# PHASE TRANSFORMATIONS IN LOW-CARBON MANGANESE STEEL 6Mn16

The kinetics of phase transformations of the austenite of 6Mn16 steel during continuous cooling are presented in a CCT diagram. Manganese partitioning between ferrite and austenite during intercritical annealing is enhanced by prior soft annealing. Due to the increased Mn concentration in austenite, the temperatures $B_s$ and $M_s$ have decreased, as compared to those achieved during cooling from the complete austenite region.

*Key words:* low-carbon manganese steel, phase transformation, CCT diagram, intercritical annealing

**Fazni preobražaji u nisko-ugljičnom manganskom čeliku 6 Mn 16.** Data je u CCT dijagramu kinetika faznih preobražaja austenita u 6 Mn 16 čeliku tijekom kontinuiranog hlađenja. Mangan raspoređen između ferita i austenita tijekom međukritičnog žaranja je povišen glede ranijeg laganog hlađenja. Zbog porasta Mn sadržaja u austenitu temperature $B_S$ i $M_S$ su snižene usporedbom sa njihovim dobivanjem tijekom hlađenja iz cijelog austenitnog područja.

*Ključne riječi:* niskougljični manganski čelik, fazni preobražaj, CCT dijagram, međukritično žarenje

## INTRODUCTION

In recent years, there has been a growing interest in steels of multi-phase structures, composed of a ferritic matrix, in which islets occur, that contain bainite-B, martensite-M and the untransformed austenite-A [1-9]. The multi-phase structure of steel with untransformed austenite promotes the increase of plasticity induced by the phase transformation – the TRIP effect [3-4, 6-8]. In steels containing up to 1.6% Mn, the stabilization of austenite was achieved by increasing the content of carbon, aluminium or silicon. In the examined steel 6Mn16 containing up to 4% Mn and up to max. 0.08% C, the effect of carbon on austenite stabilization is less than that in steels with a higher carbon content. Manganese stabilizes austenite and has a higher solubility in austenite than in ferrite. The diffusion coefficient of Mn in ferrite, on the other hand, is higher by a factor from 10 to $10^3$ compared to austenite. In order to achieve the equilibrium partition of Mn between austenite and ferrite in steels containing up to 1.6% Mn, soaking times from approx. $10^6$ to $10^8$ seconds (277 to 27777 hrs) would have to be used in the inter-critical soaking processes [7]. To reduce the soaking time until a significant Mn partition between ferrite and austenite had been achieved, an unconventional heat treatment operation was applied. This consisted in the annealing of steel 6Mn16 below the temperature $A_{c1}$ to enrich the cementite with Mn. Then, the carbides enriched

with Mn were dissolved in austenite during soaking in the interval ($\alpha+\gamma$). In order to precisely determine the parameters of this heat treatment, the critical temperatures $A_{c1}$ an $A_{c3}$ were established and the effect of Mn on the kinetics of austenite decomposition from the complete austenitization and from ($\alpha+\gamma$) interval was determined. The partition of manganese between ferrite and austenite at the inter-critical soaking temperature and, after cooling, between the ferritic matrix and the bainitic-martensitic islets was assessed.

## THE TEST MATERIAL AND THE SCOPE OF TESTS CARRIED OUT

The subject of testing was low-carbon medium-manganese steel 6Mn16 of the following chemical composition, in percents by weight: C=0.040%, Mn=3.97%, Si=0.37%, Cr=0.01%, Ni=0.17%, Cu=0.02%, Mo=0.02%, Nb=0.02%, Ti=0.017%. Dilatometry tests were performed in a DIL 805 dilatometer on cylindrical specimens $\phi$ 5 x 10 mm. CCT diagram was plotted for steel 6Mn16 cooled down with argon from the austenitizing conditions 875±3°C/ 900 s.

For specimens soaked in the interval ($\alpha+\gamma$) 700°C/1800s and cooled at a rate of V=11 to 12 °C/s, the temperatures $B_s$ and $M_s$ were determined for:

a) specimen after controlled rolling,
b) specimens after controlled rolling, pre-soaked at a temperature of 625°C for a duration from 3600 s to 216 ks.

