# THERMO-MECHANICAL TREATMENT OF 42SICR AND 42MNSI STEELS

*Ludmila Kučerová[1], Hana Jirková[1], Andrea Jandová[1]*
*[1] RTI, UWB in Pilsen, Universitni 8, 30614, Czech Republic*

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**Corresponding author: e-mail: skal@rti.zcu.cz, Tel:+420 605703670, Regional Technological Institute, UWB in Pilsen, Univerzitni 8, 30614 Pilsen, Czech Republic*

## Abstract
Two high strength low alloyed steels with 0.4%C, 0.6%Mn, 2%Si and either 1.3% of chromium or without chromium were used in this work to evaluate the effect of chromium on the final microstructure obtained by thermo-mechanical processing. Various heating temperatures, cooling rates and bainitic hold temperatures were tested. High strengths around 1700 MPa were achieved for the chromium alloyed steel, however total elongation reached only 9%. Chromium-free steel turned out to be better suited for TRIP (transformation induced plasticity) processing. The relatively high strengths around 900 MPa were in this case accompanied by very high total elongations exceeding 30%. The final microstructure of chromium-free steel was also more typical for TRIP steel, as it consisted mainly of the mixture of bainite and polygonal ferrite.

**Keywords:** TRIP steel, chromium, thermomechanical processing, scanning electron microscopy

## 1 Introduction
TRIP (transformation induced plasticity) steels are advanced steel grades with high strength and enhanced total elongation and formability. Their good mechanical properties result from a complex microstructure containing ferritic matrix, carbide-free bainite and retained austenite [1, 2]. Suitable microstructures with proper volume fractions, distributions and morphologies of individual phases and structural components are produced usually by thermo-mechanical treatment [1, 3]. Ideal processing parameters vary according to the particular chemical composition of steel. The most conventional concept is based on C-Mn-Si alloying [1, 4-5]. Further TRIP steel variations were investigated in last decades, testing other alloying elements and their combinations. Silicon was fully or partially replaced by aluminium to improve galvanizing properties of thin sheets for automotive industry [6, 7]. Micro alloying by Niobium was designed to refine the final microstructure and increase retained austenite content [8-10]. Chromium alloying of medium carbon TRIP steels has not been investigated very thoughtfully [11], probably due to its reputation of a carbide-forming element with a potential to increase the incubation time and decrease the transformation rate of isothermal bainite. The effect of chromium on higher hardenability is usually used in martensite-based steel, primarily to increase the strength [11-13]. However, chromium also retards pearlite growth rate and refines the microstructure by reducing the growth rate of prior austenite grain in steels [14-15] and improves corrosion resistance [16], which can be convenient for TRIP steels as well.

## 2 Experimental program
### 2.1 Materials characterisation
Two experimental steels with the same chemical composition but different chromium contents were used in this work. The first steel 0.4%C-0.6%Mn-2%Si-1.33%Cr (CMnSiCr) contained

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1.33% of chromium, while the second steel 0.4%C-0.6%Mn-2%Si (CMnSi) was without chromium (all concentrations are in wt %). TTT diagrams of both steels were calculated using JmatPro software (**Fig.1**). Chromium addition opened ferritic area of TTT diagram and consequently shifted pearlite formation toward longer times. This should make CMnSiCr steel a better candidate for TRIP steel processing as it should enable creation of polygonal ferrite at relatively low cooling rates, without the risk of obtaining undesirable pearlite in the final microstructure.
Mechanical properties after thermo-mechanical processing were measured by tensile test on sub-size flat specimens with the gauge length of 5 mm and the cross section 2x1.2 mm. Volume fraction of retained austenite was determined by X-ray diffraction phase analysis.

## 2.2 Thermo-mechanical treatment

Thermo-mechanical treatment of both steels was carried out at thermo-mechanical simulator, which applies precisely controlled thermal and deformation regimes including rapid incremental deformations. The active part of the processed samples had 8 mm diameter and the length of 16 mm. Thermo-mechanical processing with bainitic hold and incremental deformation steps was designed (**Table 1**) to simulate real processing of TRIP steels in rolling mills or by rotary spin extrusion and to enable higher total deformation to be applied to relatively small samples without the risk of cracking [17]. Various thermal parameters and numbers of deformation steps were applied to both steels, to evaluate their effect on the final microstructures and the mechanical properties. Soaking temperatures in the region of 850-1000 °C were tested, followed by various cooling rates in the interval of 10-50 °C/s. either 15 or 20 incremental deformation steps were applied during the cooling from the soaking temperature to deformation finish temperatures of 800 °C or 720 °C. Each deformation step consisted of a pair of tensile and compressive deformation. The total logarithmic deformation of 20 steps was always equal to 5, while the total logarithmic deformation of 15 steps was 3.6. Bainitic holds were carried out at the temperatures of 350-450 °C and the final air cooling finished each processing.

