# STRENGHTENING BEHAVIOUR OF Fe-Mn-(Al, Si) TRIP/TWIP STEEL

PODANY Pavel, KOUKOLIKOVA Martina, DLOUHY Jaromir, KUBINA Tomas, PROCHAZKA Radek

*COMTES FHT a.s., Dobrany, Czech Republic, EU,*
*comtes@comtesfht.cz*

**Abstract**

Recent research by the steel industry focuses mainly on the high strength steels with excellent formability. A new look at the role of individual elements generally used for steels and the possibility of new metallurgical technologies application have led to the development of steels with a wide range of mechanical properties and formability used in automotive industry. New possibilities appeared at the beginning of this century when the effect of strain-induced transformation of γ phase was attempted to be applied to austenitic steels. Nowadays, a new group of high-manganese austenitic TWIP steels with variable concentration of Mn, Al and Si was proposed showing their high potential. This paper deals with the description of the strengthening due to the cold rolling on experimental heats of manganese steel with TRIP / TWIP effect. Impacts on microstructure, yield strength and tensile strength are described.

**Keywords:** TRIP / TWIP steels, rolling, mechanical properties

## 1. INTRODUCTION

Utilisation of high-strength steels with high formability in the automotive industry leads to a substantial decrease of vehicle weight. It is also important from a point of view of improvement of safety during the crash, that a high capability of energy absorption is also much bigger in these steels in comparison with conventional steels. Nowadays, a new group of high-manganese austenitic steels with variable concentration of Mn, Al and Si was proposed showing high potential for their application in automotive industry. These steels feature good combination of strength and ductility. Their strengthening mechanism can be explained by the presence of alternative deformation mechanisms, such as: the creation of twins (TWIP effect), phase transitions produced by strain (TRIP) and plasticity induced by shear bands [1-5].

In a case of manganese concentration below 25 % it's possible to use TRIP effect (Transformation Induced Plasticity) consisting in steel hardening in the consequence of $\gamma \rightarrow \varepsilon$ or $\gamma \rightarrow \varepsilon \rightarrow \alpha'$martensitic transformation occurring during cold forming [6]. Martensite ε with hexagonal lattice is formed during plastic strain only when stacking fault energy SFE of austenite is lower than 20 mJ / m$^2$. The addition of aluminium into steel increases SFE and austenite stability which leads to suppressed influence on martensitic transformation. While the addition of silicon decreases SFE and allows occurring of $\gamma \rightarrow \varepsilon$ transformation. In the case when manganese concentration in the steel exceeds 25%, the stability of austenite during plastic strain is maintained enhancing mechanical properties due to mechanical twinning - TWIP effect (TWinnig Induced Plasticity) [7-11].

The role of aluminium as a solute in the manganese austenitic steels is twofold. It increases the stacking fault energy of the steel and hence reduces the probability of mechanical twinning during deformation. The higher stacking fault energy at the same time eliminates the formation of ε-martensite. Both of these effects lead to a greater resistance of the steel to hydrogen embrittlement [12].

# 2. EXPERIMENT DESCRIPTION

## 2.1. Experimental material

Chemical compositions of steel employed in this experiment are given in **Table 1**. Essentially, the only difference between the two heats is the amount of aluminium (0.40 % vs. 1.40 %). As it was stated in the introduction, the role of aluminium is important regarding the steel performance. Both heats were manufactured in a vacuum induction type furnace and cast into a round ingot mould. After cooling, they were reheated in a furnace to the forging temperature of 1100 °C. In a universal hydraulic press, these ingots were then forged into slabs of 280 × 130 mm cross-section. The slabs were, in turn, hot-rolled to strips of a final thickness of 8 mm. The rolled strips of both heats were annealed at 850 °C for 2 hours. After pickling, the annealed strips were rolled in six passes with the final reduction of 40 %. The mechanical properties were measured on standard samples and on mini-tensile test samples. This method of mechanical properties measurement on a small amount of experimental material has proved successful in earlier research [13-18]. Chemical composition **Table 1** demonstrates.

