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Effect of various heat and thermo-mechanical treatments on low alloyed CMnAlNb high strength steel

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Article abstract
Low carbon low alloyed high strength steel with the chemical composition suitably designed to support the stabilization of retained austenite was used in this work. The steel was processed by conventional annealing for a reference and several different heat and thermo-mechanical treatments were further proposed to test typical TRIP (transformation induced plasticity), DP (dual phase) steel and QP (quenching and partitioning) processing routes. All the processing methods used the same soaking temperature of 1050 °C. Processed samples were subjected to metallographic analysis, hardness measurement and tensile test to characterise resulting microstructures. While simple annealing reached tensile strength of 861 MPa with 25% of total elongation, the best combination of the highest tensile strength of 903 MPa and a total elongation of 32% was obtained after processing typical for TRIP steel. QP treatment resulted in the highest tensile strength of 1289 MPa with a total elongation of 19%.

Keywords
TRIP steel
DP steel
QP treatment
high strength steel

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1 Introduction

The development of high strength steels has gone through several stages in the last two decades. Among the first group of high strength steels are low alloyed DP (dual phase) and TRIP (transformation induced plasticity) steels [1-3]. For both of them, special heat or thermo-mechanical treatment methods were developed, respectively for steels with carbon contents typically around 0.2%. Furthermore, both types of steel were also investigated mainly for applications in the automotive industry. While DP steels aim at a two-phase microstructure consisting of the mixture of ferrite and martensite [2], the TRIP steels possess more complex microstructures of ferrite, bainite and retained austenite [3-4]. DP thus requires quick quenching once the sufficient amount of ferrite is obtained, while TRIP steels need a second isothermal hold at the temperature of intensive bainitic transformation to obtain a special, carbide-free bainite consisting of the bainitic ferrite and retained austenite laths [4]. Nevertheless, the TRIP steel requires alloying with manganese and silicon to retain a sufficient amount of retained austenite at room temperature. However, silicon was observed to decrease the surface quality of the steel and makes substantial troubles in subsequent hot-dip galvanizing, so it was later fully or partially substituted by aluminium. Furthermore, other alloying or microalloying elements such as Cu, Cr, Nb or Mo have been also often tested in DP and TRIP steels [5]. The positive effect of a controlled fraction of retained austenite at mechanical properties of TRIP steels was later successfully used also in the QP (quenching and partitioning) process which produced predominantly martensitic or martensitic-bainitic microstructures with thin films of retained austenite along lath boundaries [6 -9]. This process requires quite a tricky heat treatment with quenching interrupted between the temperatures of martensite start and martensite finish and subsequent heating up to the isothermal hold at partitioning temperature where carbon is allowed to diffuse from the super-saturated martensite into the remaining austenite [10]. All three processing methods were tested within this work on low carbon low alloyed CMnAlNb steel to optimise its mechanical properties.

2 Experimental program

High strength low alloyed steel CMnAlNb was used in this work (Tab. 1). This steel is alloyed with manganese to support austenite retention during heat or thermo-mechanical treatments. Moreover, silicon and aluminium have similar effects, they provide solid solution hardening of the ferrite at one hand and postpone cementite precipitation during the treatment on the other hand [11]. If carbon is not consumed by the precipitation of the carbides, it is available in a larger amount for chemical stabilization of the remaining austenite. As silicon has a stronger effect in solution strenghtening and precipitation hindering than aluminium, a complete substitution would decrease the strength of the steel and therefore only partial substitution of silicon with aluminium was chosen. Microalloying with niobium was proved to postpone the pearlite transformation in this type of low alloyed steel which is also advantageous for increasing carbon content, remained in the matrix, and for supporting the austenite stabilization [12-16].

The steel was vacuum cast and the 250 kg ingot was cut into four parts. Parts of the ingot were soaked at the temperature of 1150 °C and forged into bars. The bars were finally annealed for two hours at 950 °C and air-cooled to room temperature.

