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A critical assessment of deformation twinning and epsilon martensite formation in austenitic alloys during complex forming operations

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ABSTRACT

The effect of mechanical twinning and ε-martensite formation on the formability of austenitic alloys in complex strain pathways has been examined. One of the alloys studied deformed by deformation twinning and slip (TWIP), and this alloy was examined with two grain sizes. The second alloy showed three concurrent deformation modes (slip, TWIP and ε-martensite TRIP). The TWIP/TRIP alloy showed a markedly reduced formability compared to similar alloys, and this has been attributed to a combination of the early development of strain localizations, and the stress-induced formation of ε-martensite. It is suggested that the TRIP effect may not be desirable in high formability sheet steels if the transformation product is ε-martensite. Microstructural examination revealed that the different strain paths develop different twin volume fractions. Plasticity modelling has shown this to be the result of differences in texture development in the different strain paths. In microstructures where slip, TWIP and TRIP can operate concurrently, the stress to activate twinning is unaffected by the additional deformation mode becoming operative.

1. Introduction

Advanced High Strength Steels (AHSS) are of increasing interest to the automotive industry [1], and the high-manganese steels in particular can show exceptionally good strength, ductility and work hardening rates. These excellent properties are mainly due to the complex plastic deformation behaviour of the austenite [2,3] which produces both the Transformation Induced Plasticity (TRIP) and the Twinning-Induced Plasticity (TWIP) effects. The TRIP and TWIP deformation mechanisms can occur individually or in tandem, but in all cases, deformation slip is also operative. These deformation mechanisms are of interest because TRIP promotes a high rate of material hardening and consequently extended press formability [4]. TWIP steels can show even higher material hardening and almost twice the uniform elongation of TRIP steels [5]. Thus these new materials offer the potential for significantly improved formability. Despite the fact that commercial sheet metal forming comprises a complex range of strain pathways from shear deformation, to uniaxial tension, to plane and biaxial strain [6], most studies published in the literature are limited to material formability in uniaxial tension. A small number of studies on TRIP alloys suggest that the amount of strain-induced transformation correlates with material formability, and that this changes with the strain path [7–9]. However, the effect of the forming mode on deformation twin formation remains largely unknown [10,11]. Additionally, it is currently unclear how material formability is affected by the type of martensite generated during the TRIP effect. While it is widely accepted that the strain-induced transformation from austenite to α-martensite increases material hardening and improves material formability [12] the effect of ε-martensite formation on material formability has not been investigated for different strain paths. It is not even entirely clear how ε-martensite formation effects material properties in simple tension [13,14], let alone in complex strain pathways. This review of our current understanding of AHSS formability leads to two outstanding questions:

- How does twinning effect the formability of AHSS? Is twinning more or less prominent in certain strain paths, and does it limit or extend plasticity in strain paths other than uniaxial tension?
- How does ε-martensite effect the formability of AHSS? Does it provide additional formability in strain paths other than tension, or is α-martensite a better phase for the TRIP alloys?

In the present work these two research questions were examined by comparing fully-austenitic alloys with very similar compositions, but markedly different deformation behaviours. The alloys were studied in a range of strain paths, and an intensive microstructural analysis was

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Table 1
Composition (wt%) of the three steels used in this study, measured by atomic emission spectroscopy and chemical analysis.

	C	Si	Mn	Al	Fe	O	N
TRIP	0.456	0.50	18.38	0.004	79.88	0.003	0.023
Commercial TWIP	0.565	0.23	18.31	0.897	78.64	< 0.002	0.006

undertaken to quantify the effect of deformation twining and ε-martensite formation on the sheet formability.

2. Experimental Method

2.1. Material and Thermo-Mechanical Processing Procedure

Three specimen types were used in this study, and all three alloys were fully austenitic in their starting condition. A commercial automotive high-Mn TWIP steel provided by POSCO Steel, South Korea Ltd. (Korea) was examined in two grain size conditions, fine grained (FG-TWIP with a grain size of 3 μm) and coarse grained (CG-TWIP with a grain size of 20 μm). In addition, a TRIP steel was also produced, which was hot rolled and annealed to have the same grain size as the CG-TWIP alloy. The composition of the TRIP steel was chosen to be as close as possible to the TWIP alloy, whilst still being an alloy known to produce the TRIP effect. The chemical compositions of the TRIP and the automotive TWIP steels are given in Table 1. All three materials had a sheet thickness of ~1 mm.

2.2. Tensile Testing

Tensile tests were carried out in an Instron tensile test frame, type 8801, equipped with a 100 kN load cell and hydraulic jaws. Tensile samples were parallel reduced length type and had a gauge length of 25 mm, and a width of 5 mm. Tensile sample shapes as shown in Fig. 1a were water jet cut from the steel sheet; that the tensile direction was parallel to the rolling direction of the sheet. Samples were tested at strain rates of 0.001, 0.01 and 0.1 s^{-1}. Only for the lowest strain rate of 0.001 s^{-1} tests were performed until fracture. For all strain rates, tests were stopped at various cross head displacements to measure equivalent strain ranging between 5 and 45% in the gauge region.