**Table 1** Chemical composition of experimental steel

| **Heat nr.** | **Element [wt. %]** | | | | |
|---|---|---|---|---|---|
| | Mn | Si | **Al** | C | Fe |
| T15-81 | 15.1 | 1.58 | **0.40** | 0.12 | bal. |
| T15-82 | 15.0 | 1.54 | **1.40** | 0.10 | bal. |

## 2.2. Characterisation of microstructure

The specimens were prepared using standard metallographic techniques of grinding and subsequent polishing. Their microstructures were revealed by two-stage etching: first with 10 % nital, and then with the Klemm's II colour reagent [19]. Specimens for electron backscatter diffraction (EBSD) were electrolytically polished using a Lectropol machine and the A2 reagent at 30 V for approximately 20 seconds.

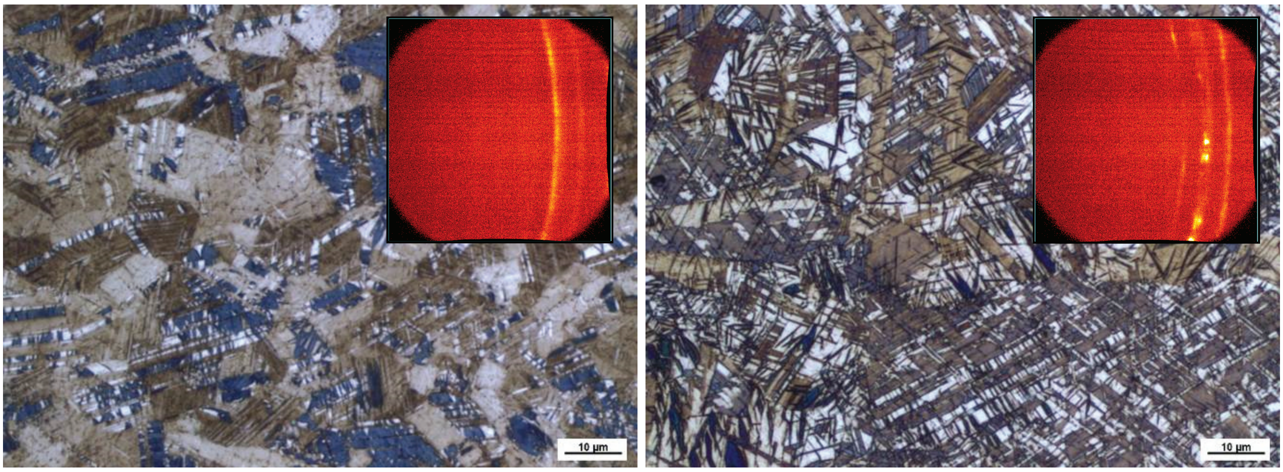
The microstructures were documented using a Zeiss Axio Observer optical microscope. EBSD analysis was performed and scanning electron micrographs taken by means of JEOL 7400F microscope and an HKL Nordlys EBSD camera from Oxford Instruments.

Phase analysis by X-ray diffraction was carried out at room temperature using a Bruker D8 Discover diffractometer. The diffracted radiation was detected by means of a planar detector. A cobalt X-ray source has been used ($\lambda K\alpha$ = 0.1790307 nm). The instrument was equipped with a polycapillary lens focusing the primary X-ray beam into a circular spot with a diameter of 0.5 mm.