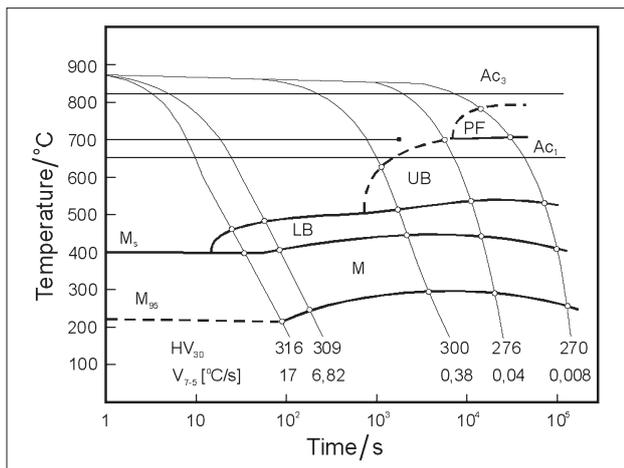J. Lis, A. Lis, Institute of Materials Engineering, Czestochowa University of Technology, Czestochowa, Poland

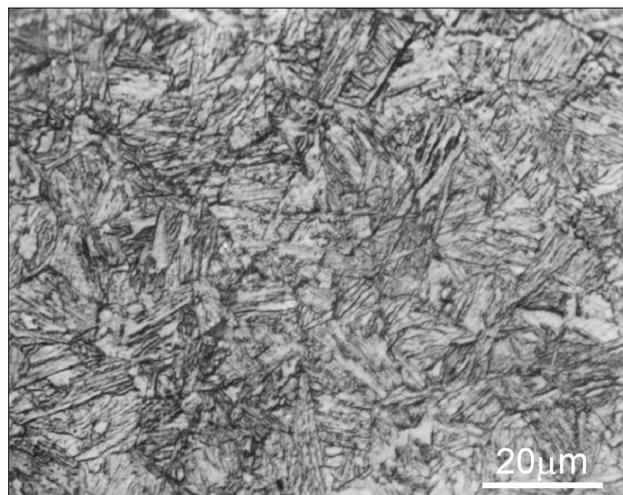**Figure 1.** CCT diagram for steel 6Mn16 cooled down from the temperature 875oC/900s.



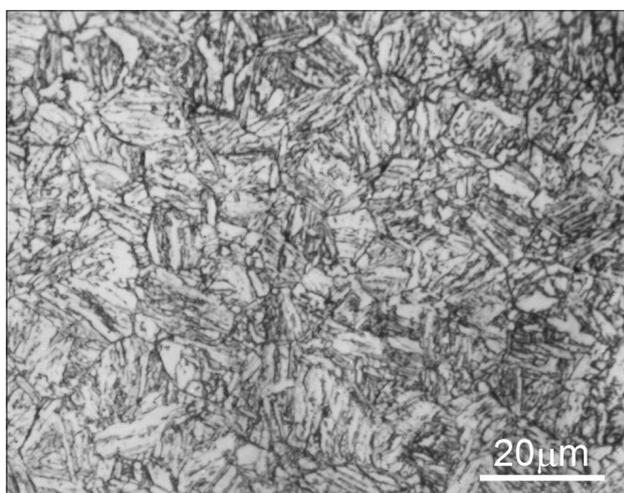**Figure 2.** Martensite-bainite structure of 6Mn16 steel after cooling rate 17°C/s.



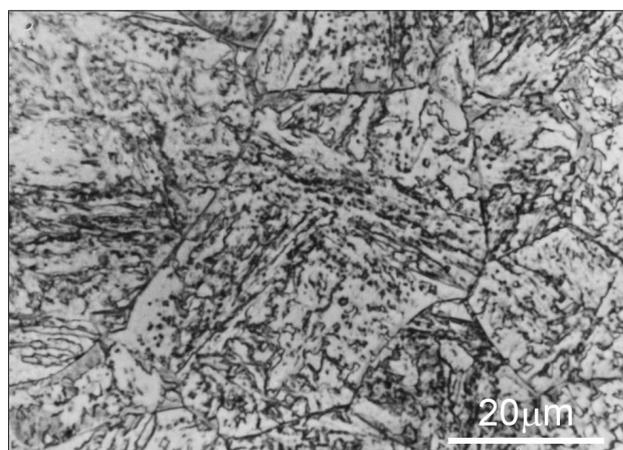**Figure 3.** Martensite-bainite structure of 6Mn16 steel after cooling rate 6.82°C/s.



