



## In situ investigation of transformation kinetics in Si-Mn TRIP steel

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Recently, a lot of effort has been paid to find a specific thermomechanical processing to produce steels with an excellent balance between the strength level and the formability. A further improvement of this balance between strength and ductility can be obtained by application of the effect of transformation induced plasticity (TRIP). Basic understanding of Si and Mn added TRIP steel is required to optimize the production process conditions which step would enable a further expansion of their practical applicability. The precise determination of the volume fraction of retained austenite is essential for the optimisation of low alloyed TRIP steels. *In situ* transformation tests have been conducted on the Si-Mn steel displaying the transformation-induced plasticity (TRIP) effect, while monitoring the phase transformation by means of neutron diffraction. Based on the structural changes observation, critical phase transformation temperatures of steel and volume fraction of ferrite and non-transformed austenite considering the austenite conditioning and isothermal holds were determined by neutron diffraction method.

### 1. INTRODUCTION

Simultaneous achievement of high strength and ductility represents a very serious scientific problem. This reason together with technical difficulties in production of these materials result in their rather limited applications nowadays. The TRIP effect is observed in high alloy metastable austenitic steels as well as in low alloy multiphase steels. Low-alloy multiphase transformation-induced plasticity (TRIP) steels have attracted more and more interest in recent years due to their high strength and enhanced formability [1,2].

Numerous alloying concepts have been developed for TRIP steels to adjust the desired microstructure and optimum properties [3,4]. The alloying elements change the thermodynamic stability of the phases and their transformation kinetics. Consequently, the transformation temperatures are shifted, the transformations are either promoted or hindered

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and the phase distribution is varied. In the case of low-alloyed TRIP steels, detailed insight in the stability range of retained austenite is regarded to be of the highest importance for controlling the materials properties. The mechanical properties of TRIP steels are determined by the amount and stability of the retained austenite.

Although the retained austenite is a key factor in controlling the final mechanical properties, there are another parameters that should be considered, such as a morphology, cooling section. A variation of the cooling rate and coiling temperature allows to change the transformation behavior and to vary the strength level in a wide range [5].

The precise, fast and cheap measurement of the amount of retained austenite is therefore an essential item for further research work, improvement and control of TRIP steels. However, its recognition is not easy and might be ambiguous sometimes. For determination of retained austenite content in TRIP steels, the X-ray diffraction measurements are preferentially used, sometimes also classical metallography, Mössbauer spectroscopy, magnetic methods and neutron diffraction have been used.

In the present paper, the *in situ* neutron diffraction (ND) method was used to quantify volume fractions of non-transformed austenite and transformed ferrite in dependence on the transformation temperature and degree of austenite deformation prior transformation. ND has been used also for evaluation of phase specific stresses resulting from  $\gamma \rightarrow \alpha$  transformation considering the prior austenite deformation as well.

## 2. EXPERIMENTAL

The chemical composition of the as-received TRIP steel is stated in Table 1. The specimens for thermomechanical processing were machined to diameter of 6 mm with the

Table 1.

Chemical composition of steel used (wt.%)

C	Mn	Si	P	S	Cr	Nir	Cu	Al	Nb
0.19	1.45	1.9	0.02	0.02	0.07	0.02	0.04	0.02	0.003

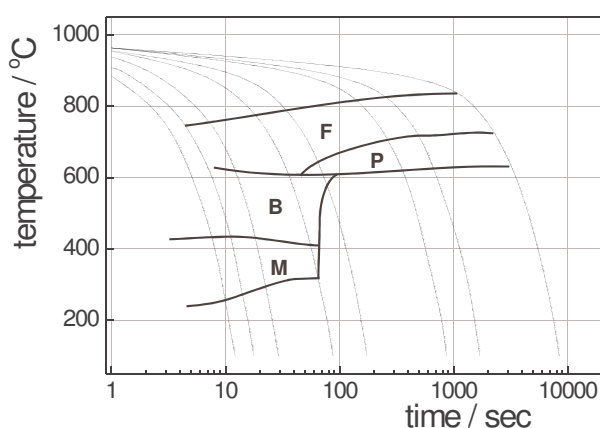


Figure 1 CCT diagram of the studied TRIP steel

deformation machine. By using the EURO THERM thermo controller, a relatively good temperature stability of  $\pm 0.5^\circ\text{C}$  in overall working temperature range is reached. This fact represents the main benefit of the used experimental method. The PC controlling system

