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The effect of chemical composition on microstructure and properties of TRIP steels

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ABSTRACT

Purpose: Various alloying strategies can be used to produce advanced high strength steels and this work offers comparison of results achieved for four different low alloyed steels with 0.2-0.4 %C, 0.5-2 %Si, 0.6-1.5 %Mn, 0.03-0.06 %Nb and with 0.8-1.33 %Cr. Microstructures obtained by two methods of thermo-mechanical treatment were analysed for each steel and compared with theoretical predictions of TTT (time temperature transformation) diagrams calculated by JMatPro.

Design/methodology/approach: Thermo-mechanical treatment of all steels was carried out at thermo-mechanical simulator. Resulting microstructures were analyses by the means of scanning electron microscopy, mechanical properties were measured by tensile test.

Findings: It was found out that microstructures typical for TRIP (transformation induced plasticity) steels can be obtained easily for low carbon steels alloyed by silicon or aluminium-silicon and micro-alloyed by niobium. Chromium addition influenced austenite decomposition causing intensive pearlite formation in low carbon steel and predominantly martensitic microstructure in middle carbon steel. These microstructures were not in agreement with calculated TTT diagrams.

Research limitations/implications: To obtain ferritic-bainitic microstructure with retained austenite typical for TRIP steels, chromium alloyed steels require substantial optimisation of processing parameters. This issue should be addressed in future work.

Practical implications: JMatPro software is well equipped to calculate TTT diagrams for steels alloyed by manganese, silicon and niobium, however further chromium addition changed behaviour of the steel in a way that the software was not able to predict.

Originality/value: Obtained results could be useful for consideration of chemical composition of low alloyed steels with respect to resulting microstructures and properties.

Keywords: Materials; Metallic alloys; TRIP steels; Alloying elements; Retained austenite

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PROPERTIES

1. Introduction

Increasing demands for high tensile strength of steels combined with good formability or deep drawing ability, presented mainly by automotive industry, have been motivating researchers and steel producers to develop new steel grades with advanced mechanical and technological properties. They are commonly developed with particular chemical compositions which are suitable for particular heat or thermo-mechanical treatment strategies [1-6].

Among advanced high strength steels with improved toughness, ductility and formability belong also multiphase TRIP (transformation induced plasticity) steels which are using the benefit of metastable retained austenite in the final microstructure. During plastic deformation of the final microstructure, retained austenite can transform to martensite. This gradual phase transformation can occur at room temperature and increases ultimate tensile strength and strain hardening of the steel.

TRIP steel microstructures are rather complex, consisting of ferrite, carbide-free bainite and retained austenite [7]. Small amounts of martensite are also often found in the microstructure, particularly in the form of larger islands of retained austenite partially transformed to martensite, which are called "M-A constituent". Retained austenite is typically found either in the form of laths in bainite, or as bulky islands spread between ferrite grains. Pearlite or any larger carbide precipitates are undesirable in TRIP steel microstructures because they deplete carbon in the surrounding areas making retained austenite stabilization very difficult [8,9].

Stabilization of retained austenite to room temperature is achieved by combination of increased carbon content within individual austenitic grains and the morphology of retained austenite grains, which is also sometimes referred to as size effect. It has been demonstrated that finer grains are more stable against martensitic transformation [9,10].

The mot typical ways how to produce TRIP microstructure are by heat or thermo-mechanical treatment with a hold in the region of bainitic transformation [11,12]. Even tough TRIP steels have been prepared also by continuous cooling process [13], the processing with bainitic hold is still predominantly used, as it is easier to produce sufficient amount of bainite by isothermal treatment at the temperatures around 400 - 450°C. The hold is also used to allow diffusion of excessive carbon into remaining austenite to increase its stability toward martensitic transformation upon subsequent cooling.

Elemental chemical composition of TRIP steels is based on 0.2-0.4 %C, 1-2 %Si and 1-2 %Mn concept, as these alloying elements help to develop typical TRIP steel microstructure [6-8]. Manganese is frequently added to advanced high strength steels as an austenite forming element, to increase austenite stability during the processing. Silicon is used for its solid solution strengthening effect and also for its ability to hinder cementite formation during isothermal holds, as silicon does not dissolve in cementite. Cementite is undesirable microstructure in TRIP steels, first because it is rather brittle and its morphology has usually bad effect on ductility and toughness of the steel and second, it consumes carbon, which would be better used for stabilization of retained austenite.

