INFLUENCE OF THE THERMAL PROCESSING ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF A HIGH-PERFORMANCE HIGH-MANGANESE STEEL

Ludovic SAMEK¹, Enno ARENHOLZ¹, R. SCHNEIDER², and J. GENTIL³

¹ Research and Development, voestalpine Stahl GmbH, voestalpine-Strasse 3, A-4031 Linz, Austria
² Upper Austria University of Applied Sciences – Campus Wels, Stelzhamerstraße 23, 4600 Wels, Austria
³ Buderus Edelstahl GmbH, Research & Development, Buderusstraße 25, 35576 Wetzlar, Germany

Corresponding author: Ludovic.Samek@voestalpine.com

Abstract
The aim of the contribution is to review the structure/property relationship of a high-performance FeMnN steel composition. In this work, the influence of the Mn content ranging from 12 wt. % to 24 wt. % on the Fe-C phase diagram was calculated by thermodynamic simulations. The influence of coiling temperature on the microstructure of the FeMnN steel was studied by annealing treatments from 350°C up to 750°C. It showed the possible presence of cementite and martensite/pearlite after long annealing treatments for temperatures close to 500°C. The steel was observed to exhibit outstanding combinations of tensile strength and ductility. The FeMnN steel exhibited at room temperature a remarkably high total elongation of about 100% with a high tensile strength level of 1100 MPa. This product, proportional to toughness, achieved an outstanding value of about 110000 %MPa. The extended tensile ductility of the high-performance FeMnN steel was attributed to the nano-size twinning induced plasticity (NS-TWIP), which was observed by in-depth transmission electron microscopy study.

Keywords:
Nano-size twinning induced plasticity, High manganese steels, Strengthening mechanisms, Transmission electron microscopy

1. INTRODUCTION

High manganese steels (HMnS) are composed of a single austenitic phase or multiphase matrix with a major volume fraction of austenite. They can be classified according to their characteristic deformation mechanisms occurring during plastic deformation. Depending on their composition and deformation mechanism, they are often referred as TRIP/TWIP (transformation induced plasticity and twinning induced plasticity steels) or TWIP (twinning induced plasticity steels). Lightweight steels with induced plasticity (L-IP) also correspond to the TWIP steels. Due to their characteristic deformation mechanisms, HMnS with increased Al contents are found as the microband induced plasticity steels (MBIP) or shear band strengthened steels (SIP) steels. In automotive industry, the different classes of HMnS, including TWIP, TRIP/TWIP, L-IP, MBIP, and SIP, are referred to as called “second generation” of Advanced High Strength Steels (AHSS).

In regard to their chemical composition, HMnS are typically designed with a Mn content ranging from 10 wt.-% to 30 wt.-%. In the development of TRIP/TWIP and TWIP steels, one concept has been investigated by Frommeyer et al.[1, 2] based on the Fe-Mn-(Al, Si) composition. In this alloying concept, the steel had a Mn content from 15 wt.-% to 30 wt.-%, a low C content (0.05 wt.-%), and equal Al and Si contents of 3 wt.-%. Al and Si have been employed to improve the mechanical properties and to limit the possible carbide precipitation in the microstructure. In addition Al and Si also contribute to a greater deoxidation of the steel. The investigated Fe-Mn-(Al, Si) steels have shown elongations between 40% and 90% with tensile strengths
between 600 MPa and 1000 MPa [3-5]. The higher tensile strength inevitably resulted in lower elongation. The product of tensile strength times elongation reached 60000-70000 %MPa. This product is well known to increase exponentially with a finer grained microstructure for a same steel composition. This product is often employed for high-Mn steels. In some manner, this product is considered as a quantity related to toughness, proportional to the ability to absorb the energy of impact in specific loading conditions. Recent alloying concepts have been developed with high-Mn and high-C contents. It has led to the development of a Fe22Mn-0.6C steel composition [6]. This steel exhibited a tensile strength of about 1000 MPa or greater with an elongation of about 50%. This steel showed a good combination in tensile strength and total elongation, where their product readily achieved about 60000 %MPa or greater. In terms of mechanical properties, most high-Mn steels have a tensile strength ranging from 800 MPa to 1200 MPa. Furthermore, based on the literature, most conventional TWIP steels have typically a product of the tensile strength times total elongation between 50000 %MPa up to 70000 %MPa [2, 6-9].