The strain distribution in the gauge section was analyzed using the optical strain measurement system GOM Aramis. A more detailed description of the GOM Aramis system can be found in [15]. To enable the measurement of the martensite volume fraction and of twins at various equivalent strain levels in tension by Scanning Electron Microscopy (SEM), samples of 10 mm length and approximately 5 mm width were cut from the gauge region. For those conditions where the optical strain analysis revealed that deformation was homogeneous, as in the case of both TWIP steels, the cuts were performed in the gauge center as shown in Fig. 1b for FG-TWIP. In the TRIP steel, deformation was inhomogeneous and samples were taken from regions where material deformation was localized (Fig. 1c). To determine the overall level of strain, six section cuts were performed along the sample width and the average equivalent strain determined over the 10 mm sample length. The overall level of equivalent strain in the sample was determined by taking the average of the six measurements.

2.3. Stretch Forming Tests

Stretch forming tests over a hemispherical dome punch were performed in an Erichsen sheet metal tester using the tooling shown in Fig. 2a and a maximum blankholder force of 220 kN used to clamp the sample. To achieve near frictionless conditions three layers of 0.5 mm polypropylene sheet with Milkfat applied on each side were used.

Round blanks of 150 mm diameter were used to achieve biaxial forming while the sample shape shown in Fig. 2b was used for plane

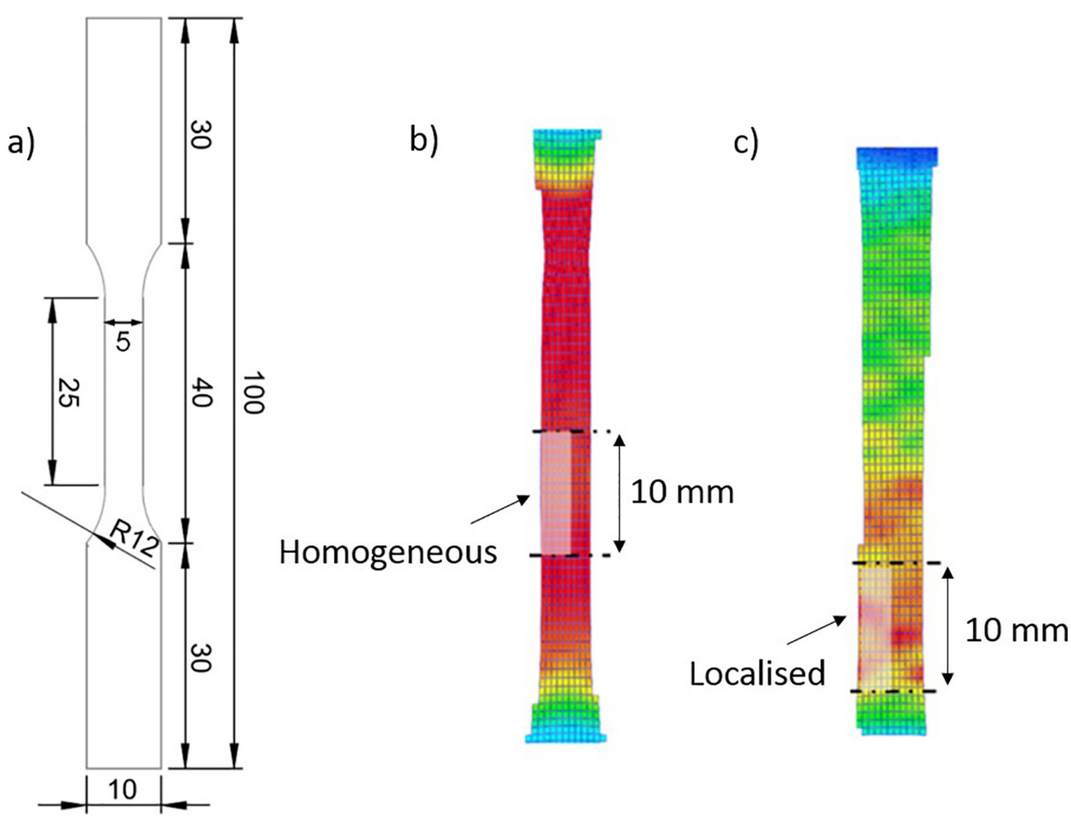

Fig. 1. a) Dimensions of the uniaxial tensile samples cut in rolling direction. Segment positions in the gauge section of tensile samples strained to 15% equivalent strain b) FG-TWIP c) TRIP.