**Figure 4.** Lower bainite-martensite structure of 6Mn16 steel after cooling rate 0.38°C/s.
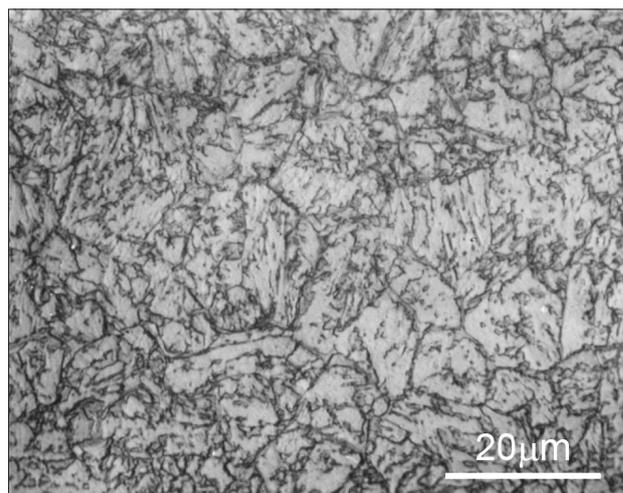
Using the Themo-Calc, Version M, the partition of alloying elements between ferrite and austenite was determined for the temperature 700°C. After cooling down from the interval ($\alpha+\gamma$) 700°C, microstructure examination and the analysis of Mn distribution in the ferritic matrix and the B-M-A islets were performed on a STEM Philips CM20 microscope with an EDX system.

## RESULTS AND DISCUSSION

### Examination of austenite transformation during continuous cooling

To make the CCT diagram - Figure 1, steel 6Mn16 was heated up to a temperature of 875°C±3°C/900 s. At this austenitizing temperature, the mean chord of the austenite grain $d_A$ was 14.8 ±3.6$\mu$m, with the maximum austenite grains being not larger than 25 $\mu$m. The critical temperatures were determined: $A_{c1}$= 654°C and $A_{c3}$=823°C. The martensitic-bainitic structures occurred within the cooling rate range from $V_{8-5}$=18.3°C/s to $V_{8-5}$=



**Figure 5.** Upper bainite structure of 6Mn16 steel after cooling rate 0.04°C/s.

0.04°C/s. For a cooling rate $V_{8-5}$ of up to 0.2 °C/s, the occurrence of the lower bainite and martensite was ascertained. The upper bainite, the lower bainite and martensite, on the other hand, occurred for cooling rates $V_{8-5}$ lower than 0.2°C/s. The presence of the polygonal
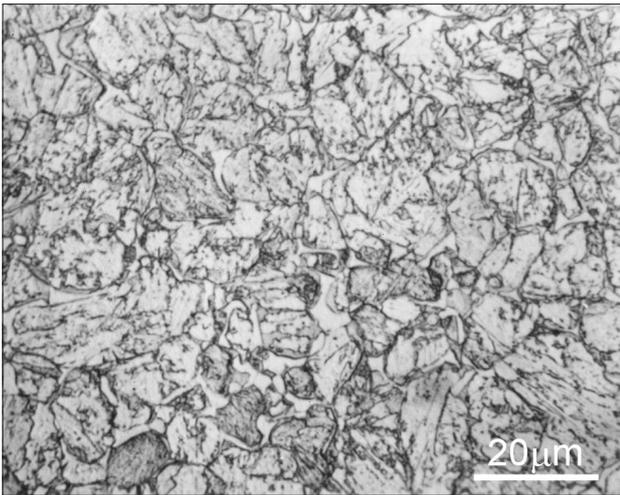
**Figure 6.** Bainite - polygonal ferrite - martensite structure of 6Mn16 steel after cooling rate 0.008°C/s.

ferrite was found for a $V_{8-5}$ of approximately 0.04°C/s. The morphologies of the structures shown in Figure 2 - 6 were confirmed by examination on an optical microscope.