Other alloying elements can be also added for various purposes to TRIP steels and this work choose four low alloyed steels to compare their suitability for TRIP steel processing. As higher silicon contents tend to cause problems with subsequent galvanization and weldability of sheet steels for automotive industry, there have been attempts to replace it by other elements with similar effects. Aluminium also possess solid solution strengthening effect in steels, even though not so strong as silicon and it also helps to avoid cementite precipitation [10,12]. Full replacement of silicon caused deterioration of mechanical properties of TRIP steel and therefore only partial replacement was chosen for this work.

Niobium makes TRIP steel less sensitive toward the changes in processing parameters, refines the microstructure and increases volume fraction of retained austenite [13,14]. Therefore it was chosen as another micro-alloying element to be tested in this work.

The last alloying element added to the basic chemical composition was chromium. Chromium has been up to now used mainly for high strength steels with martensitic matrix [15,16]. However, higher strength and further microstructure refinement could be beneficial for TRIP steels as well.

2. Experimental program

2.1. Material description

Four low alloyed high strength steels were used for this work (Table 1). One steel had middle carbon content of 0.4%, other three were low carbon steels with 0.2 %C. The steels were further alloyed by manganese, silicon, chromium, aluminium and niobium in various combinations. The middle carbon chromium alloyed steel was labelled 42SiCr. Three low carbon steels were alloyed

by niobium (CMnSiNb), or niobium and partial substitution of silicon by aluminium (CMnSiAlNb), or finally, by lower manganese content and chromium (CMnSiCr).

Table 1.
Chemical composition [weight %]

Steel	C	Mn	Si	Cr	Al	Nb
42SiCr	0.4	0.6	2	1.3	-	0.03
CMnSiNb	0.2	1.5	2	-	-	0.06
CMnSiAlNb	0.2	1.5	0.6	-	1.4	0.06
CMnSiCr	0.2	0.6	2	0.8	-	0.04

Manganese content of the steels varied between 0.6%-1.5%, and there was 0.6-2% of silicon and 0.03-0.06% of niobium in the steels. Two steels had additional chromium contents of 0.8% or 1.3% and in one case, silicon was partially replaced by 1.4% of aluminium.

TTT (time temperature transformation diagrams) of all four steels were calculated in JMatPro software for austenitizaiton temperature of 900°C (Fig. 1). Low carbon chromium alloyed steel CMnSiCr has wider areas of ferrite (F) and pearlite (P) transformations both shifted to lower temperatures and with ferrite transformation starting at shorter times than the other chromium steel with double carbon content 42SiCr. Bainite transformation (B) is on the other hand shifted to longer times with lower carbon content.

Another differences can be found for aluminium alloyed steel CMnSiAlNb, where partial substitution of silicon by aluminium resulted in significant widening of ferrite and bainite transformation areas, shifting pearlite finish and bainite finish curves markedly to the right.
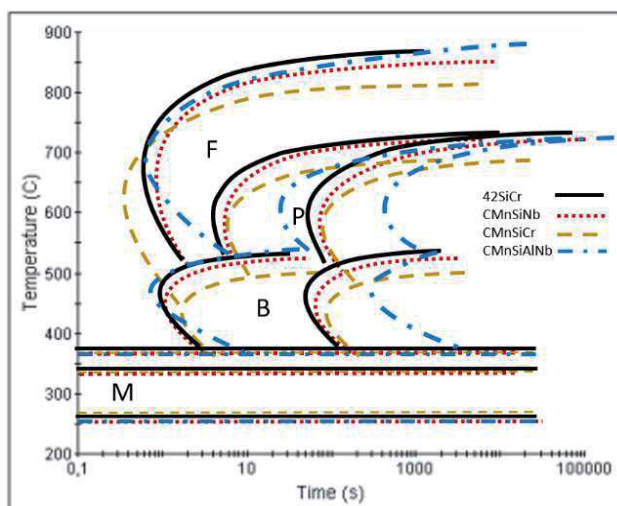

