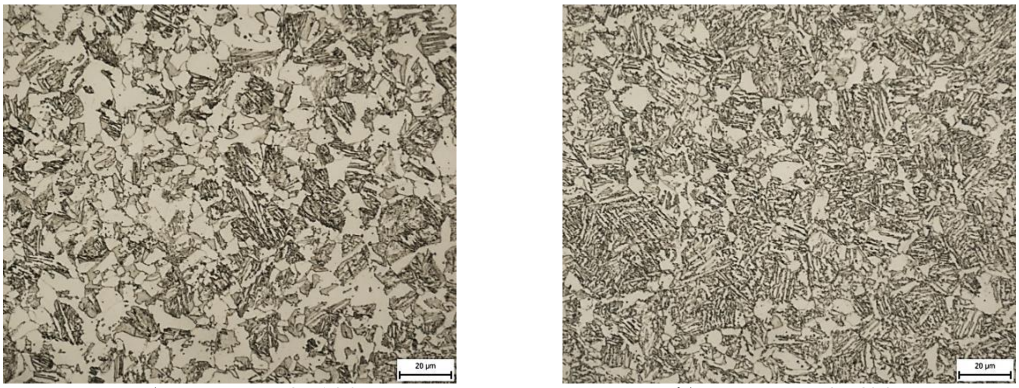
a) sequence 3, 100 s b) sequence 4, 600 s

Figure 12. CMnSiCr, cooling rate 16 °C/s, TB 425 °C, bainitic structure with some amounts of martensite, ferrite and retained austenite.



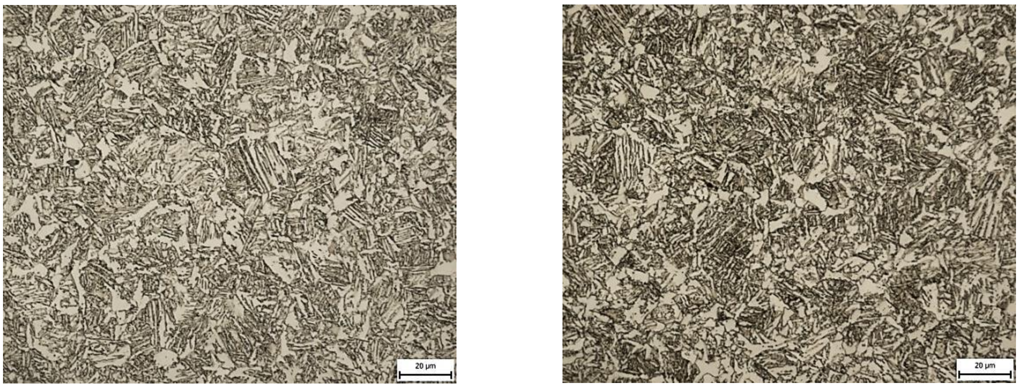
a) sequence 3, 100 s b) sequence 4, 600 s

Figure 13. CMnSiCr, cooling rate 16 °C/s, TB 425 °C/, colour etch made to reveal retained austenite.



a) sequence 3, 100 s b) sequence 4, 600 s

Figure 14. CMnSiNb, cooling rate 16 °C/s, TB 425 °C, mixture of bainite and austenite with a certain amount of ferrite.



a) sequence 5, 100 s b) sequence 6, 600 s

Figure 15. CMnSiNb, cooling rate 30 °C/s, TB 425 °C, mixture of bainite and austenite with some retained austenite.

4 Conclusion

All the heat treatment sequences applied to CMnSiCr produced a bainitic microstructure with a small amount of martensite, grains of free ferrite and 12-13 % retained austenite. Thanks the chromium content were hardness values ranged between 346 and 391 HV10, ultimate strengths were 1059-1099 MPa, and elongation reached 27-30 %. In CMnSiNb a ferritic-bainitic structure with 10-12 % retained austenite was obtained. Owing to the absence of chromium, this steel developed lower hardness and ultimate strength. Hardness values ranged between 272 and 301 HV10, ultimate strengths were 873-927 MPa, and elongation reached 34-40 %.

The amount of ferrite, and thus mechanical properties, showed dependence on the rate of cooling to the holding temperature. The holding time at this temperature had a notable effect on stability of retained austenite more in the steel CMnSiNb. With shorter times (100 seconds), austenite failed to saturate adequately with carbon, and eventually decomposed into martensite. The volume fraction of retained austenite was 10 %. After the longer hold (600 s) austenite was saturated appropriately and remained stable among bainite needles. The volume fraction of retained austenite was 13 %. The amount of retained austenite was demonstrated using colour etching.

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