# BEHAVIOUR OF HOT AND COLD ROLLED FE-MN (TWIP) STEEL

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**Abstract**

Ferromanganese TWIP steels with the manganese content of 17-20 % are fully austenitic and non-magnetic, without phase transformation. Due to the application of the twinning mechanism the TWIP steels can satisfy numerous technical requirements for production of the new generation of cars. Basic experimental results of TWIP steels exhibit high ultimate tensile strength from 600 to 1100 MPa, as well as extreme values of ductility in the range from 60 to 90 %. Castings from the Fe-Mn-C alloys were prepared by method of plasma and vacuum melting. They were gradually hot rolled by three consecutive rolling sequences (first to the height of 18 mm, then to 11 mm, and finally to 3 mm), the samples were then cold rolled metal with reduction of 15 %, or 30 % to the final heights of 2.2 mm or 2.7 mm. After the second rolling the samples with dimensions of 10x15x20 mm were prepared for stress-relaxation testing on the GLEEBLE 3800. In intermediate phases the samples were taken for metallographic analysis. Dimensions of the samples did not allow execution of tensile tests that is why only the hardness was measured. The main task was to keep the samples in plastometer GLEEBLE under stress in jaws after deformation $e$ = 0.5, followed by subsequent analysis of the recovery curves and determination of times $t$ for selected portions of the healed structure $X$ with display of the Avrami curves.

**Keywords:** Fe-Mn TWIP steel, laboratory rolling, stress-relaxation method, Avrami equation

## 1. INTRODUCTION

TWIP steels are materials characterised by high level of strain hardening with excellent plastic response. TWIP steels can reach at normal temperature the strength values exceeding 1000 MPa and total ductility is varies between 55 and 60 % (theoretical values from the literature up to 90 % are virtual). Due to their high ability to absorb energy during car crash these steels are highly in demand for use in the automotive industry. TWIP steel properties are preserved by the controlled formation of twins with existence of stacking fault energy (Stacking Fault Energy = SFE) during the controlled rolling. The process, which is associated with the above behaviour is characterised as TWIP effect, i.e. (Twinning Induced Plasticity). At lower Mn contents a TRIP effect (Transformation Induced Plasticity) is also manifested. Mechanical properties of austenitic steels depend primarily on the stacking fault energy, which controls the ability to form a perfect 60° dislocations inside partial Shockley dislocations. It is usually indicated that this value should be less than 20 mJ / m$^2$ [1 - 6]. This SFE is thus the main reason of the possibility of sliding of dissociated partial dislocations, formation of deformation twins or possibly of strain-induced martensitic transformation $\gamma \rightarrow \varepsilon$, $\varepsilon \rightarrow \alpha'$, $\gamma \rightarrow \alpha'$ where the process becomes more active with an increase of deformation.

## 2. EXPERIMENT

Part of experimental works was focused on observation of the impact of hot and cold forming on the structural characteristics and mechanical properties of high strength Fe - Mn TWIP steels in dependence on different manganese content in individual samples [7 - 8]. Steels with ordinary Mn content for TWIP steels of approx. 22 % (steel A) and extremely low content of 13 % (steel B) were deliberately chosen. At the same time the

parameters of hot and cold suitable for subsequent use in manufacturing practice had to be validated. As another effect of this research the method of stress relaxation was applied for the first time on this steel in order to verify this method and determine the Avrami curves. The alloy was prepared by vacuum melting [9-11]. The chemical composition was verified on the optical spectrometer SPECTROMAXx. The sample A_1183 had 0.71 wt. % C, 13.2 wt. % Mn; 2.85 wt. % Si and 3 wt. % Al. The sample B_1184 had 0.72 wt. % C; 22.4 wt. % Mn; 2.87 wt. % Si and 3 wt. % Al. Dimensions of the samples were 18 x 30 x140 mm.

