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# Enhancement of the strength-ductility combination of twinning-induced/transformation-induced plasticity steels by reversion annealing

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ABSTRACT

The aim of the present study was to combine the beneficial influences of both Twinning-Induced Plasticity (TWIP) and Transformation-Induced Plasticity (TRIP) effects on the mechanical properties and to adjust the contribution of both effects by suitable thermo-mechanical processing. Two high-manganese TRIP/TWIP steels were studied. In order to correlate the influence of the microstructural features to the mechanical properties, four specific conditions were set, i.e. pre-deformed, reversion-annealed, recovery-annealed and fully recrystallized. After pre-deformation, the alloys had different volume fractions of ε-martensite (5–24%). During reversion annealing at low temperature (350 °C) for 2 min, the ε-martensite was transformed to soft austenite. Recovery annealing (550 °C/5 min) resulted in annihilation of dislocations in addition to ε-martensite transformation. The corresponding bimodal microstructures were comprised of strong austenite with a high fraction of deformation twins and dislocations on the one hand and soft reverted austenite on the other hand. Due to the strong austenite, the high yield strength was retained and the soft austenite facilitated an improved work-hardening capacity.

## 1. Introduction

There is a strong demand by the automotive industry for new alloys to implement weight reduction, increase crash safety and improve manufacturing efficiency. Initiated by the works of Grässel et al. [1,2] and Frommeyer et al. [3], high manganese Twinning-Induced Plasticity (TWIP) and Transformation-Induced Plasticity (TRIP) steels have gained increased interest in the past decades, particularly in the field of structural parts for automotive applications. Due to the relatively low stacking fault energy (SFE) of these materials, mechanical twinning (in alloys with SFE in the range between 12 and 35 $mJ/mm^2$) and martensite formation (for SFE lower than 18 $mJ/mm^2$) occur in addition to dislocation slip during deformation [4]. This results in a high ductility and strength with a typical product of the ultimate tensile strength and the elongation to fracture of more than 50,000 MPa% [1,5]. This, so-called ECO-index, is a parameter to describe the maximum energy absorption capacity of a material and is therefore important, when it comes to the design of structural parts for the automotive industry. For crash relevant parts, the energy absorption at the early stage of deformation is the critical issue rather than the maximum energy absorption capacity. Therefore, a high yield strength and pronounced work hardening are required in case of a crash. Additionally, a sufficient ductility is required considering the manufacturing process.

Several approaches have been reported to increase the moderate yield strength in fully recrystallized TWIP steels, namely, pre-straining [6,7], grain refinement after recrystallization [8–11], micro alloying [12–14] and bimodal microstructures of deformed and recrystallized grains in partially recrystallized materials [15–18]. Since these approaches have shown some shortcomings, another concept was recently introduced and has gained interest in the scientific and manufacturing communities. In this approach, the recovery annealing of cold rolled TWIP steels [17,19–22] is utilized to obtain a microstructure with low dislocation density but high fraction of twins that impede dislocation motion. The cold rolling results in a high dislocation and deformation twin density and thus, a high yield strength (cf. Fig. 1a,c). Due to the thermal stability of the twins during recovery annealing, the yield strength remains at a high level while the ductility increases as a consequence of dislocation annihilation. However, this concept suffers from low work-hardening rates, since twinning provides a major contribution to the work hardening rate, the twin density saturates after medium cold rolling degrees (~40%) [23].

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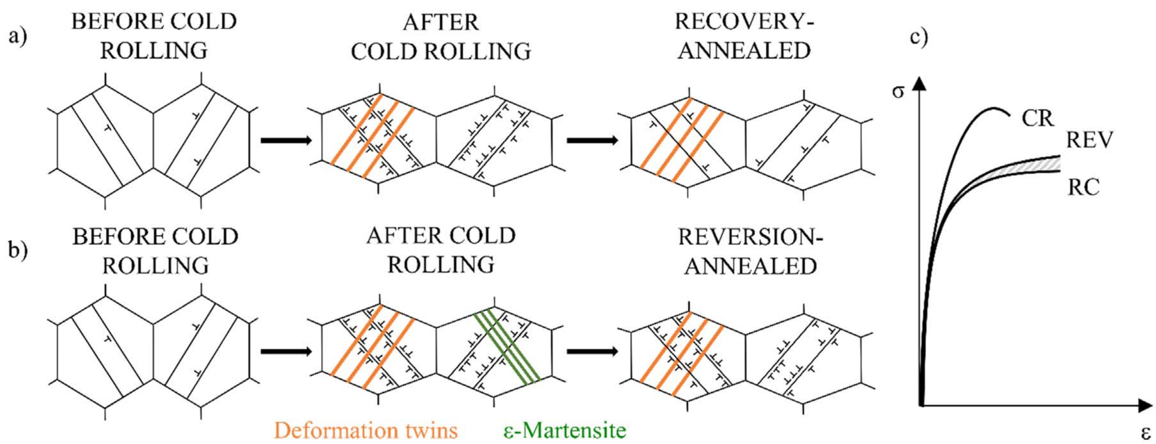


**Fig. 1.** Schematic of the microstructure evolution a) during cold rolling and recovery annealing of a TWIP steel and b) during cold rolling and reversion annealing of a TWIP/TRIP steel. The corresponding stress-strain curves are illustrated in c) (CR: cold rolled, REV: reversion-annealed TWIP/TRIP steel and RC: recovery-annealed TWIP steel).

