Thermo-mechanical Treatment of 0.4C-0.6Mn-2Si Steel with Various Soaking and Annealing Hold Temperatures

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Middle carbon low alloyed steel 0.4C-0.6Mn-2Si was subjected to thermo-mechanical treatment typical for TRIP (transformation induced plasticity steels). The processing consisted from soaking at the temperatures of 850-1000 °C and cooling at 30 °C/s to various annealing holds in bainite transformation temperature interval of 350-500 °C. During the cooling from the soaking temperature, two compressive deformations were carried out, the second one always at 720 °C. Resulting microstructures were analysed using light and scanning electron microscopy. X-ray diffraction phase analysis was carried out to establish volume fraction of retained austenite and mechanical properties were measured by tensile test. Tensile strengths in the region of 847-963 MPa were obtained and very good total elongations of 30-40% were achieved at the same time. Multiphase microstructures were obtained with various amounts of ferrite, bainite, retained austenite and pearlite.

Keywords: Middle carbon steel, Thermo-mechanical treatment, Retained austenite, TRIP steel

1 Introduction

Thermo-mechanical processing is a typical treatment used for preparation of complex multiphase microstructures which are able to display a TRIP (transformation induced plasticity) effect [1]. These microstructures usually consist of a mixture of ferrite, bainite and retained austenite and retained austenite is considered crucial for achievement of good mechanical properties [2-5]. The first generations of advanced TRIP steels possessed a matrix of polygonal ferrite with around 25% of bainite and 15% of retained austenite [1, 2]. Lately, variations of bainite-based microstructures with smaller amounts of ferrite and still around 15% of retained austenite appeared. It was generally stated that TRIP steels could be based on a simple chemical concept of 0.2-0.4% of carbon, 1-2% of manganese and silicon [6-14]. However, most of the research has been always concentrated on low alloyed steels with lower carbon contents around 0.2% C [1-8] and less attention has been paid to middle carbon steel [9-18]. Manganese is added to increase chemical stability of austenite against martensitic transformation during final cooling and thus increase the amount of retained austenite in the final microstructure. Even though silicon is a ferrite forming element, it is used in TRIP steels for the very same reason as manganese. Silicon does not dissolve in cementite and therefore postpones cementite formation during the processing, particularly during the annealing hold. Pearlitic microstructure is considered to be undesirable in TRIP steels, because it consumes carbon, which should be used for retained austenite stabilization instead [1,3].

Thermo-mechanical processing of TRIP steel is relatively simple, consisting of soaking in either fully austenitic temperature interval or at various intercritical temperatures, deformation at the soaking temperature or during cooling to the annealing hold temperature [12-16]. Annealing hold is a typical feature of TRIP steel processing, offering possibility for remaining austenite carbon enrichment and creation of sufficient amount of bainite.

In this article, the steel with higher carbon content of 0.4% C and little further alloying with 0.6% manganese and 2% of silicon.