### 2.1. Hot rolling

Before the rolling the samples in the as cast state were subjected to homogenisation annealing at 1125 °C for three hours and then cooled in water. The samples were gradually hot rolled consecutively by three rolling sequences (first to the height of 18 mm, then to 11 mm, and finally to 3 mm). The samples were then cold rolled to the final height of 2.2 to 2.7 mm. Each hot rolling ran always with three reductions with intermediate heating. **Fig. 1** shows one of the samples during rolling, and **Fig. 2** shows the selected diagram of rolling [7].

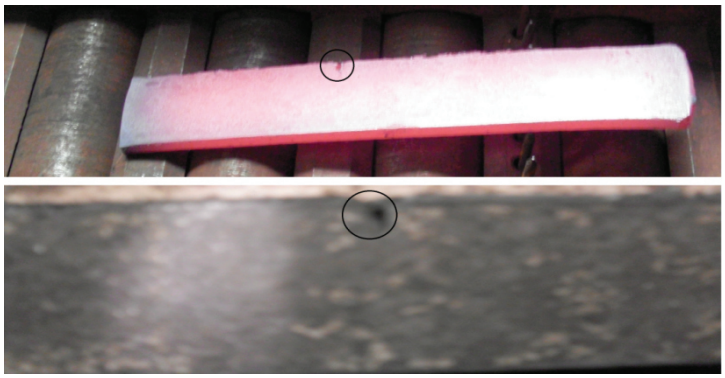


**Fig. 1** Sample B_1184 after first hot rolling

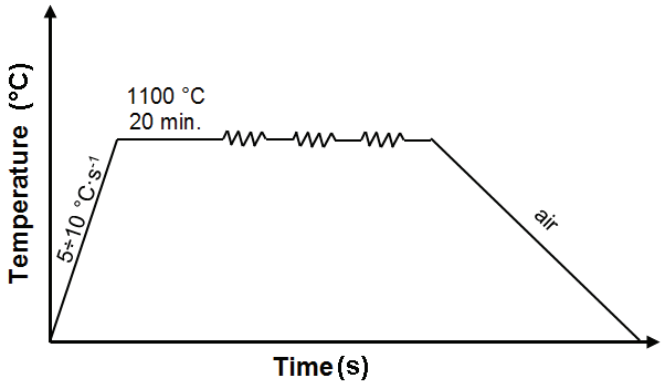



**Fig. 2** Temperature versus time (hot rolling of 1183 sample)

Purpose of the third rolling was to determine, how the microstructure will change as a result of different rolling temperatures. The rolling was performed with three reductions and under three different rolling temperature for individual samples (850, 950 and 1050 °C). All the samples achieved final height dimensions from 3.21 to 3.24 mm. The rolling was carried out on the four-high rolling mill K350 with nominal of the diameter work roll of 67 mm, and with nominal diameter of the backup roll of 140 mm, the rotational speed of the rolls was 70 revolutions/min. The samples were heated to the temperature of 1150 °C, in all cases with a dwell of 20 minutes at this temperature. The samples AV1 and BV1 were then rolled with three reductions at the temperature of 1150 °C. After the first and second reduction the samples AV1, BV1 were reheated again to the given rolling temperature. The samples AV2, BV2 were first heated up to the temperature of 1150 °C, which was then followed by a decrease to the temperature of 1000 °C, which was measured by a pyrometer. After

this rolling was performed at the given temperature with 3 reductions with reheating between individual reductions to the temperature of 1000 °C. The samples marked as BV3 and AV3 were also first reheated to the temperature of 1150 °C with subsequent cooling to the temperature of 850 °C and rolling with 3 reductions to the uniform height of 3.2 mm with intermediate heating before each reduction. Cooling of the rolled samples was carried out freely on air. After rolling the samples with dimensions of 5 x 3.2 x 41 mm were taken from each rolled product and marked as AM1 - AM6. These samples were designed for metallographic analysis and for micro-hardness measurements. The remaining samples were cut into 12 sub-samples, which were designed for cold rolling.