# 3. RESULTS AND DISCUSSION

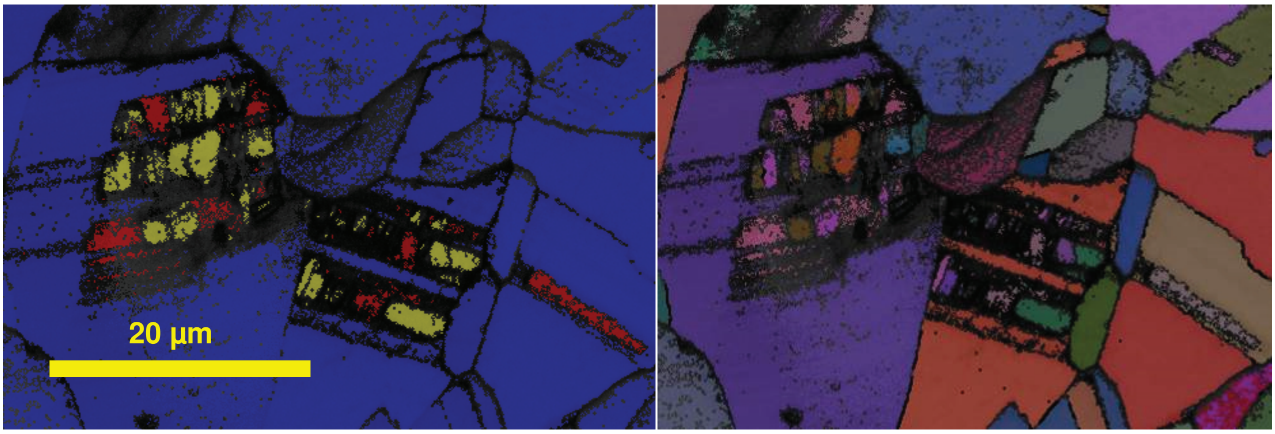
## 3.1. Microstructure

The microstructure of sheets in initial state - annealed sheets after hot rolling, is complex. It consists of austenitic grains with rather high amount of martensite (see **Figure 1**). Since etching with Klemm's reagent leaves ε martensite colourless, it appears white in micrographs. The colours of other phases are as follows: γ (austenite) yellow to brown, α´ martensite blue to dark brown. The identification of these phases was confirmed subsequently by EBSD analysis (see **Figure 2**). The difference in the microstructure between both heats is mostly in the grain size and the volume fraction of ε martensite. The heat T15-82 shows coarser microstructure and an obviously higher amount of hcp martensite modification (white phase). The coarseness of the microstructure was also visible on diffractograms (see **Figure 1b**). Also the results of x-ray diffractions (see **Table 2**) prove the difference in phase's volume fractions between both heats.



a) b)

**Figure 1** Microstructures in initial state before cold rolling and its diffractograms
a) heat T15-81-0 % - (magnification 1000x); b) heat T15-82-0 %



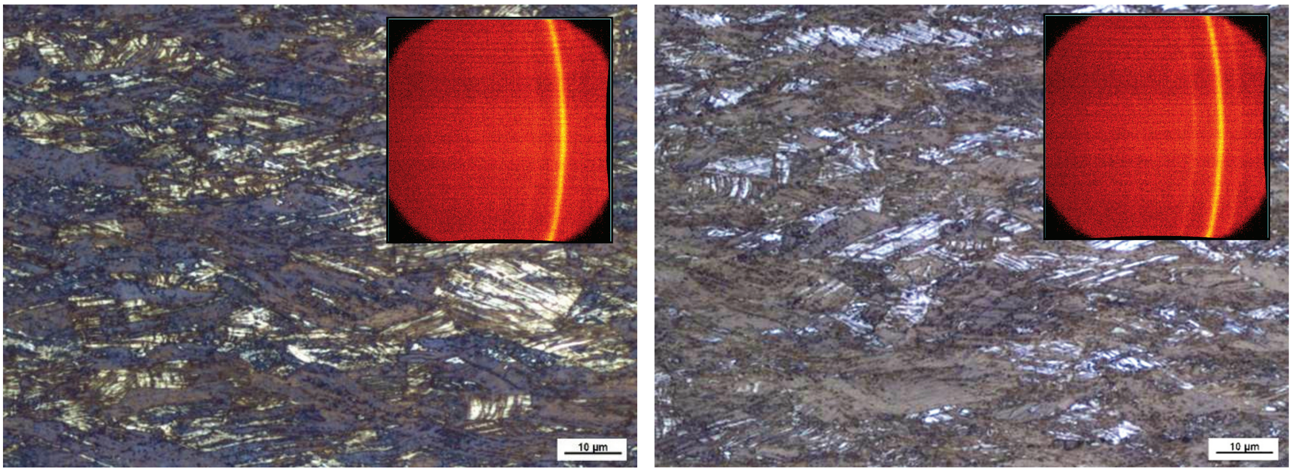

a) b)