Tab. 1 *Chemical composition of CMnAlNb steel (weight %)*

	C	Si	Mn	P	S	Cr	Al	Nb
CMnAlNb	0.2	0.6	1.5	0.008	0.003	0.19	1.5	0.06

All the samples were processed using a thermo-mechanical simulator to ensure the precise utilization of prescribed treatment conditions. The actual temperature of the sample was checked by an attached thermocouple. All heat (HT) and thermo-mechanical (TMT) treatments were carried out with the same soaking temperature of 1050 °C. This temperature corresponds to that conventionally used for the controlled rolling of this type of low alloyed steels and it lies in a fully austenitic region. Annealed samples had a 20-min hold at this temperature, while all other samples had shorter soaking of only 100 s. In all thermo-mechanical treatments, the same 10% compressive deformation steps were applied at the temperatures of 1050 °C and 750 °C. The first deformation was always carried out at the end of the soaking hold while the second one was reached during the cooling (Fig. 1).

The reference treatments were simple-annealed at 1050 °C for twenty minutes followed by a slow cooling at 1 °C/s to room temperature (1-annealed). Furthermore, two compressive deformation steps were incorporated into this thermal cycle (2- annealed TMT).

For DP steel processing, thermo-mechanical treatment with 100 s soaking hold at 1050 °C was proposed (3-DP TMT). Two compressive deformation steps were carried out at 1050 °C and 720 °C. The steel was cooled by 14 °C/s within this temperature interval to allow the ferrite formation. After the second deformation, the quicker cooling by 50 °C/s to room temperature was used to enhance martensite formation.

In the next step, TRIP steel heat treatment was designed with 100 s hold at 1050 °C, followed by 14 °C/s cooling down to the isothermal hold at 425 °C (4-TRIP HT). The hold at this temperature was 600 s and it was planned in the bainitic transformation region based on the previous works on the optimization of heat treatment of CMnAlNb steel [13]. The TRIP processing was also carried out in the form of thermo-mechanical treatment with the same two deformation steps applied at the temperatures of 1050 °C and 720 °C (5-TRIP TMT).

The last tested method was QP with very quick cooling by 50 °C/s from the soaking temperature of 1050 °C to the quenching temperature of 300 °C (6-QP-300 °C) or 350 °C (7-QP-350 °C). Once the quenching temperature was reached (according to the attached thermocouple), the samples were heated by 50 °C/s to the partitioning hold of 600 s at 425 °C.

The obtained microstructures were characterised by scanning electron microscopes Vega (Tescan) and EVO 25 (Zeiss) and by tensile tests. A retained austenite volume fraction was determined by an X-ray diffraction phase analysis.

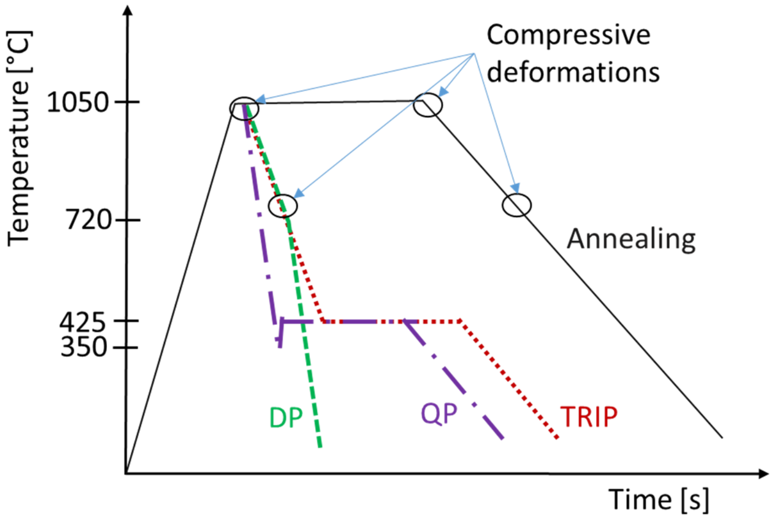

Fig. 1 *Heat and thermo-mechanical treatment schedules of CMnAlNb steel*

3 Results and discussion

The microstructure of the annealed sample was bainitic-ferritic with a chain of fine grains of proeutectoid ferrite placed at prior austenite grain (PAG) boundaries and coarse bainitic blocks (Fig. 2a). The incorporation of two deformation steps into the annealing thermal cycle resulted in refinement of bainitic blocks and a slight increase in ferrite volume fraction. The microstructure was still bainitic-ferritic with ferrite growing mainly at PAG boundaries (Fig. 2b).