**The effect of pre-soaking at 625°C on the temperatures of phase transformation of austenite after cooling down from the inter-critical interval**

Pre-soaking at a temperature of 625°C had an influence on the values of the temperatures $B_s$ and $M_s$ that were obtained during cooling down from the temperature 700°C corresponding to the interval ($\alpha+\gamma$). Their values are given in Table 1, while the changes are depicted graphically in Figure 7.

During quenching from the interval ($\alpha+\gamma$) from the temperature 700°C without pre-soaking treatment, the phase transformation start temperatures were: $M_s$=280°C and $B_s$=456°C (Table 1.), whereas for quenching after complete austenitizing they were: $M_s$= 400°C and $B_s$=470°C (Figure 1.). For specimens quenched from the temperature 700°C, the lowering of the temperatures $B_s$ and $M_s$ was achieved by increasing the soaking time before quenching at 625°C from 3600 s to 216 ks. For times of 216 ks, these temperatures were $B_s$=340°C, and $M_s$=175°C. The lowering of the phase transformation start temperatures of $B_s$ and $M_s$ was caused by the increase in manganese concentration in austenite.
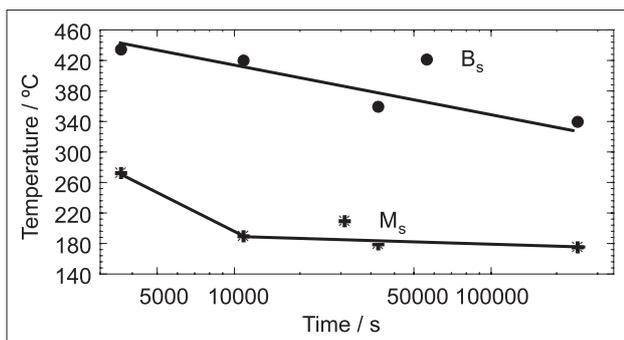


**Figure 7.** Change of the temperature of the bainitic and martensitic phase transitions with increasing time of 6Mn16 steel pre-soaking at 625°C

**Table 1.** The effect of the time of soaking of steel 6Mn16 at 625°C before heat treatment from the interval (a + g) 7000C/1800 s with subsequent cooling at a rate of V = (11 – 12) °C/s on the values of the temperatures Bs and Ms

| Soaking tim/eks | Cooling rate/°C/s | Transformation temperature/°C | |
|---|---|---|---|
| | | $B_S$ | $M_S$ |
| 0 | 17 | 456 | 280 |
| 3.6 | 12 | 435 | 274 |
| 10.8 | 11,5 | 420 | 190 |
| 36.0 | 11 | 360 | 180 |
| 216.0 | 12 | 340 | 175 |

**Table 2.** Phases and their chemical compositions occurring in steel 6Mn16 inter-critically soaked at 700°C

| Element | Phases | | |
|---|---|---|---|
| | $\alpha$Fe | $\gamma$Fe | MC |
| | / % | / % | / % |
| Fe | 97.08 | 92.29 | 0.001 |
| Mn | 2.413 | 6.925 | 0.017 |
| C | 0.0037 | 0.03 | 11.917 |
| Si | 0.362 | 0.387 | – |
| Ni | 0.099 | 0.3046 | – |
| Mo | 0.023 | 0.014 | 0.065 |
| Cu | 0.013 | 0.032 | – |
| Nb | – | – | 81.12 |
| Ti | – | – | 6.88 |
| Cr | 0.009 | 0.011 | – |
| Fraction, % | 65.05 | 34.67 | 0.275 |

This is confirmed by the partition of manganese between ferrite and austenite at 700°C, as given in Table 2. The partition is determined for the conditions of thermodynamic equilibrium, without considering the kinetics of transformation and the rate of carbide dissolution in the austenite, which affects the actual manganese partition taking place during soaking in the inter-critical interval.