Fig. 1. TTT diagrams of used steels, calculated in JMatPro

2.2. Thermo-mechanical treatment

All four experimental steels were processed by thermo-mechanical treatment (TMT) typical for TRIP steels (Fig. 2). The optimization of processing parameters of these steels is described elsewhere in more detail [13,15-16]. The processing consisted of heating to the temperatures of 900°C and 850°C and 100 s hold at either temperature, cooling by the rate 14°C/s to 600 s bainitic hold carried out at 425°C. Two compressive deformations were applied during the cooling, the first one directly at the heating temperature, at the end of the 100 s hold and the second one at 720°C. Each deformation had the size of 10% of the actual sample size at the moment.
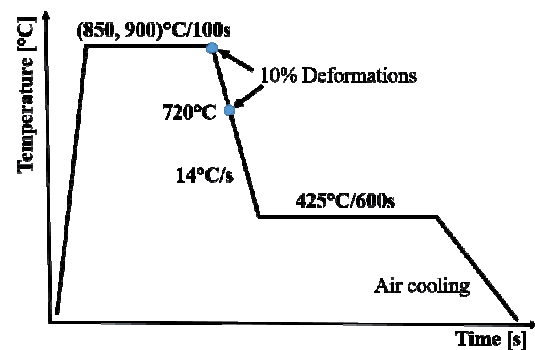

Fig. 2. TMT schedule

TMT of all steels was carried out at thermo-mechanical simulator, which enables precise control of thermal and deformation parameters and high repeatability of the treatment. The active part of the processed samples had 8 mm diameter and the length of 16 mm. This geometry ensures optimal homogeneous thermal field distribution in active part.

2.3. Microstructure observation and testing

All the microstructures were observed by scanning electron microscopes (SEM) Zeiss EVO 25 after conventional etching by 3% Nital solution.Volume fraction of retained austenite was for all samples established by X-ray diffraction phase analysis using X-ray diffraction phase analysis using automatic powder diffractometer AXS Bruker D8 Discover with HI-STAR detector and Co lamp ($\lambda K\alpha = 0.1790307$ nm). Focusing polycapillary lens was used to achieve X-ray spot with 0.5 mm diameter. Measurements were carried out in the middle of the sample within diffraction angles 25-110°2ϑ and (111), (002), (022)

diffraction lines of retained austenite and (110), (200), (211) lines of ferrite were used for calculations.

Mechanical properties were tested by tensile test of small flat samples with 1.2 x 2 x 5 mm dimensions of the active part of the sample.

3. Results

3.1. 42SiCr

Middle carbon chromium steel 42SiCr achieved high strength of 2020 MPa (Table 2) after the processing with heating temperature of 900°C. High strength was however accompanied by very low ductility of 5% and only 4% of retained austenite.

Table 2.
Mechanical properties and retained austenite (RA) volume fraction

Steel-soaking temperature	R_m, MPa	A_{5mm}, %	RA, %
42SiCr – 900°C	2020	5	4
42SiCr – 850°C	1035	15	6
CMnSiNb – 900°C	859	34	13
CMnSiNb – 850°C	805	40	15
CMnSiAlNb – 900°C	832	38	13
CMnSiAlNb – 850°C	741	41	16
CMnSiCr – 900°C	743	40	4
CMnSiCr – 850°C	741	41	8

The microstructure of 42SiCr-900°C sample (Fig. 3) contained martensitic islands of various sizes mixed with ferrite laths with typical length of several micrometres and the width below one micrometre. Retained austenite was not visible in the form of bulky islands, but it was found as thin films at the edges of some of the martensitic areas.
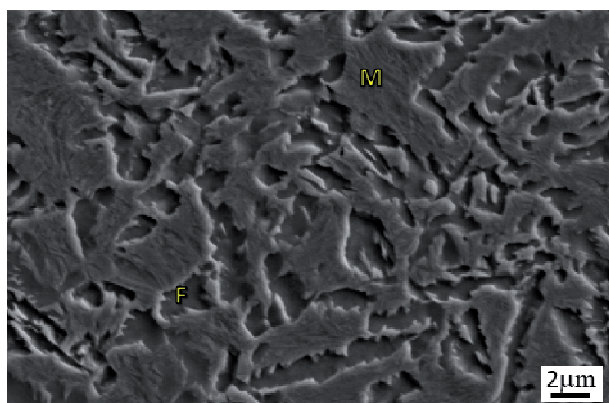