**Figure 2** Example of EBSD analysis of microstructure in initial state of heat T15-81-0 % (with 0.4 % Al):
a) Identification of phases (α´ - yellow, ε - red; γ - blue); b) euler orientation

**Table 2** Volume fraction of structural phases according to the x-ray diffraction

| Phase [volume %] | Heat number + % of cold reduction (0 % = initial state) | | | |
|---|---|---|---|---|
| | T15-81-0 % | T15-81-40 % | T15-82-0 % | T15-82-40 % |
| α´ - BCC Fe | 7.8 | 71.7 | 6.3 | 61.5 |
| ε - HCP Fe | 28.2 | 18.3 | 42.0 | 26.9 |
| γ - FCC Fe | 64.0 | 10.0 | 51.7 | 11.6 |

Microstructure evolution during the cold rolling is affected by deformation-induced transformation processes. As it was mentioned in the introduction increasing strain caused by cold rolling induces twinning in austenite, twins further transforms to ε and ε transforms to α´. The microstructure of cold deformed specimens with 40% reduction is shown in **Figure 3.** Both specimens exhibit high volume fraction of martensite. Results of these processes lead to increasing of α´ volume fraction in the microstructure and considerably higher yield and tensile strength in comparison to the initial state.

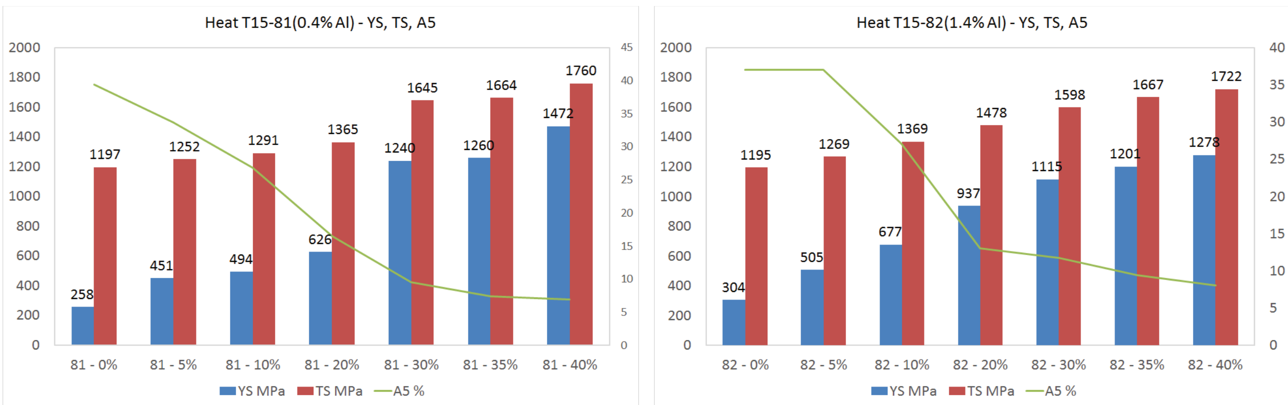



a) b)

**Figure 3** Microstructures after cold rolling with 40 % reduction its diffractograms
a) heat T15-81-40 %; b) heat T15-82-40 %

### 3.2. Mechanical properties

Standard tensile tests were carried out according to *EN ISO 6892-1*: Metallic materials - Tensile testing - Part 1: Test method at room temperature. The chosen strain rate was 0.001 $s^{-1}$. Tests were executed using servohydraulic testing system Zwick. Prior to testing, dimensions of sa*m*ples were measured and recorded. Evaluated mechanical properties $R_{p0.2}$, $R_m$, $A_5$, are summarised in **Figure 4.** Two samples from sheets had to be tested by means of a miniature tensile test because of lack of sufficient test material for the standard test (T15-81-30 % and T15-81-40 %). The dimensions of the miniature tensile test sample are 5 mm in gauge length and 0.5 x 1.5 mm in cross section. On test specimens of this small size, Digital Image Correlation (DIC) is used for strain measurement instead of conventional extensometers.




a) b)

**Figure 4** Mechanical properties of cold rolled sheets after reduction in the range 0 ÷ 40 %:
a) heat T15-81; b) heat T15-82

The DIC method employs tracking and image registration techniques for accurate 2D and 3D measurements of changes in images.