2 Experimental program

2.1 Material

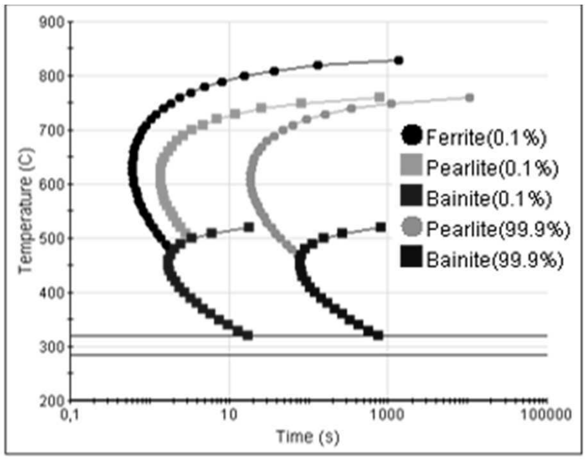

Fig. 1 *TTT diagram calculated in JMatPro*

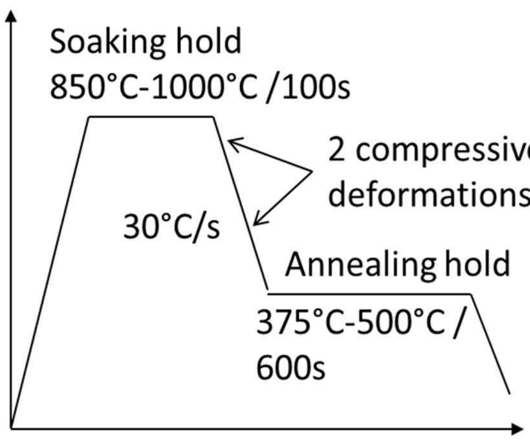

Fig. 2 *Scheme of thermo-mechanical processing*

Middle carbon, low alloyed steel 0.4%C-0.6%Mn-2%Si (in weight percents) was used in this work. TTT (time temperature transformation) diagram of this steel was calculated by JMatPro software for a soaking temperature of 850 °C (Fig. 1). Calculated bainite transformation temperatures were in the region of circa 325-510 °C. Annealing hold temperatures of 375 – 500 °C were therefore chosen for proposed thermo-mechanical treatment (Fig. 2) to ensure sufficient bainite formation. Based on JMatPro calculations, three soaking temperatures of 850 °C, 900 °C and 1000 °C were chosen, which should lie in a one-phase, fully austenitic region.

2.2 Thermo-mechanical processing

Thermo-mechanical processing was carried out at MTS FlexTestSE electro-hydraulic simulator with maximum load of 50 kN at actuator speeds of up to 3 m/s. This equipment enables precise control of heating and deformation parameters and high repeatability of desired processing conditions. The samples had cylindrical shape with diameter of 8 mm and active length of 16 mm which was optimized to ensure homogeneous distribution of heat and deformation across the active length of the sample.

Processing method typical for TRIP steels was chosen for experimental program (Fig. 2), consisting of a soaking hold in fully austenitic region, followed by two compressive deformations during the cooling to an annealing hold. The size of each deformation corresponded to 10% of an actual sample length and the last deformation was always applied at 720 °C. The cooling rate was kept 30 °C/s for all the samples, the soaking temperatures varied from 850 °C to 1000 °C. First of all, a set of annealing hold temperatures of 375 – 500 °C was tested for processing with the lowest soaking hold of 850 °C. Annealing hold which yielded the best resulting properties was then used in thermo-mechanical treatments with increased soaking temperatures of 900 °C and 1000 °C. Soaking hold was 100 s for all soaking temperatures and annealing hold of 600 s was used for all annealing temperatures.

2.3 Microstructure analysis and testing

Microstructures were characterized in the central part of processed samples by the means of BX61 Olympus light microscope and VEGA 3 and EVO 25 scanning electron microscopes (SEM) with a tungsten and a LaB6 cathode respectively. Volume fraction of the retained austenite was determined by an X-ray diffraction phase analysis using an AXS Bruker D8 Discover automatic powder diffractometer. Resulted volume fractions were rounded to the closest whole number. Carbon content in the retained austenite was calculated considering the effect of alloying elements according to [1]:

$$a = 3{,}572 + 0{,}0012\ Mn - 0{,}00157\ Si + 0{,}0056\ Al + 0{,}033\ C \quad (1)$$

Where:

a … lattice parameter of the retained austenite calculated from the three austenite peaks measured by X-ray diffraction phase analysis.

Mechanical properties were measured by tensile test of flat samples with an active length of 5 mm and a cross section of 1.2 x 2 mm. Two samples were tested for each processing method and average values are used in further text.

3 Results and discussion

3.1 Effect of various annealing hold temperatures

Thermo-mechanical processing with a soaking temperature of 850 °C was carried out with the same thermal and deformation parameters except of an annealing hold temperature, which varied from 375 °C to 500 °C to cover the calculated interval of bainitic transformation temperatures. The aim of these variations was to find the most convenient annealing temperature with regard to the final microstructure and mechanical properties.

