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Thermo-Mechanical Treatment of Chromium Alloyed Low Carbon Steel

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***Abstract*—**Thermo-mechanical processing with various processing parameters was applied to 0.2%C-0.6%Mn-2S%i-0.8%Cr low alloyed high strength steel. The aim of the processing was to achieve the microstructures typical for transformation induced plasticity (TRIP) steels. Thermo-mechanical processing used in this work incorporated two or three deformation steps. The deformations were in all the cases carried out during the cooling from soaking temperatures to various bainite hold temperatures. In this way, 4-10% of retained austenite were retained in the final microstructures, consisting further of ferrite, bainite, martensite and pearlite. The complex character of TRIP steel microstructure is responsible for its good strength and ductility. The strengths achieved in this work were in the range of 740 MPa – 836 MPa with ductility A_{5mm} of 31-41%.

***Keywords*—**Pearlite, retained austenite, thermo-mechanical treatment, TRIP steel.

I. Introduction

MODERN TRIP steels have been developed as low alloyed high strength materials with good ductility, formability, and ability to absorb impact energy. This made them very practical for applications in an automotive industry, which has been on the lookout for materials enabling safe construction of lightweight car parts. There have been lately some attempts to apply TRIP steels also to the production of seamless tubes [1] or wires [2].

Multiphase microstructure of TRIP steels with retained austenite is typically commercially prepared either by cold rolling [3] and subsequent two-step annealing, or by thermo-mechanical processing [4], [5] with controlled cooling and the hold at the temperatures in bainitic region. This hold ensures creation of sufficient amount of carbide-free bainite and carbon diffusion into remaining austenite. Higher local carbon contents suppress martensite start temperature of these particular islands below room temperature providing the final microstructure with around 5-15% of metastable retained austenite. Properly stabilized retained austenite gradually transforms to martensite during cold plastic deformation utilizing the TRIP effect and enhancing tensile strength and ductility of the steel [6].

Various alloying concepts have been investigated for TRIP steels and other advanced multiphase high strength steels, usually based on carbon, manganese, silicon, aluminum and phosphorus [7], [3]. Suitable combinations of alloying elements are in the case of TRIP steel mainly used to stabilize retained austenite, postpone pearlitic transformation, and delay carbide precipitation, particularly during bainitic hold. It has been already successfully demonstrated in the case of quenching and partitioning (QP) processing that chromium can also play a positive role in delaying pearlite formation and generally improving mechanical properties of this steel [7], [8]. The addition of low contents of chromium to dual phase (DP) high strength steel has been also proved to be beneficial for its mechanical properties [9]. As both, TRIP and QP processing are based on retained austenite stabilization in the final microstructure; the effect of chromium on the performance of low carbon low alloyed TRIP steel was tested in this article. High strength low alloyed steel with 0.5% Cr was further reported to show improved corrosion resistance [3].

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II. Experimental Program

Low alloyed steel with 0.2% of carbon was used for this experimental program (Table I). The steel is alloyed by 0.6% of manganese to support austenite stabilization and by 2% of silicon to suppress cementite formation during isothermal hold in bainitic region. Silicon is further used for an effective solid solution strengthening of the steel. While these three elements are typical for most of the TRIP steels, special addition of 0.8% of chromium was used in this case to improve mechanical properties and further enhance ferritic area in TTT (time temperature transformation) diagram. TTT diagram of used steel was calculated by JMatPro software (Fig. 1).