The present study is aimed at reviewing the structure/property relationship of a modern advanced steel, referred to the nano-size twinning induced plasticity steels. The aim of the present contribution is to study the influence of the thermal processing on the microstructure and mechanical properties a modern advanced steel, referred to the nano-size twinning induced plasticity steels. The influence of the annealing parameters was investigated by dilatometry. The steel microstructure was characterized by light optical microscopy and transmission electron microscopy, and the mechanical properties by mechanical tensile testing.

2. EXPERIMENTAL PROCEDURE

A laboratory FeMnN steel composition was investigated in hot-rolled and cold-rolled conditions. The composition of the FeMnN steel is given in Table 1. Thermodynamic simulations were conducted by means of THERMOCALC [10]. Dilatometry investigations were carried out using a Bähr Dil 805 A/D dilatometer to investigate varying holding times and temperatures, which correspond to arbitrary coiling curves close to conventional industrial processing parameters. In the Fig. 1 (b-c), different typical cooling cycles for structural steels are indicated as a reference. These experiments are critical for the hot-rolling and coiling stages, and they allow to optimize the microstructure in terms of grain size, carbides,…

The mechanical properties were evaluated at room temperature by means of tensile tests. The tensile tests and sample dimensions were according to the EN ISO 6892-1 standard specification. The tests were performed with an initial strain rate of $5.6 \times 10^{-4}$ s$^{-1}$, which was increased after a strain of 3.4% to $5.6 \times 10^{-3}$ s$^{-1}$. The in-depth microstructural observation of the specimens was performed by using a transmission electron microscope (TEM), a Philips CM20 STEM, operated at an accelerating voltage of 200 kV with employing a double tilt goniometer stage.

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Al</th>
<th>P</th>
<th>Ti</th>
<th>Nb</th>
<th>N</th>
<th>Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeMnN</td>
<td>0.79</td>
<td>15.8</td>
<td>0.05</td>
<td>&lt;0.05</td>
<td>0.03</td>
<td>0.002</td>
<td>0.022</td>
<td>0.036</td>
<td>0.03</td>
</tr>
</tbody>
</table>
3. RESULTS

3.1 Thermodynamic simulations

In term of alloying composition, Mn is an austenite former, which enlarges the austenitic stability range, but it remains less stronger than Ni does. The thermodynamic simulations were carried out to assess the influence of Mn and C on the phase stability. Fig. 2 shows the influence of Mn from 12 wt.-% to 24 wt.-% in the ortho-equilibrium Fe-C phase diagram. In austenite, high contents of Mn as well as Cr and Ni allow to enhance the solubility of N in liquid iron. N is an interstitial alloying element with a high solubility in the austenite lattice due to the larger octahedral interstices of the austenite, and N remains a much stronger austenite stabilizer than Ni. Additionally N promotes a more effective solid solution strengthening effect than C. In austenitic steels e.g. Hadfield steel, it has been reported that N additions promote twinning \[11\]. In this present work, the sufficient alloying addition with N allows to strongly increase the stability of the austenite.

Fig. 2 Fe-C phase diagram in ortho-equilibrium for a Mn content ranging from 12 wt.- % to 24 wt.-%.

3.2 Light-optical microscopy

Fig. 3 shows the light optical microscopy of the samples at different annealing temperatures and times. The precipitation of carbides in the austenitic microstructure was shown to be relatively important at 450°C and 550°C. A clear presence of carbides, especially cementite, was revealed at 550°C for annealing time greater than 3000 s. Cementite was shown to preferably form at grain boundary, but it was also observed within the grains. For a holding time longer than 10000 s, the formation of martensite and pearlite occurred at the
temperature of 550°C. In the Figure the micrographs showing cementite precipitation are displayed to the right beyond the red marking line. In the Figure, for long holding time at relatively high temperatures, the formation of cementite occurred especially at the grain boundary. This indicates that the choice of the coiling temperature and quenching strategy have to be adapted to avoid the important formation of carbides. Based on these results, in this work the FeMnN steel was laboratory processed with a rapid quenching to room temperature after the finishing hot-rolling temperature in austenite region in order to obtained a relatively fine grained fully austenitic microstructure. Depending on the hot-rolling and quenching strategy, the steel had a grain size ranging from 5 µm to 50 µm in hot-rolled condition.