Tab. 1 *Parameters of thermo-mechanical treatment with two compressive deformations and cooling rate 30 °C/s, resulting mechanical properties (yield strength Re, ultimate tensile strength Rm, total elongation A_{5mm}), retained austenite volume fraction (RA) and carbon content in retained austenite (C_{RA}).*

Soaking [°C] / [s]	Deformation temperatures [°C]	Annealing hold [°C]	Re [MPa]	Rm [MPa]	A_{5mm} [%]	RA [%]	C_{RA} [%]
850/100	850, 720	375	523 ±3	918 ±3	38 ±2	12	0.36190
		400	617 ±0	857 ±2	40 ±1	13	0.36237
		425	603 ±4	855 ±4	41 ±1	10	0.36231
		450	595 ±5	858 ±0	35 ±1	5	0.36191
		500	627 ±7	847 ±1	30 ±0	-	-
900/100	900, 720	425	616 ±4	884 ±2	43 ±0	10	0.36218
1000/100	900, 720	425	638 ±2	925 ±3	42 ±1	15	0.36216

The lowest annealing temperature of 375 °C resulted in a multiphase microstructure with rather fine ferritic matrix, coarser bainitic blocks and small areas of pearlite (Fig.3, Fig.4). Detailed images from SEM showed the presence of larger blocks of M-A constituent, which forms when austenitic grains are not stable enough to resist martensitic transformation during the cooling and significant part of these islands transforms to martensite. Despite the occurrence of pearlite, there was still 12% of the retained austenite in the final microstructure, which corresponds to the amount expected in steels displaying transformation induced plasticity effect. This could be also responsible for good mechanical properties of this microstructure, which reached an ultimate tensile strength of 918 MPa with a total elongation of 38%.

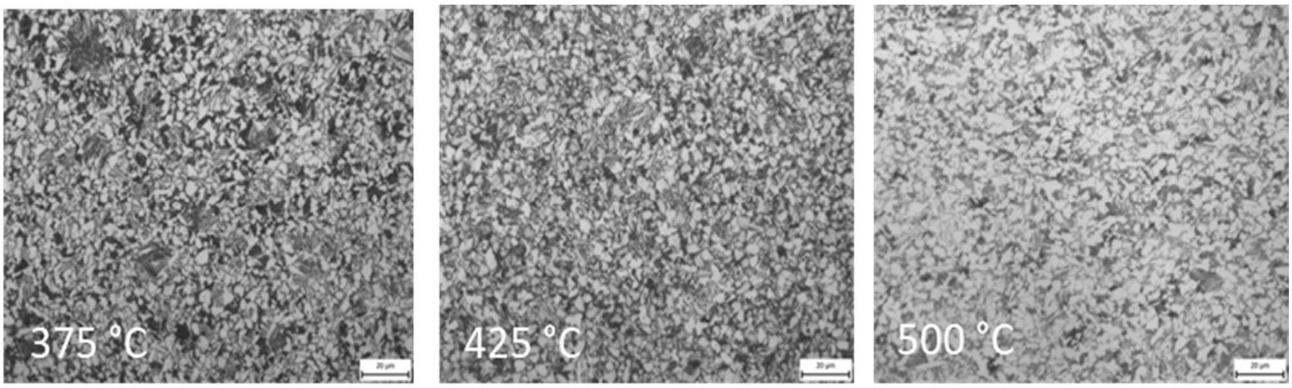

Fig. 3 *Light micrographs of microstructures annealed at 375 °C, 425 °C and 500 °C (left to right)*