TABLE I
Chemical Composition (in weight %)

C	Mn	Si	P	S	Cr	Nb
0.2	0.6	2	0.009	0.004	0.8	0.04

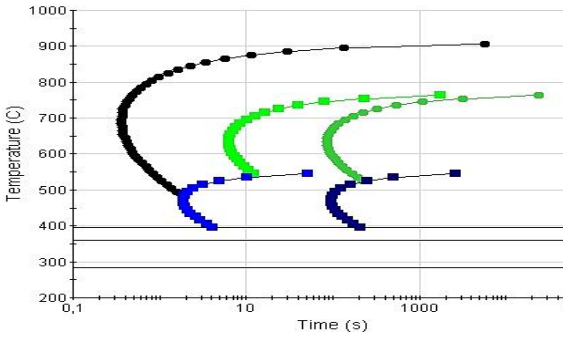

Fig. 1 TTT diagram of used steel calculated in JMatPro

Processing of all samples was carried out at thermo-mechanical simulator (Table II). The simulator enables precise control of thermal and deformation parameters and high repeatability of the processing. Several methods of thermo-mechanical processing were designed for this steel. Thermo-mechanical processing always consisted of soaking at the temperatures of 850 °C or 900 °C for 100 s. Two or three deformation steps were carried out during the cooling from soaking temperatures to 750 °C, 720 °C, 700 °C or 680 °C. Various cooling rates of 16 °C/s, 20 °C/s or 30 °C/s were used to cool samples from soaking temperatures down to bainitic hold at the temperatures of 400 °C or 425 °C.

In the first set of samples, soaking temperature of 900 °C was used and the first deformation was always carried out at this temperature at the end of 100 s soaking hold. The temperature of the second deformation was either 720 °C or 700 °C and in one case, the third deformation was added at 680 °C. Three processing had the same 600 s bainitic hold at 420 °C. The best processing with two deformations at 900 °C and 720 °C was repeated with lower bainitic hold of 600 s at 400 °C. Lower holding temperature was supposed to refine bainitic microstructure. All processing methods used average cooling rate 16 °C/s which was chosen on the base of previous results [10].

In the second step, soaking temperature was decreased to 850 °C to increase free ferrite fraction and to keep the processing as cost efficient as possible. All the processing with this soaking temperature had two deformations; the first one being applied at 850 °C, the second at 720 °C. Bainitic holds at 425 °C and 400 °C were again tested. Three average cooling rates 16 °C/s, 20 °C/s, and 30 °C/s were applied to the samples with lower bainitic hold at 400 °C. Higher cooling rates were used to prevent pearlite formation during the cooling.

TABLE II
PROCESSING PARAMETERS, MECHANICAL PROPERTIES AND RETAINED AUSTENITE VOLUME FRACTION (RA)

T_S [°C]	Def. Number	T_{def} [°C]	Cooling rate [°C/s]	T_B [°C]	UTS [MPa]	A_{5mm} [%]	RA [%]
900	2	900, 720	16	425	743	41	4
900	2	900, 700	16	425	756	37	6
900	3	900, 720, 680	16	425	786	31	5
900	2	900, 720	16	400	768	42	7
850	2	850, 720	16	425	743	40	7
850	2	850, 720	16	400	729	43	7
850	2	850, 720	20	400	760	34	6
850	2	850, 720	30	400	836	35	10

T_S Soaking Temperature (hold always 100 s), T_{def} Temperature of Individual Compressive Deformations, T_B Bainite Hold Temperature (always 600 s hold time.

The main aim of the optimization of processing parameters was to obtain typical TRIP microstructure consisting of ferrite, bainite, retained austenite and possibly island of austenite partially transformed to martensite (M-A constituent) and to achieve the best combination of tensile strength and ductility. All the deformations were compressive, and each was equal to 10% of actual size of the sample. The original size of the sample was cylindrical with 8 mm diameter and 16 mm active length. This size ensures homogeneous distribution of thermal and deformation fields in the active part of the sample.

Resulting microstructures were analyzed by scanning electron microscopy using Ziess 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 measured by tensile test on small flat samples with sample geometry 2 mm x 1.5 mm and 5 mm active length. The ability to absorb deformation energy during plastic deformation could be further evaluated by tensile strength to ductility balance (UTS x A_{5mm}), which is the measure typically used for TRIP steels for automotive applications.