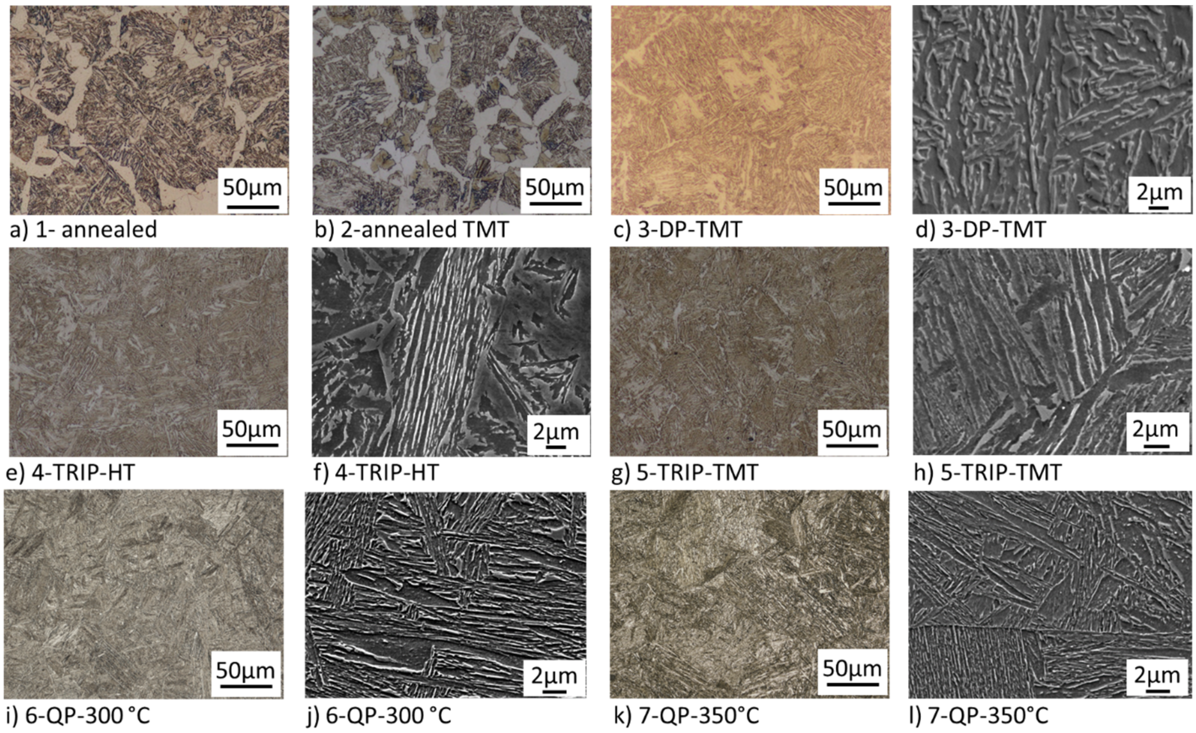

Fig. 2 *Microstructure of the CMnAlNb steel, light microscopy a)-c), e), g), i),k) and scanning electron microscopy d), f), h), j), l).*

The samples consisted of around 10% of retained austenite, even though no special treatment was carried out to enhance austenite stabilization (Tab. 2). Due to very similar microstructures, both samples 1-annealed and 2-annealed-TMT had very similar mechanical properties, reaching the tensile strength of 860 MPa with the elongation of 25%.