### 2.2. Cold rolling

The objective of the cold rolling was to determine how the microstructure and properties of individual samples will change during cold forming with different amount of deformation for individual samples, which were previously hot rolled under various rolling temperatures. The samples AV1_3, BV1_3 were cut in half and marked with additional lowercase letters "a" or "b". The samples were then cold rolled for one group of the samples with the relative deformation of 15 %, and for the second group of the samples with the relative deformation of 30 %. The samples were rolled with several reductions. The number of reductions was depended on the previous hot rolling. The samples that were rolled at higher rolling temperatures had lower flow stress than the samples that were rolled at lower temperatures, and smaller number of reductions reflected it. The samples that were during previous rolling formed at 850 °C showed big flow stress, which was caused by bigger strain hardening due to lower rolling temperatures [7].

### 2.3. Stress-relaxation method

Plastometric tests of stress relaxation tests were conducted on the universal plastometer GLEEBLE 3800, which is installed in the Regional Materials Science and Technology Centre at the VSB - Technical University of Ostrava. For this purpose prismatic samples measuring 10 x 15 x 20 mm (height x length x width) were taken from both investigated steels after the first hot rolling. The samples were heated electric resistance heated at the heating rate of 2.5 °C $s^{-1}$ directly to the selected deformation temperature (A1 and B1_950 °C (0.1 $s^{-1}$); (A2 and B2_950 °C (10 $s^{-1}$); (A3 and B3_1050 °C (0.1 $s^{-1}$); (A4 and B4 _1050 °C (10 $s^{-1}$); followed by a 30 second dwell at this temperature. The samples were then deformed by one reduction of the size of height logarithmic deformation of 0.5 at the chosen strain rate (0.1 or 10 $s^{-1}$). The deformation was followed by a 30 second dwell of the sample at the deformation temperature in the final position of jaws, during which was read, among others, the drop in strength (stress) at this isothermal dwell (analysis of the first through the third part of the relaxation curve). The heating was then turned off, followed by a free cooling of the samples (uncontrolled heat removal from the samples into swages. The stress value and consequently the share of the *X* recrystallised structure in the analysed second part of the curve can then be calculated as [12 - 17]:

$$\sigma = (1 - X)(\sigma_{01} - \alpha_1 \log t) + X(\sigma_{03} - \alpha_3 \log t) \quad (1)$$

where the indexes 1 and 3 refer to the first and third part of curves.

This equation can be also used for calculation of the share of the recrystallised phase in the given time

$$X = \frac{\{[\sigma_{01} - \alpha_1 log(t)] - \sigma\}}{\{(\sigma_{01} - \sigma_{03}) - (\alpha_1 - \alpha_3) log(t)\}} \quad (2)$$

where $\alpha$ is the slope of curves, $\alpha_1$ is the recovery phase, $\alpha_3$ final phase, $\sigma_1$, $\sigma_2$ are the stresses corresponding to the time $t$ = 1s.

