METALLOGRAPHIC EXPLORATION OF TWIP STEEL

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Abstract

Steels with 17–22 wt. % Mn and 0.6 wt. % C exhibit low stacking fault energy (SFE) at room temperature. The optimum recommended stacking fault energy value is between 18 and 30 mJ·m⁻². During deformation, this causes mechanical twinning and, when combined with dislocation gliding, it leads to the twinning-induced plasticity phenomenon (TWIP). Exceptional mechanical properties in this TWIP alloy with face-centred cubic lattice are provided by the interaction between dislocation slip (reduced free path), mechanical twinning and the formation of complex microstructure (competing martensite formation (ɛ-martensite or α’-martensite)). When compared with other steels used in automotive industry, such as HSLA, DP or TRIP, the TWIP-based steels exhibit a strain hardening coefficient n of 0.4 at low strains, which is a twice higher value. This strengthening effect results in tensile strength of approximately 1200 MPa, combined with increased elongation with peaks up to 70 %. Recently, these steels began to be used more widely, particularly in the automotive industry.

Keywords:
high manganese steel, TWIP, metalography

1. INTRODUCTION

The solubility of carbon in austenite is high. An addition of manganese thus stabilizes austenite and, at the same time, strengthens the solid solution and the steel's lattice. It restricts the potential for ɛ-martensite by raising the value of stacking fault energy. The combined effect of manganese and carbon on the structure of steel of certain chemical composition is illustrated in Fig. 1. [1]. Furthermore, the impact of Nb upon these TRIP/TWIP steels was explored. It was found that the addition of 0.017% Nb increased the stacking fault energy and thus inhibited martensitic transformations. This resulted in an increase in elongation of the TWIP steel and in a strength decrease. Evaporation of a significant portion of manganese during melting dictates that it is added in greater than the resulting amount.

Advantages of TWIP steels include their ability to be produced using proven manufacturing procedures for other steel grades and compatibility with processing methods, such as continuous casting, rolling, pressing and welding. Minor technical difficulties might occur in metallurgical production of these steels. A portion of manganese might be lost during melting due to high manganese vapour pressure.

Fig. 1 Dependence of the stacking fault energy on the manganese content in the Fe–Mn system, as reported by various authors [1]
The course of transformation depends, besides chemical composition, on temperature and strain rate, on the orientation and size of initial grains and on thermal and deformation processing history. Formation of the $\varepsilon$ phase precedes the formation of $\alpha'$-martensite. Transformations of $\gamma$ to $\varepsilon$ phase, as well as $\varepsilon$ to $\alpha'$ phase remain incomplete. The $\alpha'$ phase forms at the expense of the $\varepsilon$ phase. Consequently, the amounts of individual phases at various stages of deformation are varied.

The restricting factor for the sequence of transformations of $\gamma$ to $\varepsilon$ and then to $\alpha'$ is the transformation of $\gamma$ to $\varepsilon$-martensite. The above suggests that the propensity of the steel to form $\varepsilon$ phase and the initial content of this phase will have a strong impact on the microstructure stability.

The stability of austenitic steels with low stacking fault energy when subjected to deformation can therefore be characterized as their resistance against $\gamma$ to $\varepsilon$ transformation. Stability of an austenitic steel during deformation may be affected by two factors. One of them is its propensity for forming $\varepsilon$ phase and for its growth during deformation. The other is the amount of $\varepsilon$ phase present before deformation.

![Figure 2](image1.png)

**Fig. 2** Dependence of mechanical properties of the Fe–23Mn–2Si–2Al–Nb steel on the test temperature: a) strength properties, b) elongation [2]

An impact of the initial grain size is reported to have an effect as well [3, 4]. Dynamic recrystallization leads to formation of fine grain in steel, which effectively prevents martensitic transformation. When compared to the effect of concentration of lattice defects, grain size appears to be the dominating factor in promoting or suppressing the transformation. Where large numbers of twins are present, they may prevent the movement of Shockley partial dislocations and may act as barriers to the growth of martensite plates. The combined effect of twins and of the presence of fine grain provides austenite with an extreme stability. It was reported that martensitic transformation was completely suppressed in a dynamically recrystallized microstructure produced by hot deformation at 1100°C, where the grain size was 10 $\mu$m [4]. On the other hand, in a microstructure with a large grain size (40 $\mu$m) and low twin density, the transformation of austenite to martensite can be easier.

2. EXPERIMENTAL

The experiment comprised several stages. First, experimental batches of the material were planned and cast. The chemical composition of the resulting ingots was verified; their as-cast microstructure was examined by metallographic techniques; and the microhardness of as-cast material was measured. The material was then heat treated. Its samples were hot rolled using various thermomechanical schedules and sectioned to specimens. Gleeble plastometer testing. Metallographic evaluation of microstructure, measurement of microhardness. Tension tests and evaluation of fracture characteristics.Cold rolling, mech. properties testing and metallography [5 - 8].

![Figure 3](image2.png)

**Fig. 3** Appearance of cast ingots of the experimental alloy
A gas ionization-based plasma furnace with a horizontal crystallizer was employed for processing the samples. Chemical composition of the five samples produced was as follows: C (wt. %) from 0.65 to 1.01; Mn from 21.34 to 23.11 and Nb from 0.010 to 0.015.

As-cast microstructure is shown in the following micrographs. Chemical composition of the material on the cross section of specimens was tested with energy dispersive microanalysis (EDAX). Area analysis and measurement of dendrite bodies showed, in most cases, the ratio of Mn/Fe at the level of 25/75, whereas interdendritic spaces showed the proportion of 32/68.