III. RESULTS

Processing with higher soaking temperature 900 °C, the second deformation applied at 720 °C and bainitic hold at 425 °C produced fine microstructure containing ferrite (F), bainite (B), M-A constituent and very fine pearlitic (P) areas growing either from ferrite grain boundaries or at the edges of larger islands of M-A constituent (Fig. 2). There was about 4% of retained austenite, tensile strength was 743 MPa and ductility A_{5mm} =41%.

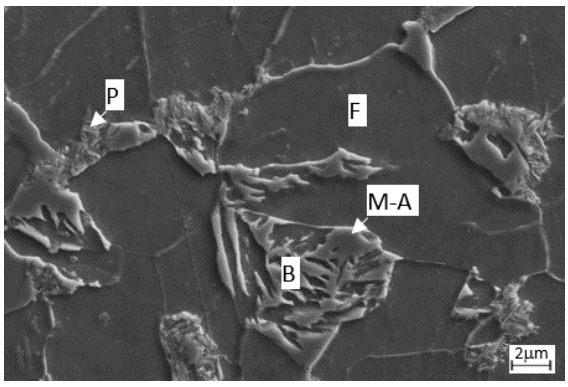

Fig. 2 Heating 900 °C / 100 s, two deformations at 900 °C and 720 °C, cooling rate 16 °C/s, bainitic hold at 425 °C

Decrease of the deformation finish temperature resulted in microstructural changes. Drop of deformation finish temperature from 720 °C to 700 °C was accompanied by coarsening of pearlite lamellas and the areas of M-A constituent (Fig. 3). There was just a slight increase in tensile strength obtained after this processing; however, ductility was

lower than in the case of deformation finish temperature of 720 °C. The amount of retained austenite was practically the same as in previous sample. Further decrease of deformation finish temperature to 680 °C resulted in the growth of larger pearlitic areas with very fine lamellas on the expense of bainite and M-A constituent, which nearly disappeared (Fig. 4). This microstructure development was reflected in the increase of tensile strength to 786 MPa and decrease of ductility A_{5mm} to only 31%.

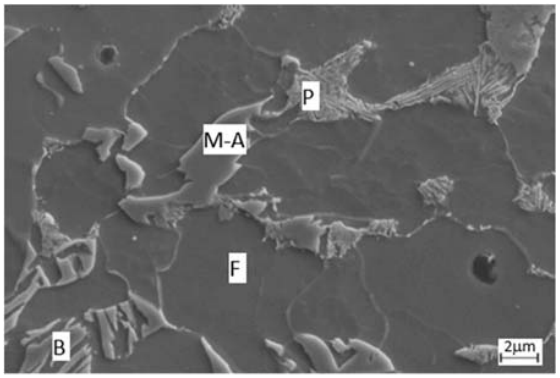

Fig. 3 Heating 900 °C / 100 s, two deformations at 900 °C, 700 °C, cooling rate 16 °C/s, bainitic hold at 425 °C

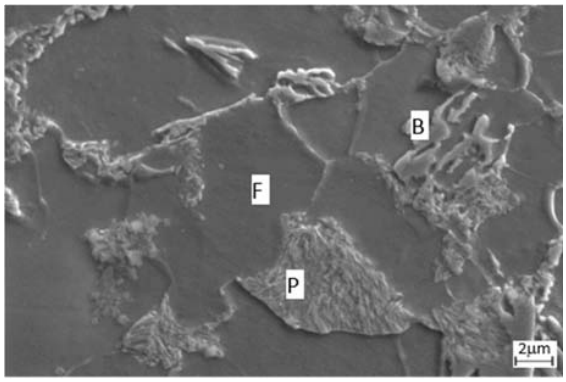

Fig. 4 Heating 900 °C /100 s, three deformations at 900 °C, 720 °C, and 680 °C, cooling rate 16 °C/s, bainitic hold at 425 °C

The best combination of tensile strength 768 MPa and ductility A_{5mm}=42% was achieved for the processing with the second deformation carried out at 720 °C and lower bainitic hold at 400 °C. The distribution of small bainitic and pearlitic areas is the densest and most homogeneous of all the microstructures produced by soaking at 900 °C. The areas of very fine pearlitic lamellas are of the same size or slightly larger than bainitic blocks, both being in the range of approximately 2-5 micrometers (Fig. 5).