**Table 1** Thermo-mechanical processing parameters and resulting volume fraction of retained austenite (RA) and the mechanical properties

| **Steel** | **Soaking [°C]/[s]** | **Def. steps** | **Def. temp. [°C]** | **Cooling rate [°C/s]** | **Bainitic hold [°C]/[s]** | **Rm [MPa]** | **$A_{5mm}$ [%]** | **RA [%]** |
|---|---|---|---|---|---|---|---|---|
| CMnSiCr | 850/100 | 15 | 850-720 | 15 | 425/600 | 1616 | 7 | 6 |
| CMnSiCr | 850/100 | 20 | 850-720 | 15 | 425/600 | 1820 | 8 | 7 |
| CMnSiCr | 900/100 | 20 | 900-720 | 15 | 425/600 | 1700 | 9 | 8 |
| CMnSiCr | 900/100 | 20 | 900-720 | 15 | 450/600 | 2217 | 8 | 7 |
| CMnSiCr | 900/100 | 20 | 900-720 | 10 | 425/600 | 1904 | 7 | 6 |
| CMnSi | 900/100 | 20 | 900-720 | 15 | 350/600 | 888 | 33 | 3 |
| CMnSi | 900/100 | 20 | 900-800 | 15 | 350/600 | 1022 | 10 | 4 |
| CMnSi | 900/100 | 20 | 900-800 | 15 | 400/600 | 909 | 39 | 7 |
| CMnSi | 900/100 | 20 | 900-800 | 15 | 425/600 | 890 | 26 | 3 |
| CMnSi | 900/100 | 20 | 900-800 | 20 | 425/600 | 900 | 32 | 5 |
| CMnSi | 900/100 | 20 | 900-800 | 30 | 425/600 | 880 | 32 | 8 |
| CMnSi | 900/100 | 20 | 900-800 | 50 | 425/600 | 913 | 36 | 10 |
| CMnSi | 1000/100 | 20 | 950-800 | 30 | 425/600 | 858 | 36 | 9 |

Processing of CMnSiCr steel consisted of heating at 850 °C or 900 °C for 100 s, followed by 15 or 20 deformation steps during the cooling to 720 °C. Cooling rate was either 10 or 15 °C/s.

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Bainitic hold of 600 s was carried out at 425 °C or 450 °C. CMnSi steel was soaked at 900 C or 1000 °C and deformed always by 20 deformation steps during the cooling to 720 °C or 800 °C. Cooling rates of 15 °C/s, 20 °C/s, 30 °C/s and 50 °C/s were applied to cool the samples to isothermal hold at 350 °C, 400 °C or 425 °C. Resulting microstructures were analysed by light and scanning electron microscopy after etching in 3% Nital.

## 3 Results

Multiphase microstructures of predominantly lath morphologies were obtained for both steels for all processing variants. Volume fraction of retained austenite varied from 3% to 10% for various processing methods.

### 3.1 Chromium alloyed steel CMnSiCr

The CMnSiCr steel possessed multiphase microstructures with coarse bainite-like blocks, consisting of laths of bainitic ferrite and M-A constituent with predominantly martensitic microstructure (**Fig. 2 – Fig. 4**). Only the thin laths with the thicknesses around several hundreds of nanometres were made of pure retained austenite. There were also larger blocks of M-A constituent alone, which had rather untypical shapes with complicated geometries of the edges (**Fig. 2**). Various processing conditions resulted in retention of 6-8% of retained austenite in this steel (**Table 1**). Generally, coarser microstructures with larger bainitic laths were obtained after the processing with higher soaking temperature of 900 °C and higher cooling rate of 15 °C/s. High tensile strengths in the region of 1616-2217 MPa were obtained, however the total elongation was only around 8%. These results are only in partial agreement with previous works [18 - 20], which stated that chromium addition resulted in more martensite in the final microstructure due to lower stability of remaining austenite and significant increase of tensile strength above 1000 MPa with total elongation around 20%.