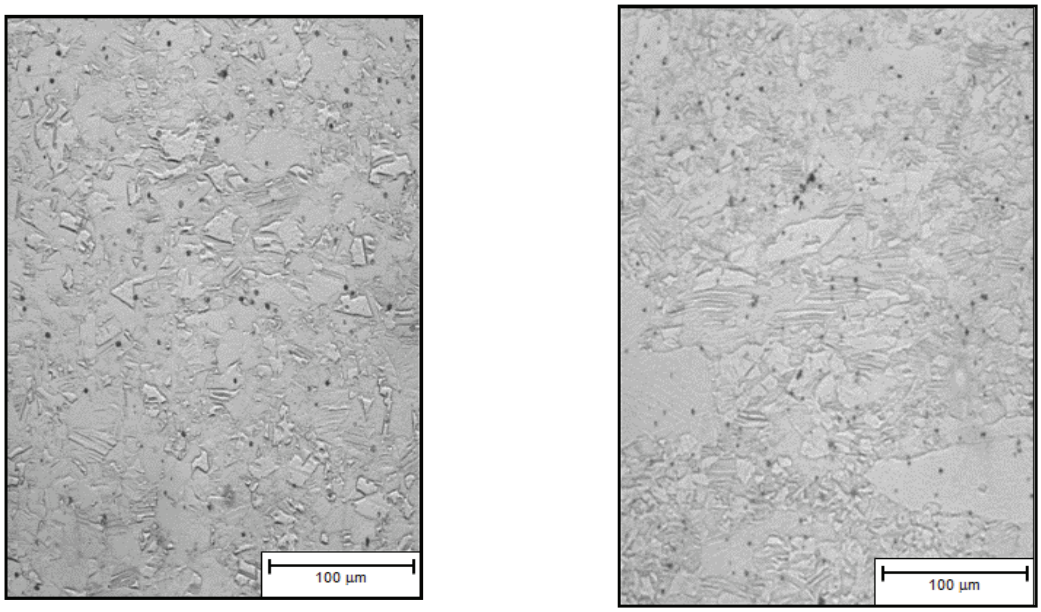
## 3. RESULTS

### 3.1. Hot and cold rolling

In all the samples deformation bands and numerous twins of different dimensions were observed after hot forming. The material structure in all the samples appears to be fully austenitic, no martensite was found in the structure (see **Fig. 3**). After forming under various thermo-mechanical conditions it was not proved that higher values for the samples B had demonstrably bigger influence on the strength properties and on formation of twins. For the samples rolled at higher temperature the presence of the healing processes and especially of recrystallization was detected. The structure at rolling under lower temperatures was considerably more fine-grained and hardness values were significantly higher.

**Table 1** Hardness HV 0.1 recalculated to the strength (UTS) according to [18].

| | UTS (MPa) | (%) |
|---|---|---|
| **BV1a** | 1400 | 31.8 % |
| **BV1b** | 1370 | 16.7 % |
| **BV3a** | 1575 | 30.5 % |
| **BV3b** | 1400 | 15.3 % |




Sample AV3 (A_1183_13 % Mn; T = 850 °C) Sample BV3 (B_1184_22 % Mn; T = 850 °C)

**Fig. 3** Samples after third hot rolling on *h* = 3 mm

Deformation bands and twins of various dimensions were observed in all the samples evaluated after cold forming. Material structure in all cases appears to be fully austenitic [19]. Results of hardness show extreme values. After conversion of hardness to the strength limit the *UTS* values were achieved between 1350 - 1575 MPa. These extreme values might have been be influenced by the larger number of forming processes. The results also indicate that increasing deformation leads to higher values of strength. This experiment demonstrated higher strength properties of the sample B with higher manganese content, but only in the samples, which were formed in the previous experiment at lower temperatures. In the samples, which were formed at higher temperatures, the strength values in both samples with different manganese content were almost identical. During rolling the material manifested characteristic cracking in the peripheral parts of the

sample. Currently, the samples after hot and cold rolling were metallographically prepared for investigation and study on electron microscope, and the results will be published in future publications.

### 3.2. Stress-relaxation

Results of evolution the curves obtained after the completed deformation of the samples e = 0.5 and held in the jaws for 30 s were in the form of GLEEBLE file *.d0x first transferred to Excel. After that the end of deformation was analysed, and in the program Origin all the curves of stress drop with time were constructed. Two curves are presented as example; namely for the sample A_1183 (13 % Mn at the temperature of 1050 °C and strain rate of 0.1 $s^{-1}$), and for the sample A_1183 (13 % Mn at the temperature of 950 °C and strain rate of 0.1 $s^{-1}$).