The processing with lower soaking temperature 850 °C followed by two deformations at 850 °C and 720 °C and bainitic hold at 425 °C caused microstructure refinement. Bainitic and pearlitic areas were smaller and fewer (Fig. 6), and volume fraction of retained austenite was by 3% higher than for the same processing with higher soaking temperature. However mechanical properties were the same as for the same processing with soaking temperature 900 °C (743 MPa and 40%), suggesting that 50 °C change in heating temperature did not influence mechanical properties of the steel. In addition, even the decrease of bainitic hold to 400 °C did not bring any significant changes to mechanical properties, producing tensile strength of 729 MPa and ductility A_{5mm} of 43%. However, lower bainitic hold caused formation of higher amount of fine bainite and finer islands of M-A constituent in the microstructure (Fig. 7).

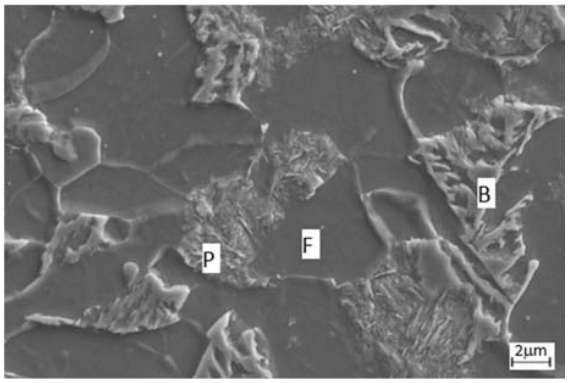

Fig. 5 Heating 900 °C / 100 s, two deformations at 900 °C and 720 °C, cooling rate 16 °C/s, bainitic hold 400 °C

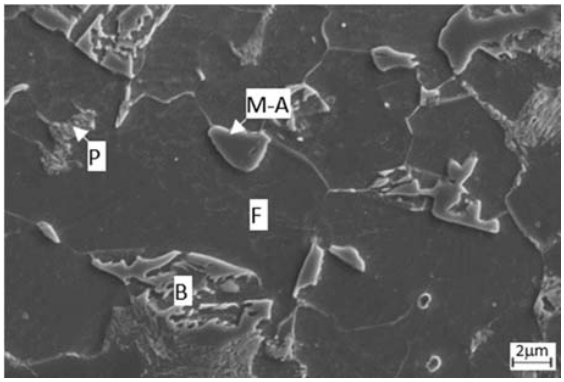

Fig. 6 Heating 850 °C / 100 s, two deformations at 850 °C and 720 °C, cooling rate 16 °C/s, bainitic hold at 425 °C

More important impact on mechanical properties than soaking and bainitic hold temperatures turned out to have cooling rate from the soaking temperature to bainitic hold temperatures. Cooling rates of 16 °C/s, 20 °C/s, and 30 °C/s were tested. Cooling rate 16 °C/s was previously used for TRIP steel processing of the steel with similar chemical composition without chromium [10]. Despite the fact that chromium addition was supposed to further postpone pearlite formation, this cooling rate repeatedly produced pearlite in the final microstructures, and therefore, quicker cooling rates were also applied to the steel (Figs. 8 and 9). However, even the quickest cooling by 30 °C/s was not sufficient to avoid the pearlite completely, and few small areas with lath length below 0.5 micrometer were observed (Fig. 9). This is probably

the reason why this microstructure had the highest volume fraction of retained austenite of 10%, the highest strength of 835 MPa, and still reasonable ductility A_{5mm} of 35%.