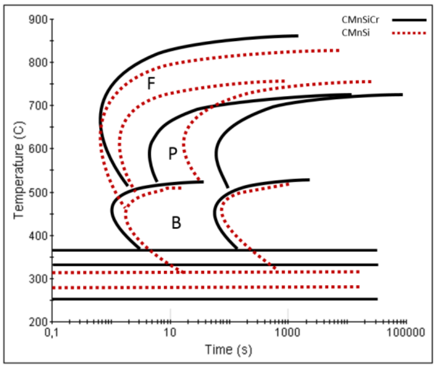


**Fig. 1** Calculated TTT diagrams of CMnSiCr (full line) and CMnSi (dotted line) steel

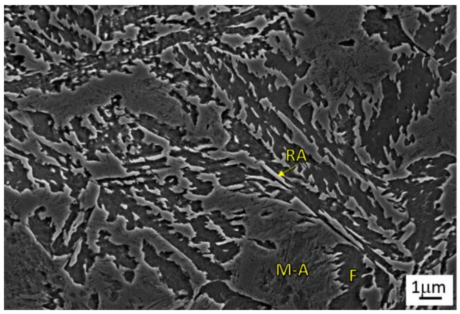


**Fig. 2** CMnSiCr -850°C/100s-15 deformation steps to 720°C - cooling rate 15°C/s – 425°C/600s

Lower soaking temperature of 850 °C combined with lower number of deformation steps (15) resulted in rather dendritic distribution of bainitic laths in the final microstructure (**Fig. 2**). The strength of this microstructure was therefore the lowest one of all CMnSiCr samples, reaching only 1616 MPa. Lower cooling rate of 10 °C/s was not quick enough to prevent formation of

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pearlite in the microstructure (**Fig. 3**), however pearlite presence did not deteriorate significantly the mechanical properties, as tensile strength was still 1904 MPa with 7% total elongation. The best combination of high strength above 2200 MPa with total elongation of 8% was obtained for the processing with higher soaking temperature of 900 °C combined with higher bainitic hold temperature of 450 °C (**Fig. 4**). This final microstructure consisted mainly of the mixture of martensite and bainite and resembled closely the microstructures and the properties of Q-P treated steel with the same chemical composition [12]. It suggests that hardenability of the steel was indeed increased by chromium addition preventing transformation of austenite to ferrite and slowing down bainitic reaction [19, 20].

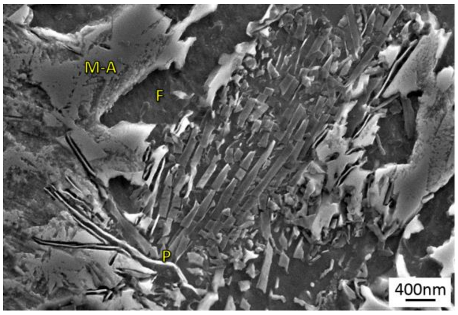


**Fig. 3** CMnSiCr - 900°C/100s-20 deformation steps to 720°C- cooling rate 10°C/s - 425°C/600s –pearlitic areas

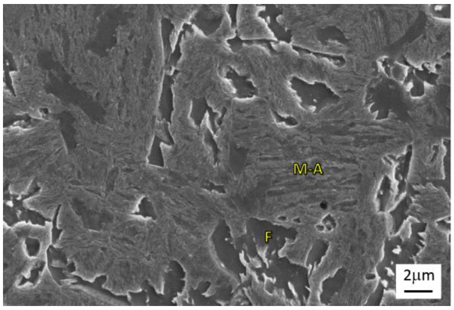


**Fig. 4** CMnSiCr - 900°C/100s- 20 deformation steps to 720°C - cooling rate 15°C/s - 450°C/600s

### 3.2 Steel CMnSi without chromium

CMnSi steel was first processed by soaking at 900 °C followed by 20 deformation steps during the cooling at 15 °C/s to 720 °C or 800 °C. It turned out that lower deformation finish temperature of 720 °C resulted in high amounts of pearlite in the final microstructure (**Fig. 5**). As the amount of pearlite was much lower after the same processing with deformation finish temperature of 800 °C, the higher finishing temperature was used for the rest of the experimental treatments. Bainitic hold was carried out in the range of 350°C-425 °C. While keeping other processing parameters the same, the tensile strength of the steel decreased from 1022 MPa to 890 MPa with the increase of bainitic hold temperature from 350 °C to 425 °C. The final microstructures in all three cases consisted of rather coarse blocks of martensite and bainite and low amount of fine ferrite grains at prior austenite boundaries (**Fig. 6**). Rather low volume fractions of retained austenite (3-7%) were measured in these samples. The highest amount of retained austenite (7%) was found in the sample with bainitic hold at 400 °C and it was also reflected by the highest total elongation of 39%.