Fig. 3. 42SiCr-900°C, martensitic-ferritic microstructure

Decreasing heating temperature by 50°C to 850°C resulted in remarkable drop of tensile strength to 1035 MPa, which is nearly one half of the value obtained after TMP from 900°C. Ductility increased three times to 15%, even though there were only 6% of retained austenite. There were still large martensitic islands, however areas of fine bainitic laths are also visible at the micrographs (Fig. 4) of 42SiCr-850°C sample.
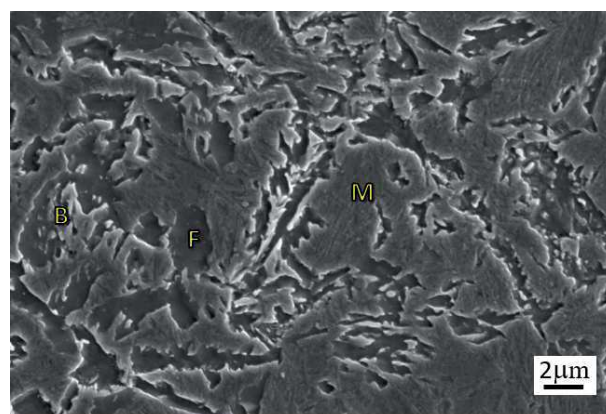

Fig. 4. 42SiCr-850°C, microstructure consisting of martensite with bainitic blocks and free ferrite

3.2. CMnSiNb

Low carbon CMnSiNb steel micro-alloyed by niobium possessed typical microstructure of TIRP steel with ferritic grains, bainite and around 14% of retained austenite.

There was remarkable difference in the microstructure of the steel processed with 900°C heating temperature and 850°C. Higher heating temperature resulted in small areas of predominantly granular bainite consisting of very fine laths of retained austenite distributed among bainitic ferrite (Fig. 5). Large grains of M-A constituent were also found in the microstructure.

On the other hand, the microstructure produced by lower heating temperature in CMnSiNb-850°C sample was coarser, bainitic blocks were larger and the laths were longer. The bainite was only of the lath type. The islands of M-A constituent (Fig. 6) were also slightly larger.

The difference in the microstructures was also reflected by the difference in mechanical properties. Finer microstructure with granular bainite obtained by 900°C treatment had higher tensile strength 859 MPa and lower ductility 34% than the coarser microstructure with lath bainite, which reached the strength of 800 MPa with 40% ductility.
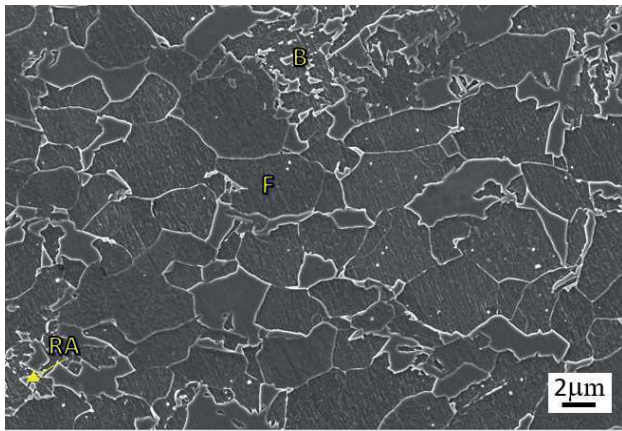
Fig. 5. CMnSiNb-900°C, typical TRIP microstructure with polygonal ferrite, granular bainite and retained austenite
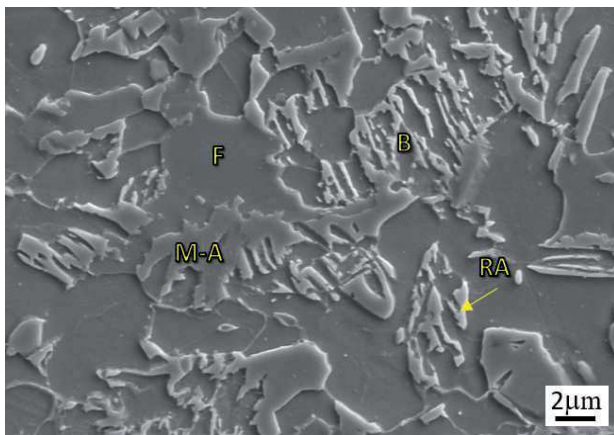

Fig. 6. CMnSiNb-850°C, coarse TRIP microstructure with larger blocks of lath bainite and M-A constituent islands

3.3. CMnSiAlNb

Partial substitution of silicon by aluminium in both cases resulted in increase of ductility of the steel at the cost of decrease of the strength. For 900°C treatment, the strength was 832 MPa with ductility 38% and for the lower temperature treatment, tensile strength dropped to 741 MPa with ductility 41%. Volume fraction of retained austenite was practically the same, as for CMnSiNb steel. The treatment with lower heating temperature of 850°C produced slightly higher volume fraction of retained austenite in both steels.