gauge length of 15 mm, the thermocouple was welded directly on the specimen surface. Neutron diffraction experiments were realized at the dedicated high-resolution stress/strain diffractometer TKS-400 in NPI Řež (instrumental resolution of  $\Delta d/d \cong 2 \times 10^{-3}$ ). This facility is mainly used for *in situ* investigations of the deformation processes in different materials [6, 7]. The instrument is equipped with a special deformation rig for tension/compression loading up to the force of 20 kN. The resistant heating system dismantled directly to the water-cooled and modified grips of the

enables the independent control of the deformation machine, cooling system and also the diffractometer. Such a flexible controlling system allows even rather complicated scheme of thermomechanical loading. The diffractometer is dedicated stress/strain instrument with a linear PSD providing diffraction spectrum in a relatively narrow  $2\theta$  band of about  $2\theta=10^\circ$ . The detector window was set to cover both ferrite (110) and austenitic (111) reflection.

### 3. RESULTS AND DISCUSSION

The specimens were heated to solution temperature of  $1000^\circ\text{C}$  for 5 min, then cooled to  $900^\circ\text{C}$  followed by 25% compressive deformation. The temperature was consequently decreased to the different transformation temperatures  $T_t$  of 800, 775, 750,  $700^\circ\text{C}$ , derived

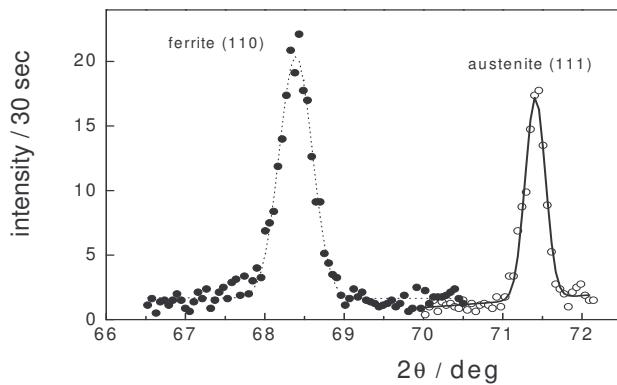


Figure 2. The neutron diffraction profiles of (110) of ferrite ( $T=20^\circ\text{C}$ ) and (111) austenite ( $T=750^\circ\text{C}$ ).

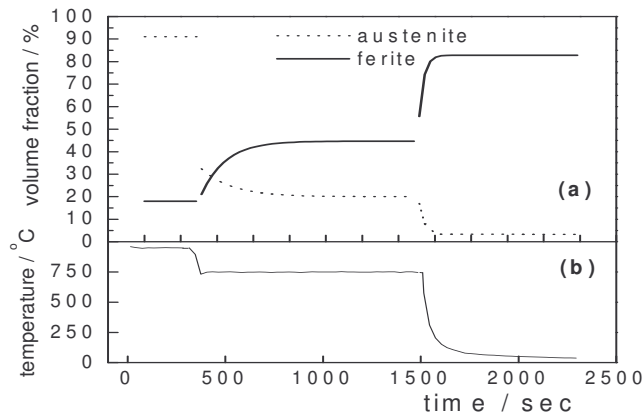


Figure 3. Time evolution of the volume fraction of both phases during the thermal loading, transformation temperature  $T_t=750^\circ\text{C}$  (a); temperature record (b).