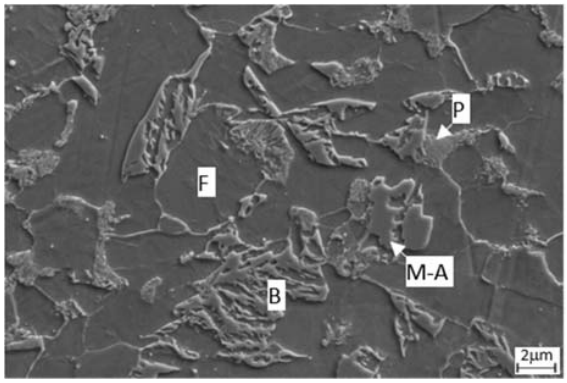

Fig. 7 Heating 850 °C / 100 s, two deformations at 850 °C and 720 °C, cooling rate 16 °C/s, bainitic hold at 400 °C

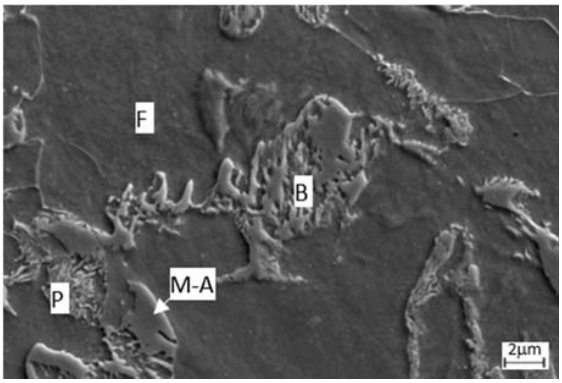

Fig. 8 Heating 850 °C / 100 s, two deformations at 850 °C, 720 °C, cooling rate 20 °C/s, bainitic hold at 400 °C

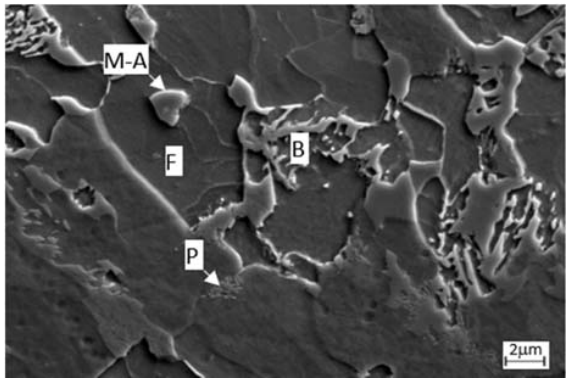

Fig. 9 Heating 850 °C / 100 s, two deformations at 850 °C, 720 °C, cooling rate 30 °C/s, bainitic hold at 400 °C.

IV. Conclusions

Complex multiphase microstructures consisting of ferrite, bainite, M-A constituent, and small pearlitic colonies with extremely fine lamellas were obtained by used thermo-mechanical processing. Despite the presence of pearlite in all the samples, 4%-10% of retained austenite were detected in the final microstructures and good combinations of mechanical properties were achieved. Ductility A_{5mm} in the region of 31%-43% was combined with ultimate tensile strengths ranging from 729 MPa to 836 MPa.

Increasing cooling rate from 16° C/s to 30 °C/s resulted in an increase of tensile strength from 729 MPa to 836 MPa and a drop of ductility A_{5mm} from 43% to 35%. Positive effect of chromium addition on the hindrance of pearlite formation was not confirmed; even the highest cooling rate of 30 °C/s still produced very fine pearlitic areas in the final microstructure. This highest cooling rate however helped to stabilize the highest amount of retained austenite (10%) and to achieve the highest strength of 836 MPa.

Decrease in deformation finish temperature from 720 °C to 680 °C also caused increase of tensile strength from 743 MPa to 789 MPa and decrease of ductility A_{5mm} from 41% to 31%.

The best combination of high strength 768 MPa and ductility A_{5mm}=42% with the highest strength to ductility balance was obtained for the processing with higher soaking temperature 900 °C, deformation finish temperature 720 °C, cooling rate 16 °C/s and bainitic hold at 400 °C.

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