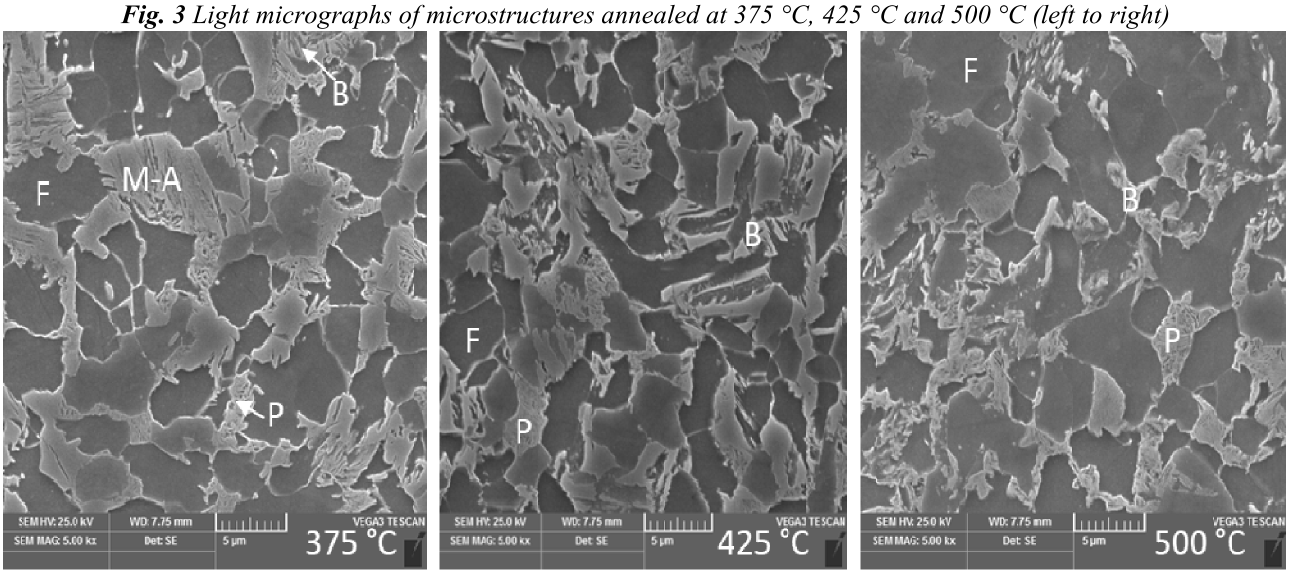

Fig. 4 *Scanning electron micrographs of microstructures annealed at 375 °C, 425 °C and 500 °C (left to right, F – polygonal ferrite, P – pearlite, B –bainite, M-A- austenitic islands partially transformed at martensite)*

An increase of an annealing temperature to 400 °C resulted in lower amount of martensite in the final microstructure, which was reflected by lower tensile strength of 857 MPa and slightly higher total elongation of 40%. The volume fraction of the retained austenite reached 13%, which was the highest value obtained in this work. It should be however noted, that 1% difference in retained austenite volume fraction is in this case insignificant. More important role for behaviour of the microstructure under mechanical load would play different carbon content in the retained austenite. Higher carbon content suggests higher stability of austenite obtained by the processing with annealing hold of 400 °C.

Increase of the annealing temperature to 425 °C did not cause any change in mechanical properties and the microstructure was very similar to the one obtained by annealing at 400 °C. Volume fraction of the retained austenite was smaller, reaching only 10%, however its carbon content remained practically the same.

Further increase of the annealing hold to 450 °C resulted in a drop of total elongation to 35%, while the strength still reached 858 MPa. This was caused by higher amount of carbides formed at higher annealing hold and accompanying drop of retained austenite volume to only 5%.

Further deterioration of total elongation was observed for the processing with the highest annealing hold of 500 °C. Ultimate tensile strength was still around 850 MPa in this case, but the total elongation reached the lowest value of 30%. The microstructure was basically a ferritic-pearlitic one and the amount of the retained austenite was below the detection limit of X-ray diffraction phase analysis. It can be seen from the comparison of this microstructure with the ones produced by processing with annealing holds of 400-425 °C that stabilization of about ten percent of the retained austenite in a bainitic microstructure increased the total elongation of the steel by one third, while the change of an ultimate tensile strength was negligible.

The observed changes of the mechanical properties were not in agreement with the results obtained for the same steel after two step heat treatment without deformations [10]. The reason of the discrepancy probably lies in the large volumes of pearlite formed during the cooling from soaking temperature to the annealing temperature in the case of thermo-mechanical treatment, leaving lower amount of remaining austenite for further phase transformation and less carbon in remaining austenite.