Engineering stress-strain curves are summarised on **Figure 5**. The strengthening behaviour due to the TWIP and TRIP effect is clearly visible on the curves of samples 81 and 82 with 0 %, 5 % and 10 % of cold reduction.

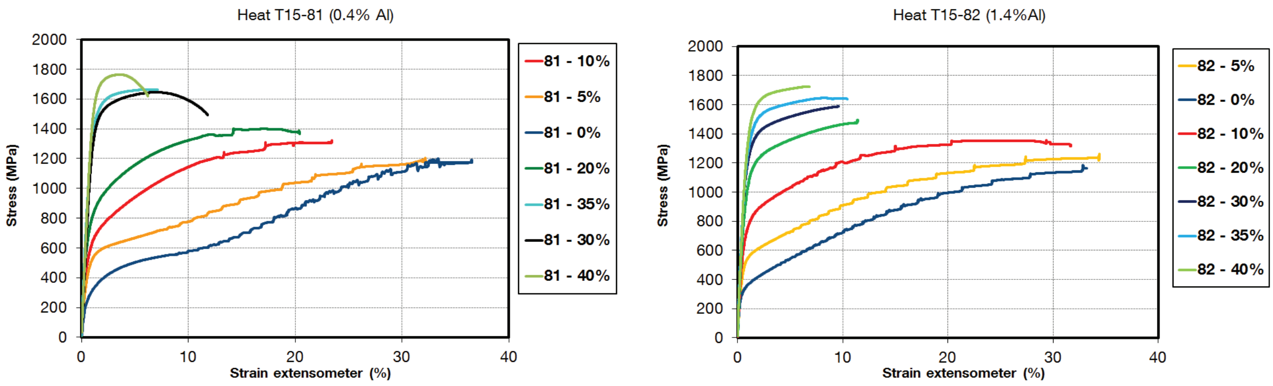



**Figure 5** Examples of engineering stress-strain curves of cold rolled sheets after reduction in the range 0 ÷ 40 %: a) heat T15-81; b) heat T15-82

## 4. CONCLUSION

The strengthening behaviour of two heats of the manganese steel with two aluminium levels has been studied. By means of qualitative (optical microscopy and EBSD) and quantitative (X-ray diffraction) techniques, the following phases have been identified in both heats: γ (FCC) and two crystallographic variants of martensite, ε (HCP) > α´ (BCC). It was found that the increased amount of aluminium in the T15-82 heat (1.4 %) causes a substantial increase in the ε martensite fraction in annealed steel before cold rolling. By, contrast, the fraction of α´ martensite in the annealed microstructure is much smaller. On the contrary to the results of Ryu et al. [12], the combination of alloying elements in our investigated experimental heats (15 Mn-1.5 Si-0.4 / 1.4 Al-0.1C) showed the higher content of ε martensite in steel with higher aluminium content. Nevertheless, the ε martensite content drops with higher deformation due to the cold rolling as ε transforms to α´.

The strength of the steel made as heat T15-81 reaches, upon cold rolling with 40 % reduction, the level of 1760 MPa, with the yield strength of 1472 MPa. In annealed state before cold rolling, strength was 1197 MPa and yield strength becomes 258 MPa. However, elongation rises from 7 % (in cold rolled condition) to 39 %. The strength of the steel made as heat T15-82 (with 1.4 % of Al) reaches, upon cold rolling, the level of 1722 MPa, with the yield strength of 1278 MPa. In initial state (before cold rolling), strength is 1195 MPa and yield strength becomes 304 MPa. Elongation drops from 37 % (for the specimen in the annealed initial state with a high strengthening effect due to the deformation induced processes) to 8 % in the cold rolled state.

## ACKNOWLEDGEMENTS

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