phases was determined in the course of the thermal loading. An example of such a record for the transformation temperature  $T_t=750^\circ\text{C}$  is shown in Fig. 3. The integral intensities of the austenite and ferrite diffraction profiles can be assumed as a measure of the phase volume fractions yielding thus information on kinetics of isothermal transformation. The results are summarized in Fig. 4. Generally, the results pointing out to amount on phase transformed are in good agreement with CCT diagram (Fig. 1) of experimental steel.

from ferrite transformation temperature region according to CCT diagram of the steel, Fig.1. The hold time at transformation temperatures was of 20 minutes in all cases. During all this thermal exposure, the neutron diffraction spectra were collected in 30 sec sequences, recording evolution of (110) ferrite and (111) austenite reflection, respectively. The example of these diffraction profiles is shown in Fig.2. Relevant information on transformation characteristics can be extracted from integral intensities and angular positions of the individual profiles. The austenite and ferrite integral intensities can be assumed as a measure of the phase volume fractions whereas the profile positions can be used for estimation of the elastic lattice strains evolving in both phases during transformation. The integral intensity of the diffraction profile is proportional to the phase volume fraction, however, but also strongly depends on the temperature. To eliminate the temperature effect, the calibration dependence of the (110) intensity as a function of the temperature was measured in a single ferrite phase state of the steel. The time evolution of the volume fraction of both

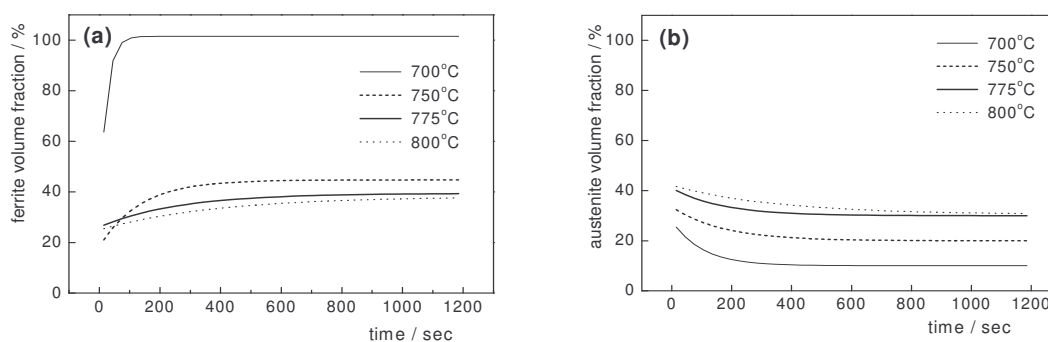


Figure 4. The time evolution of the ferrite (a) and austenite (b) phase-volume fractions, respectively, for different transformation temperatures.

Moreover, the precise evaluation of angular shifts of individual profiles can be used also for assessment of the internal strains and stresses in both phases originated at phase transformation, for more details see Ref. [8]. This method is based on the precise measurement of the deviations of  $d_{hkl}$  lattice spacing from stress-free state in particularly oriented crystal grains. The phase specific stresses arise during cooling due to different thermal expansion coefficient of the ferrite and austenite and depend thus on a phase volume fraction and temperature. In the present experiment we focused on stress examination of the ferrite phase only. Compressive residual stresses of about 100 MPa have been identified in the ferrite phase during transformation. This result is quite reasonable when taking into account the lower volume of the crystal unit cell of the newly born austenite.

#### 4. CONCLUSION

The new experimental ND method has been tested for characterization of the austenite transformation proceeding in TRIP steels during the thermomechanical treatment. Due to relatively low absorption of thermal neutrons in steel specimens, the neutron diffraction method yields relevant information from large sampled volume in situ during high temperature exposure and deposited mechanical load prior transformation. This is the main benefit of the applied method in comparison with other available experimental methods. The transformation dynamics has been described by measuring of the time evolution of ferrite and austenite phase volume fractions.

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