DP processing unfortunately did not result in an expected two-phase microstructure. On the other hand, the resulting microstructure consisted of a martensitic-bainitic mixture (Fig. 2c, d). This result indicates that the cooling rate from the soaking temperature was still too high to enable ferrite formation. Considering the small amount of ferrite in previous annealed samples with cooling at 1 °C/s, it further shows that the suitable cooling rate would have to be significantly lower than this. Thus, this would make the processing rather inconvenient, combining extremely slow and quick cooling rates in the same method. In the case of this DP processed steel, the more suitable way how to create the ferrite-martensite microstructure seems to be the intercritical annealing route which creates the substantial ferrite fraction directly during the soaking. Due to the quenched microstructure, the tensile strength of this sample reached nearly 1200 MPa with a total elongation of 10%.

Tab. 2 *Mechanical properties: yield tensile strength (YTS), ultimate tensile strength (UTS), total elongation (TE) and retained austenite volume fraction (RA)*

	YTS [MPa]	UTS [MPa]	TE [%]	RA [%]
1-annealed	520±8	861±1	25±1	11
2-annealed-TMT	520±8	861±1	25±1	9
3-DP-TMT	686	1193	10+3	Not detected
4-TRIP-HT	735±5	903±10	32±0	12
5-TRIP-TMT	808±1	935±4	28±1	11
6-QP-300°C	1056±3	1215±2	18±0	9
7-QP-350°C	1045±20	1289±3	19±0	6

TRIP steel processing without deformation (4-TRIP-HT) resulted in a multiphase microstructure which mainly consists of the carbide-free bainite with small occasional ferritic areas (Fig. 2e, f). About 12% of retained austenite was detected by an X-ray diffraction phase analysis. The bainite is mainly granular with occasional areas of relatively long bainitic laths. Granular bainite further contained a larger island of martensite or M-A (martensitic-austenitic) constituent. These islands of austenite remained in the microstructure during the isothermal hold at 425 °C which was not enough stable to resist martensitic transformation during the final cooling to room temperature. In the case of M-A constituent, areas of retained austenite remained in the mainly martensitic islands. This is a typical microstructure feature in low alloyed TRIP steels. Observed mechanical properties were also very promising for this type of steel, with the tensile strength of 900 MPa and the elongation of 32% (Tab. 2).

Very similar microstructure (Fig. 2g,h) with the same volume fraction of retained austenite and similar mechanical properties were also reached in the case of thermo-mechanical TRIP processing (5-TRIP-TMT). The deformation refined the lath bainite in the microstructure and increased its amount at the expense of granular bainite. This slightly increased the yield and tensile strength of the steel.

Finally, QP processing with two different quenching temperatures was investigated. The choice of quenching temperature determines the fraction of austenite and martensite prior to partitioning hold. During this hold, carbon can diffuse from martensite into austenite to stabilize it. Lower quenching temperature would result in the transformation of a larger amount of martensite. However, it should be noted that a higher austenite fraction after quenching does not necessarily ensure a higher retained austenite fraction after the final cooling, as more carbon will be needed to stabilize it. This can be seen nicely from the retained austenite fractions obtained in samples 6-QP-300°C and 7-QP-350°C. Nevertheless, the microstructure of those samples showed otherwise little difference and both consisted of fresh and tempered martensite (Fig. 2i-l). The traces of precipitates were found in 7-QP-350°C suggesting that carbide precipitation was not quite successfully prevented during partitioning hold at 425 °C. This might be contributed to a rather high partitioning temperature used in this treatment, which is more than 100 °C above the temperatures typically used for QP steels [14]. However, those fine precipitates might contribute to the highest strength of this sample (7-QP-350°C) which reached nearly 1300 MPa and was accompanied by a very promising elongation of 19%.

Conclusions

Four methods of heat and thermo-mechanical treatments typically used for various high strength steels were tested on low-alloyed CMnAlNb steel, resulting in a wide range of mechanical properties. The annealing resulted in a bainitic-ferritic microstructure with a good combination of a tensile strength of 860 MPa and an elongation of 15%. TRIP steel processing produced a bainite-based microstructure with 12% of retained austenite, a tensile strength of 900 MPa with 32% of total elongation. The highest tensile strength of 1300 MPa with a total elongation of 19% reached the martensitic microstructure obtained after QP processing.

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