Both samples of CMnSiAlNb steel had much finer ferrite grains and more bainitic microstructure than any sample of 42SiCr or CMnSiNb steels. Higher heating temperature of CMnSiAlNb-900°C sample resulted in

bainitic-ferritic microstructure with fine free ferrite grains and larger islands of M-A constituent (Fig. 7). Bainitic areas are also relatively fine and mostly of granular morphology. Parts of the microstructure, consisting mostly of free ferrite grains and individual grains of M-A constituent, were deformed (prolonged) in the same direction, while the surrounding microstructure does not bear any traces of deformation.

Lower heating temperature of CMnSiAlNb-850°C produced nearly fully bainitic microstructure with lath morphology (Fig. 8). M-A constituent does not form bulky individual islands, but it can be found in larger bainitic laths.
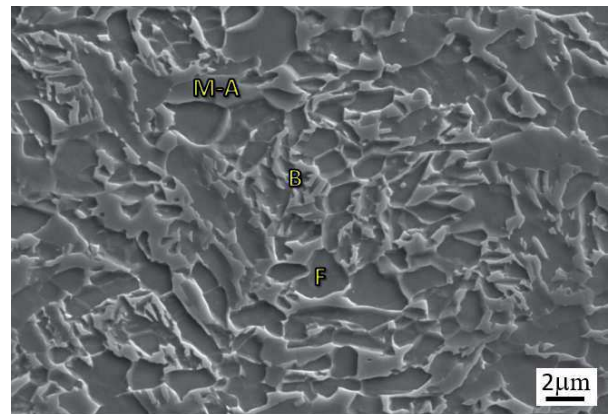

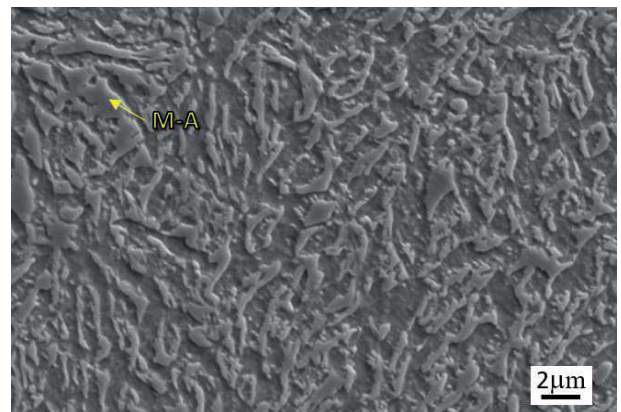Fig. 7. CMnSiAlNb-900°C, bainitic-ferritic microstructure with M-A constituent

Fig. 8. CMnSiAlNb-850°C, very fine bainitic matrix with coarser laths of M-A constituent

3.4. CMnSiCr

Low carbon steel alloyed with chromium possessed very good ductility of 40% in both samples, however the strengths around 742 MPa were the lowest of all the samples used in

this work. There was not any visible difference between mechanical properties of samples with different heating temperatures. Volume fraction of retained austenite was also relatively small, reaching 4% for CMnSiCr-900°C and 8 % for CMnSiCr-850°C.

The microstructures obtained for CMnSiCr steel are not typical for TRIP steels, as they contain quiet low amount of bainite and there is pearlite in both microstructures (Fig. 9, Fig. 10). High pearlite fraction was also responsible for low amount of retained austenite, because it consumed carbon necessary for austenite stabilization. However, pearlitic areas were typically reaching the size up to several micrometers and ferrite and cementite laths were very fine.