## The structure of steel 6Mn16 after quenching from the interval ($\alpha+\gamma$)

In the examination of the structure using a TEM with an EDS analyzing attachment, islands of BM or BMA with a variable manganese concentration were observed. It was found that the increment of manganese concentration in the islets increased with the time of pre-soaking at 625°C before heating up for quenching. For specimens soaked for a duration from 1.08 ks to 3.6 ks and then quenched from the temperature 700°C, the Mn concentration in the ferritic regions was 2.8%, in bainitic ferrite grains 3.8%Mn, and in the B-M islands 5.4%Mn (Figure 8).
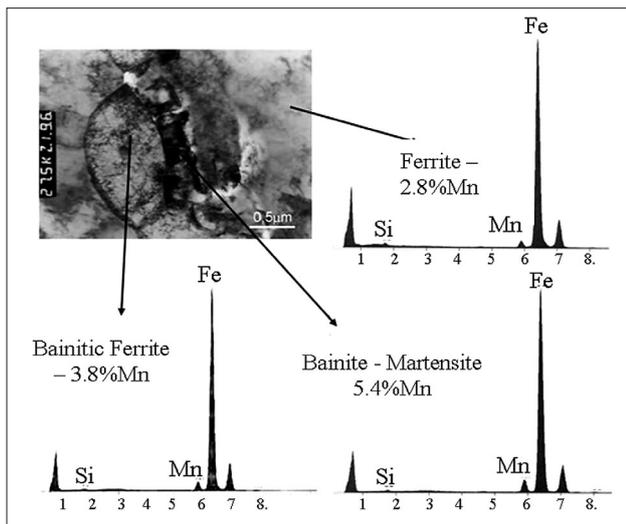
**Figure 8.** A multi-phase structure with the spectra of characteristic radiation and concentration of alloying elements occurring in the structural components of steel 6Mn16 heat treated from the interval ($\alpha + \gamma$) 700°C/1800s and cooled down at V≅12°C/s
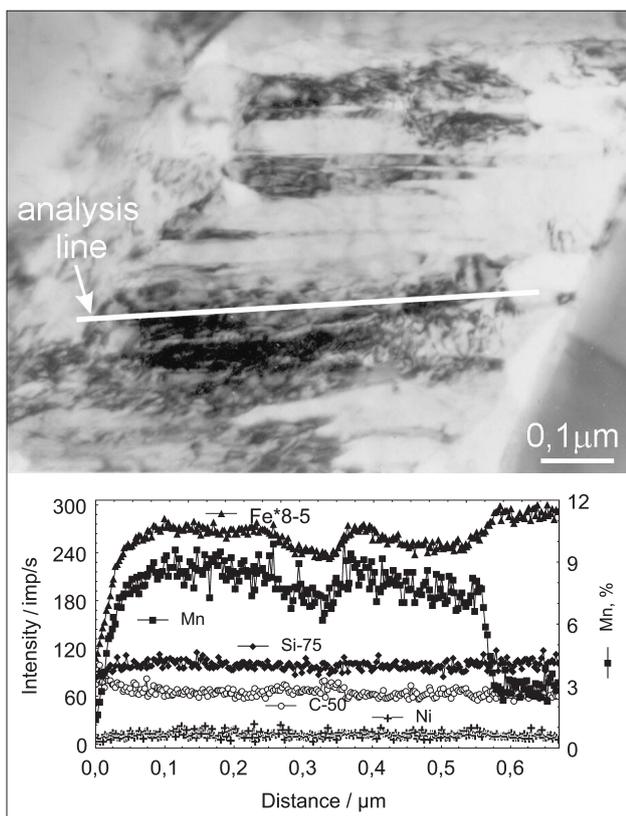


**Figure 9.** Microstructure of a BM islet in the ferritic matrix of steel 6Mn16 and the concentration of alloying constituents along the line analyzed