The observed trends of mechanical properties also differ from the results published for low carbon TRIP steels, where increasing the temperature of the bainitic hold generally resulted in a decreasing strength and an increasing total elongation [19]. The plateau of tensile strength was also reported by Hausmann et al. [20] for 0.2C-2.6Mn-0.8Si-0.025Nb steel with tensile strengths in the region of 1200–1000 MPa, which also reached nearly constant strengths for hold temperatures in the interval of 425–450 °C, followed by a quick drop after the treatment with a 475 °C hold. The total elongation gradually increased from 12% to 18% with increasing hold temperature. Similar behaviour was observed for Al alloyed TRIP steel [4], where the highest total elongations were reached for annealing holds around 425 °C, however these annealing temperatures produced relatively low tensile strengths which increased both at lower and higher annealing temperatures. It can be therefore seen, that even though temperatures around 425 °C are generally considered to be the best option for the annealing of TRIP steels, there is not a uniform trend of development of mechanical properties through the whole bainitic transformation temperatures interval.

3.2 Effect of soaking temperatures

Low soaking temperatures have the benefit of providing processing with lower energy consumption and thus higher cost efficiency. In the case of a soaking temperature of 850 °C, the resulting microstructures were relatively fine and had homogeneous distribution of phases and fine ferrite matrix. On the other hand, the amount of bainite was low and pearlite was observed in all the microstructures. Increased soaking temperatures of 900 °C and 1000 °C resulted in microstructure coarsening, particularly of bainitic blocks (Fig. 5, Fig. 6). The microstructures were predominantly of a ferritic-bainitic type with fine areas of pearlite formed at the edges of bainitic blocks.