The microstructure of CMnSiCr-900°C sample consist of the mixture of polygonal ferrite and fine pearlite, with individual grains of M-A constituent and occasional bainitic areas (Fig. 9).
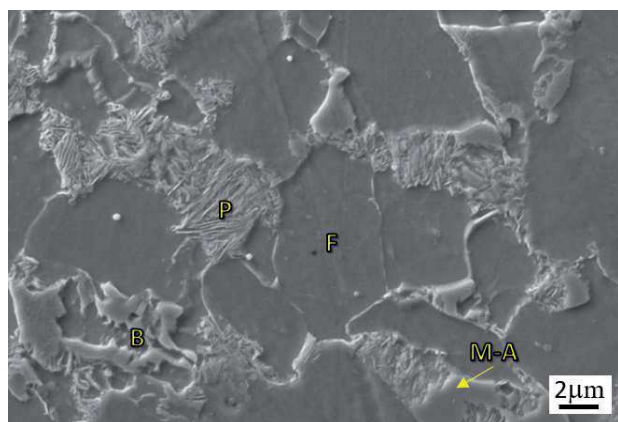

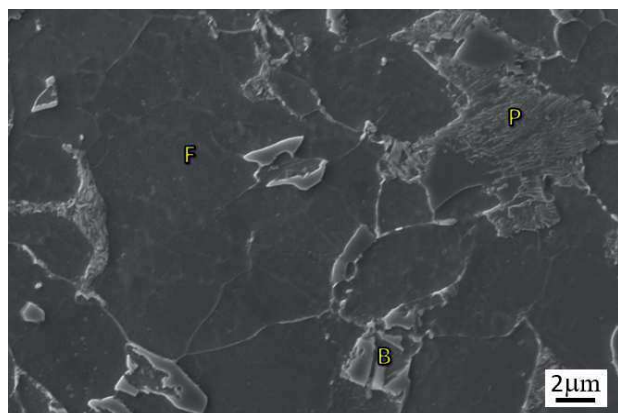Fig. 9. CMnSiCr-900°C, ferrite-pearlite microstructure with bainite and M-A constituent

Fig. 10. CMnSiCr-850°C, microstructure of large ferrite grains, pearlite areas with fine lamellas and small bainitic areas

3.5. Comparison of the microstructures with calculated TTT diagrams

Final microstructures obtained by processing with higher heating temperature 900°C, which should ensure full austenitization of all steels, were compared with calculated TTT diagrams. Microstructure type, morphology and distribution of individual phases and structural component of all steels were also compared.

The final microstructure of 42SiCr looked like bainitic microstructure at low magnifications (Fig. 11a). However, all the space between ferritic laths was filled by martensite with only occasional M-A constituent. According to the TTT diagram, this steel should achieve very similar microstructure to CMnSiNb steel, which clearly did not happened. There was no polygonal ferrite and very little of retained austenite. Higher carbon content combined with chromium alloying postponed bainitic transformation of the steel.

Most convenient TRIP steel microstructure was obtained for CMnSiNb-900°C sample (Fig. 11b), where ferritic-bainitic microstructure also possessed good balance of high strength and good ductility. This steel could be therefore considered as a reference material and all other microstructures were evaluated in comparison with this one.

Aluminium alloyed CMnSiNbAl-900°C steel had very little of free ferrite, the microstructure being predominantly bainitic with occasional island of M-A constituent (Fig. 11c). Calculated TTT diagrams predicted widest bainitic area for this steel, however it seems that 600 s hold at 425°C was long enough to achieve bainitic transformation in most of the samples. On the other hand, practically missing free ferrite corresponds to the shape of calculated ferrite start curve, which is quickly retreating to the right bellow ferritic nose.

Low carbon chromium alloyed steel CMnSiCr steel produced microstructures with high amount of fine pearlite in relatively coarse ferritic matrix (Fig. 11d). These microstructures are interesting because they do not correspond to calculated TTT diagram of the steel. According to the diagrams, CMnSiCr steel should have practically the same pearlite start temperatures and times as the CMnSiNb steel and there is no reason for pearlite appearance during the processing with the same parameters.