## 2. Reversion annealing for improved mechanical properties of TWIP/TRIP steels

To overcome the disadvantage of low work-hardening rates in recovery-annealed TWIP steels, we propose a novel approach. It is aimed to achieve a high yield strength, improved work-hardening capacity and sufficient ductility compared to TWIP steels. Specifically, it is proposed to combine the benefits of both the TWIP and TRIP effects to design a steel with a bimodal microstructure and tailored mechanical properties. As schematically depicted in Fig. 1b, pre-deformation of a fully austenitic TWIP/TRIP steel by cold rolling is expected to introduce dislocations, deformation twins, and ε-martensite, resulting in a high yield strength. Subsequently, a reversion heat treatment performed at low temperature (350 °C) for short annealing time (2 min) transforms the ε-martensite into soft austenite, while the other microstructural features remain preserved due to their thermal stability. The achieved bimodal microstructure is then expected to consist of soft and deformed austenite with deformation twins and a high dislocation density. During further deformation by tensile straining, the thermally stable twins and high dislocation density in the deformed austenite potentially contribute to a high yield strength (Fig. 1c), whereas the soft austenite provides an increased work-hardening capacity through twinning and ε-martensite transformation.

Numerous studies have focused on the martensite to austenite transformation and the respective effect on the mechanical properties. Lü et al. [24] showed by differential thermal analysis that the austenite start and finish temperatures during the reverse transformation in a high manganese TWIP/TRIP alloy were 180 °C and 350 °C, respectively. This temperature range was confirmed for different heating rates. For this reason, Lü et al. [24] suggested that the transformation occurred by a diffusionless mechanism. In pure TRIP steels, reversion of α´- and ε-martensite at temperatures around 600–700 °C results in a strong grain refinement due to partial recrystallization [25–29]. Behjati et al. (Fe-Cr-Mn-C TRIP steel) [30], Escobar et al. (Fe-Mn-C TWIP/TRIP steel) [31], Challa et al. (Fe-Cr-Ni) [32] and Kisko et al. (Fe-Cr-Mn steel) [33] obtained fairly good mechanical properties by annealing at temperatures between 700 °C and 1000 °C, which caused a change in phase composition and (partial) recrystallization of the material. However, due to the simultaneous occurrence of phase transformations, recovery and recrystallization, no conclusive microstructure-property correlations could be drawn [25–33]. In addition to the investigations on reversion annealing, the work-hardening behaviour of TWIP/TRIP steels has been the subject of many studies. Sabzi et al. [34], Ding et al. [35] and Pierce et al. [36] found superior mechanical properties due to the combination of deformation twinning and strain-induced martensite formation, whereas Behjati et al. [37] outlined the influence of varying martensite contents on the mechanical properties of a high manganese TWIP/TRIP steel.

In the current study, two high manganese steels were investigated to examine the potential of the new concept proposed above. The alloys investigated were chosen based on their SFE values, with alloy I being in the transition range, where both TWIP and TRIP mechanisms are active, and alloy II (with a significantly lower SFE) in the pure TRIP range. Thus, the upper and lower limits of the SFE, which facilitates the activation of the desired deformation mechanisms (Fig. 1b), were tested. A low annealing temperature was used for reversion annealing in order to be able to directly correlate ε-martensite reversion to the changes in mechanical properties, caused by the phase transformation only. Additionally, recovery annealing was applied to compare the work-hardening rates of reversion- and recovery-annealed materials.

## 3. Experimental

### 3.1. Materials chemistry and processing

The chemical composition and SFE values of the two alloys investigated are shown in Table 1. The SFE was calculated using a subregular solution thermodynamic model [38]. Both alloys were ingot-cast and subsequently homogenization-annealed at 1150 °C for 5 h in a muffle furnace. Afterwards, the ingots with an initial height of 140 mm were forged at 1150 to 55 mm followed by homogenization and hot rolling at 1150 °C reducing the thickness to 2.4 mm. Alloy I was pre-deformed by cold rolling with a rolling degree of 50%. Various annealing treatments were applied in order to set different microstructural states as listed in Table 2, namely, Reversion-annealed (RV), Recovery-annealed (RC) and Fully Recrystallized (FRX). Alloy II was cold rolled to 50% rolling degree and subsequently annealed for 1 h at 800 °C to a fully recrystallized state. To achieve a suitable ε-martensite content the material was then pre-deformed by tensile tension parallel to the transverse direction (TD) to 5% strain. Further annealing treatments to achieve the similar microstructural states as in alloy I are listed in Table 2. Annealing treatments were performed in a sand bath and an air furnace for temperatures up to 600 °C and at 800 °C, respectively.

**Table 1**
Chemical composition and SFE values of the investigated alloys.

| Alloy | Fe (wt%) | C (wt%) | Mn (wt%) | Al (wt%) | Si (wt%) | SFE (mJ/$m^2$) |
|---|---|---|---|---|---|---|
| I (TWIP/TRIP) | Bal. | 0.321 | 16.80 | 1.470 | 0.03 | 18.9 |
| II (TRIP) | Bal. | 0.081 | 23.40 | 0.005 | 0.06 | 5 |