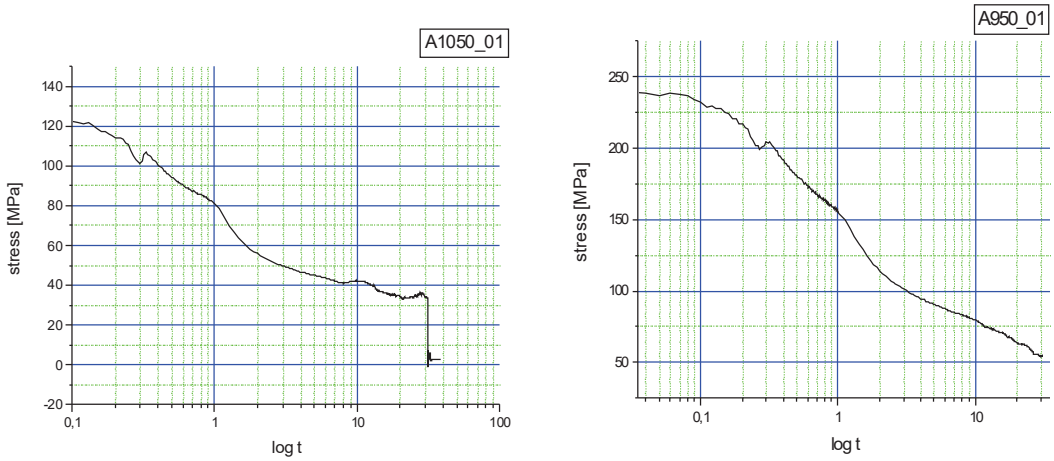



**Fig. 4** Stress-relaxation curves for **A**_1183 (13% Mn at temperature 1050 °C and strain rate 0.1 $s^{-1}$) - left and for **A**_1183 (13% Mn at temperature 950 °C and strain rate 0.1 $s^{-1}$) - right

Using the equations (1) and (2) we then determined the X values of the recovered structures for selected times *t* = 0.1 s, or 1; 10 s. Next diagrams show evolution of the Avrami curves for different samples, deformation temperatures and strain rates. However, it must be noted that the number of samples, which were used in the experiment, was very limited by initial inputs (original of the cast sample had dimensions of 18 x 30 x 140 mm), and only a very small was designed for these trials on the GLEEBLE. Furthermore, we must also admit that although our experience with evaluation of the curves is far from primitive, everyone who did similar analyses, knows well that reading of significant points and tangents on the curves in **Fig. 4** and in other figures is somewhat subjective. It appeared that in cases of both chosen temperatures the peak of the stress-strain curve was achieved already at the deformation *e* = 0.5, which means that recrystallization is meta-dynamic rather than classically static. As an example the constants were introduced into the equation (3) for A_1050 (10), where *k* = 1.273; *n* = 0.290, and for B_1050 (10), where *k* = 1.758; *n* = 0.232).

$$X = 1 - exp(-k \cdot t^n) \quad (3)$$

## 4. CONCLUSION

The issues concerning the nature of the TWIP effect and mechanism of twins formation during deformation were published and discussed in the theoretical part. The twinning mechanism created during deformation ensures to these materials high stress hardening. The resulting strength properties can achieve the values in tension of 600 to 1100 MPa at extreme values of ductility in the range from 60 to 90 %. Hot and cold rolling was conducted according to the proposed plan. Evaluation was conducted from the results of microanalyses and from results of micro-hardness tests. The structural condition appears in all the samples to be fully austenitic (martensite was not detected in the structure), with a significant share of deformation twins and deformation bands. On the basis of results from the microhardness test after rolling it was possible to assessthe

influence of deformation temperature and different Mn content on the hardness values after conversion and also on the strength values.