Higher cooling rates of 20 °C/s, 30 °C/s and 50 °C/s were further tested to avoid formation of fine pearlitic areas in the final microstructures. For the soaking temperature of 900 °C, cooling rate of 50 °C/s was needed to prevent pearlite occurrence in the microstructure (**Fig. 7**). The final microstructure was also the finest of all analysed samples, with polygonal ferrite grain size around 1 micrometre. The bainite was homogeneously distributed and did not form larger blocks separated by surrounding ferrite grains. As the cooling rate increased, the amount of pearlite decreased leaving more carbon for austenite stabilization. Therefore, for the four processing which differed only in cooling rates, volume fraction of retained austenite increased from 3% for

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the processing with cooling rate 15 °C/s to 10% for the processing with cooling rate 50 °C/s. This trend is followed also by total elongation that increased from 26% to 36% for the same samples.

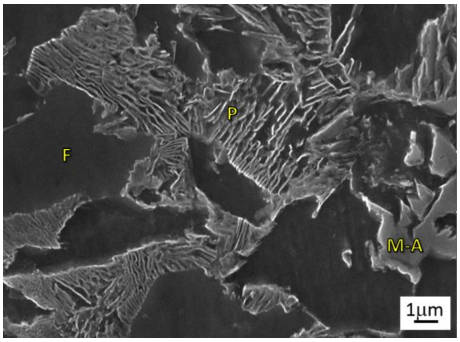


**Fig. 5** CMnSi 900°C/100s-20 deformation steps to 720°C - cooling rate 15°C/s - 350°C/600s

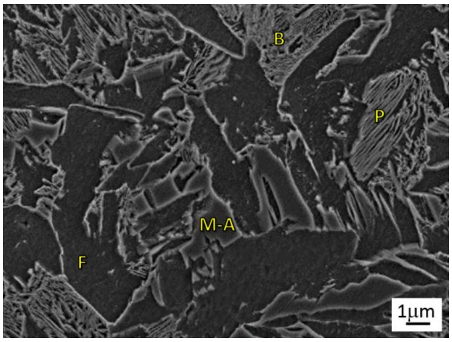


**Fig. 6** CMnSi-900°C/100s-20 deformation steps to 800°C - cooling rate 15°C/s - 400°C/600s

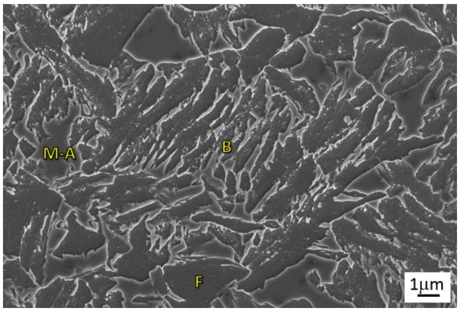


**Fig. 7** CMnSi 900°C/100s-20 deformation steps to 800°C - cooling rate 50°C/s - 425°C/600s

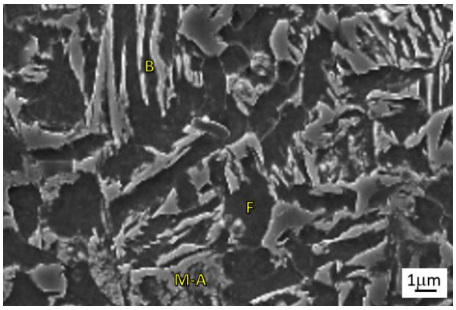


**Fig. 8** CMnSi -1000°C/100s-20 deformation steps 950-800°C - cooling rate 30°C/s - 425°C/600s

Cooling rate of 50 °C/s is relatively high for practical applications, which is the reason why a processing combining higher soaking temperature 1000 °C and slower cooling rate 30 °C/s was designed. In this case, no pearlite was found in the microstructure consisting of the mixture of upper and lower bainite with small amount of polygonal ferrite (**Fig. 8**) and 9% of retained austenite. High total elongation of 36% was maintained for this processing. The microstructure is however slightly coarser than after the processing with 900 °C soaking hold followed by cooling at 50 °C/s and that was reflected in the drop of tensile strength by 50 MPa.

## 4 Conclusions

High strengths in the region of 1616-2217 MPa with relatively low total elongation of 7-9% were achieved for CMnSiCr steel. There was no pearlite in the microstructure of any sample processed by cooling rate of 15 °C/s.

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High cooling rates reaching at least 30 °C/s had to be applied to CMnSi steel to prevent pearlite formation for the processing with soaking temperature of 900 °C. The strength of the steel increased with decreasing bainitic hold temperature. The best combinations of strength above 900 MPa and total elongation of 36% was achieved for CMnSi steel.

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