The as-cast samples were homogenized at 1125°C for 3 hours and water-cooled prior to the actual rolling process. The purpose of the homogenisation was to eliminate segregations of alloying additions. The first rolling stage was aimed at reducing the thickness of the cast ingots and crushing the as-cast structure. Identical conditions were used for all specimens, except sample 7. Samples 5, 6, 8 and 9 were soaked at 1100°C for 20 minutes to ensure their temperature is uniform throughout. They were then reduced in two rolling passes to a thickness of 8 mm. Specimen 7 was rolled to a thickness of 10.7 mm. It was sectioned to 8.5×15×20 mm prisms and used for testing in the Gleeble 3500 simulator.

Rolled and sectioned samples were then rolled from the temperature of 1100 °C to various final thicknesses between 3 and 6 mm with the finish rolling temperatures of down to 950 °C.

Microstructures of all rolled specimens were examined and their microhardness was measured with a Vickers indenter using ten indentations and a load of 0.2. Grain size was measured by comparison with standard patterns according to the ČSN EN ISO 643 standard. In selected specimens, grain size was also measured using the linear intercept method.
Tension testing was performed and selected specimens were used for metallographic observation on their cross-sections and longitudinal sections through the fraction surface. Types of fracture and fracture angles were determined.

Analysis of results of tension tests, microhardness data, flow stress values calculated from rolling forces, stress-strain curves from continuous and interrupted tests, activation energies, mathematical description of peak strains and the degree of softening and other experiment are published elsewhere [5-8], as well as mechanical properties upon the subsequent cold rolling.

However, an illustrative finding is that through the hot rolling process, higher yield strengths were achieved at lower temperatures (1000 °C) and with larger reductions (60%). The ratio between the yield and ultimate strengths Rp/Rm decreases with increasing temperature but, at the same time, declines with increasing reduction. Contrary to expectations, higher carbon level (which strengthens the solid solution) in the samples did not lead to a definite increase in strength.

![Microstructures of specimens with different amounts of reduction](image)

**Fig. 6.** Microstructures of specimens with different amounts of reduction: a) Specimen 5/1 with the reduction of 66.4% (20 μm) b) Specimen 5/2 with the reduction of 27.9% (70 μm)

Metallographic sections through tension test specimens exhibited significantly higher number of slip bands and twins due to severe strain introduced during tension test. Microstructure of material upon this deformation at room temperature is shown in Fig. 7 with a micrograph of a transverse cross section. Longitudinal sections exhibit deformation pattern in the form of elongation of grains in tension direction.

Examination of fracture surfaces of tension test specimens brought interesting findings. No necking or localised deformation occurred prior to fracture. The fractures were transgranular and ductile with dimples; typically at an angle of 45°. Figure 8 shows the fracture surface of the specimen 5/1.

Some of the above-described specimens upon tension test were used for cold rolling. The specimens were cut to two parts and their edges were removed by milling in order to eliminate surface cracks. Rolling was performed in the Q110 laboratory four-high rolling mill with working rolls diameter of 62 mm. Specimens were rolled to various reductions of 15 or 30% at room temperature. Rolling led to elongation of austenite grains in the rolling direction. The resulting grain pattern is more pronounced upon 30% reduction. The deformation mechanism was slip but the microstructure of specimens also clearly indicates of twinning.

Surface roughness of cold-rolled specimens varied greatly upon particular passes, as seen in specimen 5. Roughness depth in this part of specimen is between 27 and 38 micrometres. History of specimens had an impact as well: greater amount of oxides was found in specimens rolled at higher temperatures [9].
3. **CONCLUSION**

The paper gives an overview of metallographic observation of a laboratory-processed TWIP steel. The micrographs show as-cast microstructures and areas examined using EDAX analyzer. The as-cast microstructure of specimens was observed upon etching. The centre and near-surface areas were
compared. Typical as-cast dendritic microstructure was found, showing extensively branched dendrites. Neither segregations, dendritic segregations nor significant amount of inclusions were observed. In some specimens, mild porosity was found. Some of the pores could have been the remainders of inclusions, which had already been etched away. The only difference between the centre and the edges of specimen consisted in the directional alignment of grains (dendrites) due to the thermal gradient between the edges and the centre during cooling of castings. The manganese content as measured by the EDX analysis is slightly higher than the weight percentage results of the spectral analysis of cast samples. At the same time a number of micrographs show that interdendritic spaces contain up to 5% more manganese than the dendrites.

Microstructures of all specimens showed slip bands and numerous twins with varying thickness. The microstructure of the material appears to be austenitic in all cases. No martensite was detected. As the chemical composition of experimental specimens matched that of TWIP steels, according to [1] one can assume that the stacking fault energy ranges between 18 and 35 mJ/mm², and therefore twinning comes into play during deformation. This was evidenced by the micrographs.

Fracture surfaces of tension test specimens were explored using EDX microanalysis and isolated inclusions were examined. Generally, no undesirable carbides were detected, even in specimen 6, which had the highest carbon content. Small amounts of the following inclusions were found: oxide-sulphide inclusions with certain proportion of aluminium or aluminium oxides.

Prior to cold rolling, the specimens’ microstructure was austenite. Rolling led to elongation of austenite grains in the rolling direction. The resulting grain pattern is more pronounced upon 30% reduction. The deformation mechanism was slip but the microstructure of specimens also clearly indicates occurrence of twinning.

Surface roughness of cold-rolled specimens varied greatly upon particular passes. The depth of roughness is on the order of tens of micrometres. History of specimens played a role as well: greater amount of oxides was found in specimens rolled at higher temperatures. In the microstructure, work-hardened partially orientated martensite was found [8].

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LITERATURE