Large amount of free ferrite is on the other hand in good agreement with calculated TTT diagram, which shows pronounced ferrite nose shifted significantly to the shorter times in comparison with all the other steels.
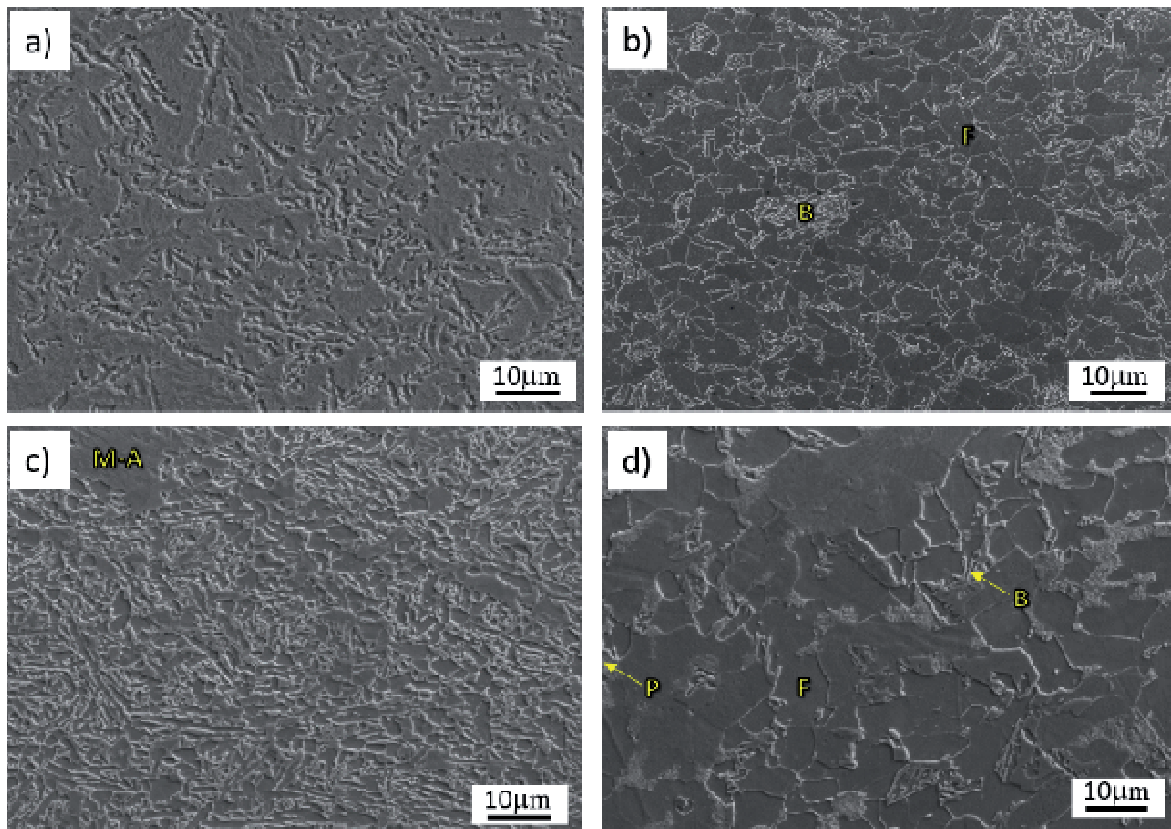
Fig. 11. Overview micrographs of all steels after TMT with 900°C heating: a) 42SiCr-900°C, b) CMnSiNb-900°C, c) CMnSiNbAl-900°C, d) CMnSiCr-900°C

4. Conclusions

Two schedules of thermo-mechanical treatment with different heating temperatures of 850°C and 900°C were applied to four experimental low alloyed steels. In both schedules, two compressive deformations were carried out at the end of soaking hold and at 720°C, cooling rate was 14°C/s and bainitic hold of 600 s at 425°C was performed. One of the steels had 0.4 %C, the other three only 0.2 %C and all of them were alloyed by manganese and silicon. The further alloying elements were chromium, aluminium and niobium.

- Both steel alloyed with chromium possessed microstructures unsuitable for utilization of TRIP effect. 42SiCr steel with 0.4 %C was predominantly martensitic, even for the lower heating temperature of 850°C and both sample had high strengths with minimal ductility.
- The most suitable TIRP microstructures were found in CMnSiNb and CMnSiAlNb steels, with around 14% of retained austenite spread in ferritic-bainitic micro-structure. CMnSiNb steel reached slightly higher strength of 859 MPa with reasonably good ductility 34%, while CMnSiAlNb steel possessed higher ductility of 38% with 932 MPa tensile strength.
- Aluminium addition in CMnSiAlNb steel resulted in significant increase of bainite fraction in the final microstructures, particularly after TMT with lower heating temperature 850°C.
- In all steels, lower heating temperature slightly increased volume fractions of retained austenite.
- With the exception of CMnSiCr steel, lower heating temperature also decreased strength of the final microstructure and improved ductility.
- TTT diagrams calculated in JMatPro failed to predict real microstructures in chromium alloyed steels. The problems arise particularly at lower transformation temperatures, where either martensite (42SiCr) of pearlite (CMnSiCr) were formed in the steels in contradiction to the calculated curves.

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