MBA islets were also observed (Figure 9), in which the manganese concentration was from 6% to 10%, and varied within the island. A reduction in Mn concentration occurred in the centre of the island. This unequal partition of manganese has an effect on the retained austenite occurring in the structure of the steel examined. The manganese-enriched areas close to the $\alpha/\gamma$ inter-
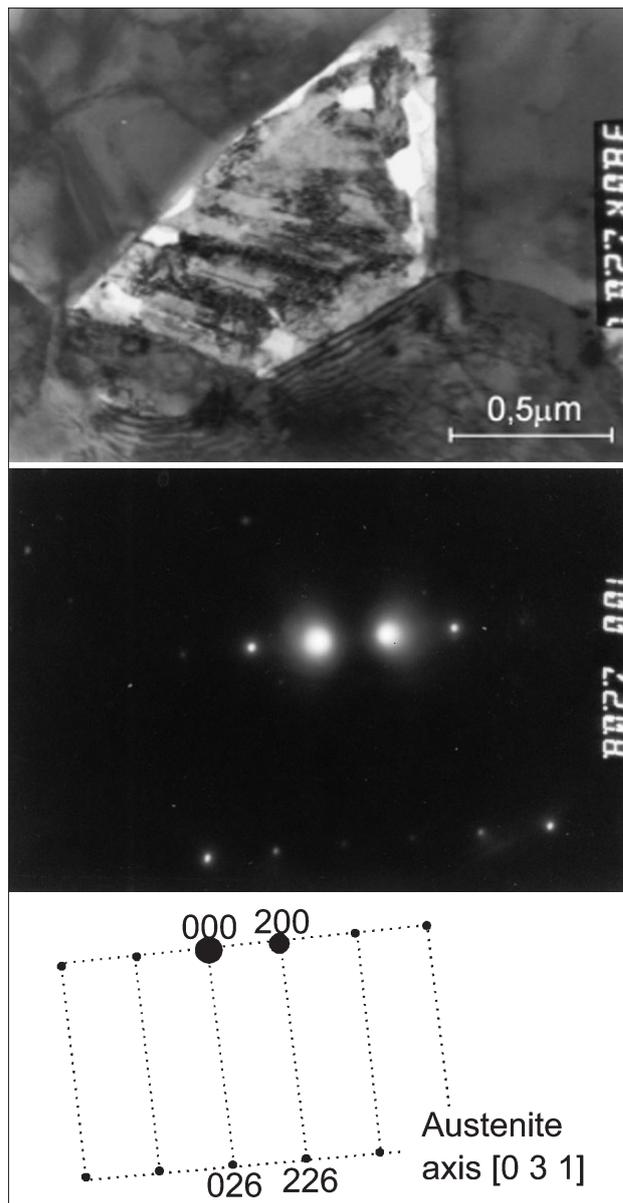


**Figure 10.** Microstructure of steel 6Mn16 after soaking in the interval ($\alpha+\gamma$) 700°C/1800s and cooled down at V≈12°C/s; a) bright area, b) diffraction, c) diffraction solution

face, formed during soaking in the interval ($\alpha+\gamma$), have an effect on austenite transformation during cooling.

The more Mn-enriched areas, $\gamma$, do not undergo transformation and remain as retained austenite, while the remaining areas of austenite undergo transformation into bainite and martensite. A characteristic morphology of a bainitic-martensitic island containing untransformed retained austenite is shown in Figure 10. The figure shows also an electron diffraction from the austenite and its solution.

## CONCLUSIONS

1. Steel 6Mn16 after cooling down from the complete austenitization interval is characterized by high bainitic hardenability.

2. The lower bainite and martensite occur for cooling rates higher than 0.2°C/s.

3. Pre-soaking of steel 6Mn16 at a temperature of 625°C before heat treatment from the interval $(\alpha+\gamma)$ at a temperature of 700°C for 1800 s and cooling down at a rate of V=11÷12°C/s results in a lowering of the temperatures $B_s$ and $M_s$.

4. Increasing the concentration of Mn in austenite during soaking in the interval $(\alpha+\gamma)$ causes a reduction in the temperatures $B_s$ and $M_s$.

5. The Mn partition existing between the austenite and the ferrite at 700°C is inherited by bainitic-martensitic islets and bainitic-martensitic islands with retained austenite, formed during rapid cooling from the interval $(\alpha+\gamma)$.

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**Note:** The responsible translator for English language are the Authors.