![Micrographs showing cementite precipitation](image)

**Fig. 3** Light optical microscopy showing the development of the microstructure after dilatometry experiments for an holding time varying from 1000 s to 600000 s and for temperatures between 350°C and 750°C. The Figure shows a microstructure composed of austenitic grains and some eventual presence of carbides and/or martensite/pearlite.

### 3.3 Mechanical properties

Figure 4 (a) shows the engineering stress-strain curves of the FeMnN steel in the hot-rolled and in the cold-rolled and annealed conditions. A high tensile ductility corresponding to the permanent increase in length of a tensile specimen before fracture was observed in the hot- and cold-rolled conditions. The solution annealing was required to obtain the sufficient recrystallization of the cold-rolled microstructure. The optimum mechanical properties in cold-rolled and annealed condition were obtained at 900°C and 950°C. The steel exhibited a total elongation of about 100%. Slightly better mechanical properties were obtained for the annealing temperature of 950°C.

The engineering curves exhibited a continuous yielding, as shown in Fig. 4(a). The Figure illustrates the discontinuities observed on the stress-strain curves. The two types of different discontinuities were labeled of “a-type” and “b-type” respectively. This behavior is due to the initiation and propagation of localized Portevin-le-Chatelier bands (PLC)[12, 13]. PLC characterizes serrated yielding or jerky flow phenomenon during straining. This corresponds to the thermal activation of dislocation moving with the aid of stress and the collective interactions between mobile dislocations and solute atoms due to dynamic strain ageing (DSA). It can satisfy the negative strain rate sensitivity of flow stress, which is believed to be one of the most special features associated with the PLC effect.
3.4 Transmission electron microscopy

The microstructure of the FeMnN steel was investigated by transmission electron microscopy. In the non-strained cold-rolled and annealed condition, the FeMnN steel had a fully austenitic microstructure. A clear refinement of the microstructure by an intense nano-size twinning induced plasticity deformation mechanism was observed in the austenitic FeMnN steel (Figure 5). This remarkable refinement of the microstructure occurring during straining significantly differs with the conventional twinning induced plasticity deformation of conventional TWIP steels[14]. An accurate measurement of the density of nano-sized twins is however particularly difficult with being statistically accurate by TEM. The nano-size twinning induced plasticity (NS-TWIP) deformation mechanism of the FeMnN steel has been revealed to be responsible of the outstanding mechanical properties exhibited by the FeMnN steel. Based on the TEM microstructural analysis, supported by the indexation of the diffraction patterns, no formation of ε- and α'-martensite phases were observed before and after straining.

![Fig. 5](image-url) Transmission electron micrographs showing the NS-TWIP effect in the strained microstructure of the FeMnN steel, showing the bright field (BF) (left) and dark field (DF) (right) with the selected area diffraction pattern.
4. CONCLUSIONS

In the FeMnN steel, the cold-rolled annealed microstructure plays a crucial role to obtain superior mechanical properties. The TEM study revealed an important refinement of the microstructure due the nano-size twinning induced plasticity. This strengthening mechanism results in a microstructure consisting of a small spacing between the nano-size twins. This mechanisms results in an intense reduction of the mean free path for dislocation movement inside the grains.

Compared to TWIP steels, it results in a high ductility of the steel during tensile testing and high hardening rate. Two mechanisms explained the observed important hardening rate, i.e. observed $n$-value: dislocation-dislocation interaction, a “dynamic Hall and Petch effect”[15] due to twin formation and the NS-TWIP effect.

The current research work was focused on filling the gap for superior toughness properties using modern advanced steel concepts with an adapted processing route. The FeMnN steel may offer a remarkable potential for manufacturing complex component, but it may also be ideally suited for crash energy absorptions. The remarkable properties make the steel suited to different applications, namely for forming and for automotive crashworthiness related components.

5. LITERATURE