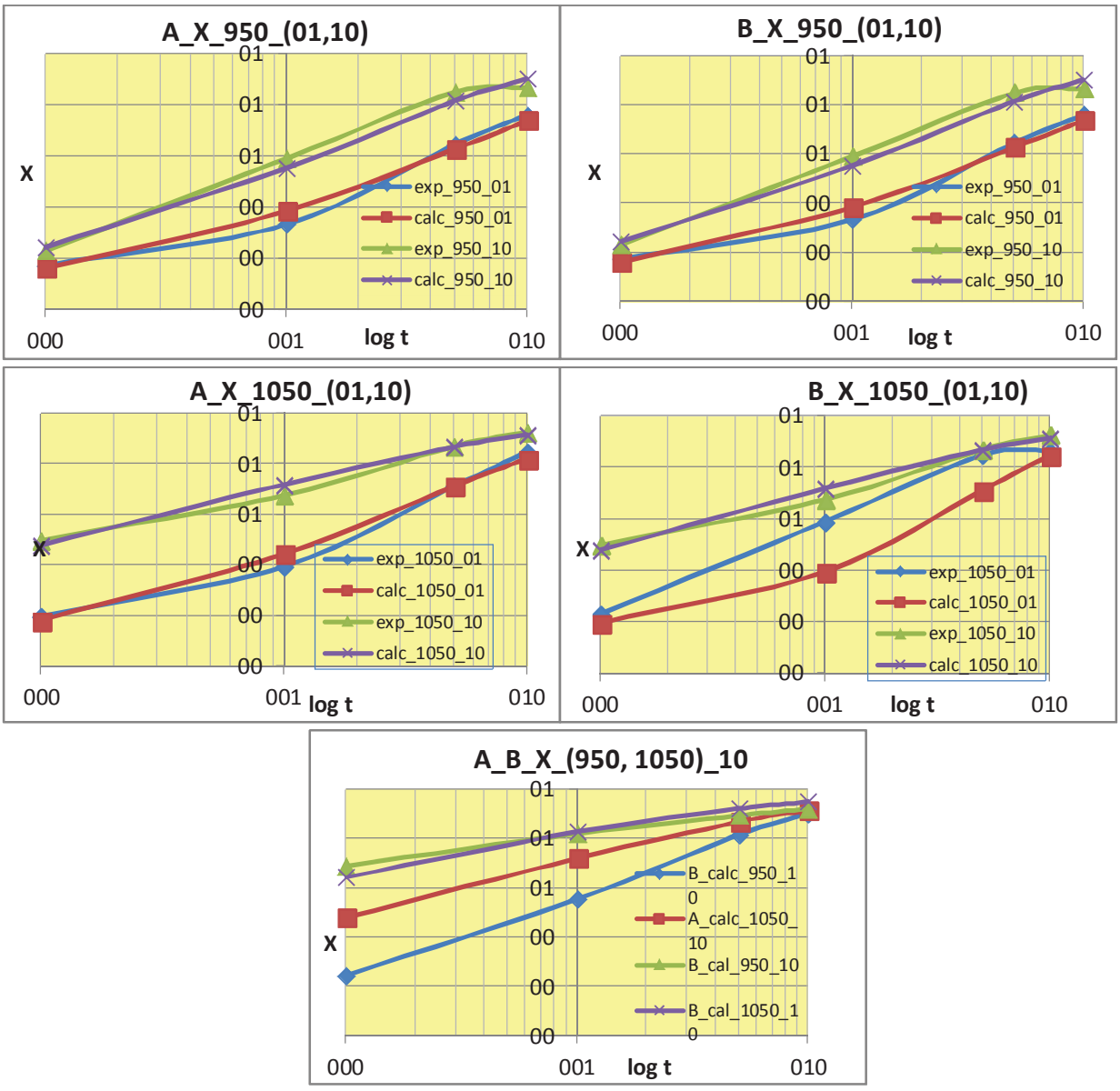



**Fig. 5** Avrami curves for various samples (A_1183 (12 % Mn); B_1184 (22 % Mn) and temperatures and strain rates

From the results it is possible to assume that during hot rolling the greatest influence on the hardness and strength have the thermo-mechanical conditions of forming. At cold forming higher strength properties were achieved in the samples containing higher levels of manganese, but only in the samples, which were in the previous process of hot forming rolled at a lower temperature. Avrami recrystallization curves for both steels are in the relaxation area in the austenitic state. Fairly significant difference in the basic content of Mn (steel A_1183 (13% Mn) steel B_1184 (22 % Mn) was not markedly proved, as is evident from the comparison in **Fig. 5**. However, this difference was proved at the strain rate of higher approx. by two orders; higher rate of deformation shifts the times of recrystallization to the left and the structure heals faster. For all experiments performed, which are partly shown in **Fig. 5**, the constants *k*; *n* were determined for the Avrami equation.

## ACKNOWLEDGEMENTS

***This paper was created on the Faculty of Metallurgy and Materials Engineering in the Project No. LO1203 "Regional Materials Science and Technology Centre - Feasibility Program" funded by Ministry of Education, Youth and Sports of the Czech Republic.***

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