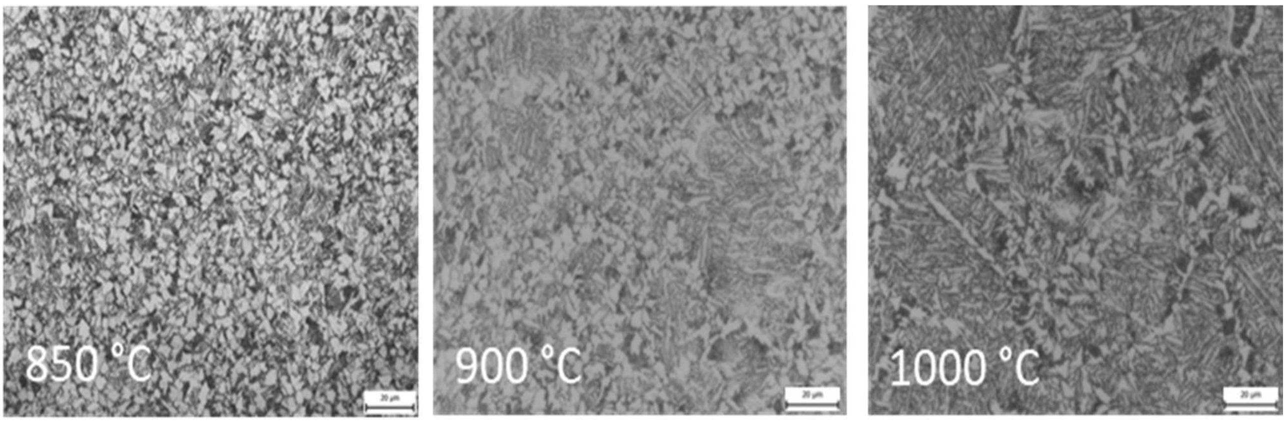

***Fig. 5** Light micrographs of microstructures soaked at 850 °C, 900 °C and 1000 °C (left to right)*

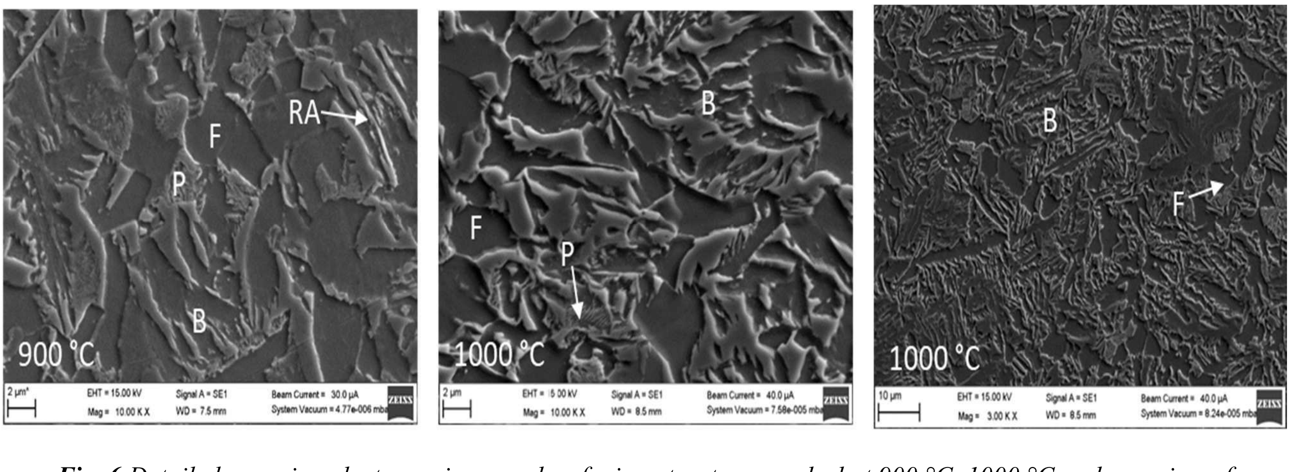

***Fig. 6** Detailed scanning electron micrographs of microstructures soaked at 900 °C, 1000 °C and overview of microstructure soaked at 1000 °C (left to right, F – polygonal ferrite, P – pearlite, B –bainite, RA- retained austenite)*

Soaking temperature of 900 °C produced microstructure with higher strength of 884 MPa and the best total elongation of 43%, the amount of the retained austenite was the same as in the case of the same processing with soaking temperature of 850 °C. Retained austenite formed laths in bainite and only few coarser islands of M-A constituent were observed. Better mechanical properties should therefore be attributed mainly to the increased amount of bainite, rather than to the retained austenite alone. Smaller bainitic blocs were made of a granular bainite, while lath bainite prevailed in larger bainitic blocks.

The highest soaking temperature caused further coarsening of bainitic blocks which were separated by the chains of fine grains of proeutectoid ferrite. Larger areas of lath bainite were observed in this microstructure, with granular bainite at the edges or inside of small bainitic blocks. As in the previous microstructure, extremely fine pearlitic areas were found at the edges of bainitic blocks. This bainite-based microstructure with 15% of retained austenite possessed very interesting combination of high strength of 925 MPa accompanied by high total elongation of 42%.

In comparison with the behaviour of the same steel processed by two step heat treatment (without deformations) [8], the tensile strength in both cases increased with increasing soaking temperature. However, in the case of thermo-mechanical treatment, the total elongation very slightly increased with increasing temperature, while in the case of heat treatment alone, the highest total elongation of 47% was obtained for processing with soaking at 850 °C and it gradually dropped with increasing soaking temperature to 26% for 1000 °C soaking hold.

4 Conclusions

Thermo-mechanical treatment of 42SiMn steel with 0.4 %C was carried out with various soaking temperatures of 850 – 1000 °C, cooling rate 30 °C /s and several annealing hold temperatures in the range of 375 -500 °C. Two compressive deformations were applied during the cooling from a soaking to an annealing hold.

Cooling rate of 30 °C/s was not quick enough for low soaking temperature of 850 °C to provide pearlite free microstructures, however retained austenite volume fractions were still around 10% for lower annealing hold temperatures. These microstructures consisted of the mixture of fine polygonal ferrite grains, bainitic areas, rather fine pearlite and for the lowest annealing hold of 375 °C there were large islands of M-A constituent. The best combinations of tensile strengths around 850 MPa and total elongations around 40% were achieved for annealing holds of 400-425 °C.

When soaking temperature of used thermo-mechanical treatment with an annealing hold 425 °C was increased to 900 °C and 1000 °C, even better mechanical properties were obtained. The microstructures were bainitic-ferritic with 10-15% of retained austenite and very fine pearlitic colonies. Tensile strength increased with increasing soaking hold to 925 MPa with total elongations above 40%.

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