## Abstract:

This report provides a detailed and comprehensive analysis of twinning-induced plasticity (TWIP) steels, a class of advanced high-strength steels known for their exceptional mechanical properties. The report explores the underlying mechanisms behind TWIP steel's unique characteristics, including the formation and role of deformation twins during plastic deformation. It delves into the factors influencing the TWIP effect, such as alloy composition, processing techniques, and microstructural characteristics. Additionally, the report discusses various fabrication methods and potential applications of TWIP steels in industries such as automotive and aerospace.

## Introduction

Twinning-induced plasticity (TWIP) steels have gained significant attention in recent years due to their exceptional combination of high strength and good ductility. This section provides an introduction to TWIP steels, highlighting their significance in the field of advanced materials. The motivation for studying TWIP steels is discussed, emphasizing the potential advantages and applications of these materials in various industries. TWIP steels are a class of iron alloys and steels with great potential for enhancing plasticity, making them attractive for engineering applications. The success of utilizing TWIP steels relies on a deep understanding of the underlying mechanisms and their activation during straining. Steel design based on composition, microstructure, and processing parameters is crucial to exploit the benefits of TWIP steels effectively.

Traditional formable ferritic steels often sacrifice ductility for higher strength, but TWIP steels offer a solution to this conflict. Fully austenitic steels or austenite-containing multi-phase steels with enhanced strain hardening rates can achieve high strength and good formability simultaneously. TWIP steels demonstrate high strain hardening, large uniform elongation, and high ultimate tensile strength, making them potential lightweight materials for automotive, LNG-shipbuilding, oil-and-gas exploration, and non-magnetic structural applications. The understanding of TWIP steels' mechanical behavior has advanced significantly due to global research efforts. Computational thermodynamics, first principal calculations, and advanced techniques for microstructural characterization have contributed to the fundamental understanding of TWIP steels. Furthermore, analyzing the strain rate and temperature dependence of mechanical properties has provided insights into the underlying mechanisms of TWIP steel strength and plasticity. The review highlights the groundbreaking contributions of previous studies on Fe-Mn-Si-Al TWIP steels, which triggered extensive research to uncover the plasticity-enhancing mechanisms during their deformation. TWIP steels exhibit exceptional strength-ductility combinations, with large tensile elongations and high strain hardening rates. These properties have opened up possibilities for developing new steel grades with a wide range of properties. The strain hardening behavior of TWIP steels plays a defining role in their strength and plasticity enhancement. The review discusses the taxonomy of strain hardening stages and compares the properties of TWIP steels with Ti-stabilized interstitial-free (Ti-IF) ferritic steels.

TWIP steels show higher strain hardening rates, larger uniform elongation, and greater ultimate tensile strength. However, they have relatively low yield strength, zero post-uniform elongation, and sometimes exhibit serrations on the stress-strain curve at large strains. TWIP steels with alloy compositions typically consisting of Mn, C, Al, and Si, and additional secondary alloying elements, exhibit high stacking-fault energies. The interaction between glide dislocations, grain boundaries, wide stacking faults, and deformation twins leads to sustained high strain hardening during deformation. The contribution of twinning to the overall strain in TWIP steels depends on the twin volume fraction and crystallographic texture.

In conclusion, the review provides a historical overview and assessment of the current understanding of the mechanical properties of TWIP steels. The unique properties of TWIP steels, such as high strain hardening, large uniform elongation, and high ultimate tensile strength, make them promising materials for various applications. Further research and development in this area have the potential to unlock new possibilities in steel design and engineering.

286 *B.C. De Cooman et al. / Acta Materialia 142 (2018) 283–362*

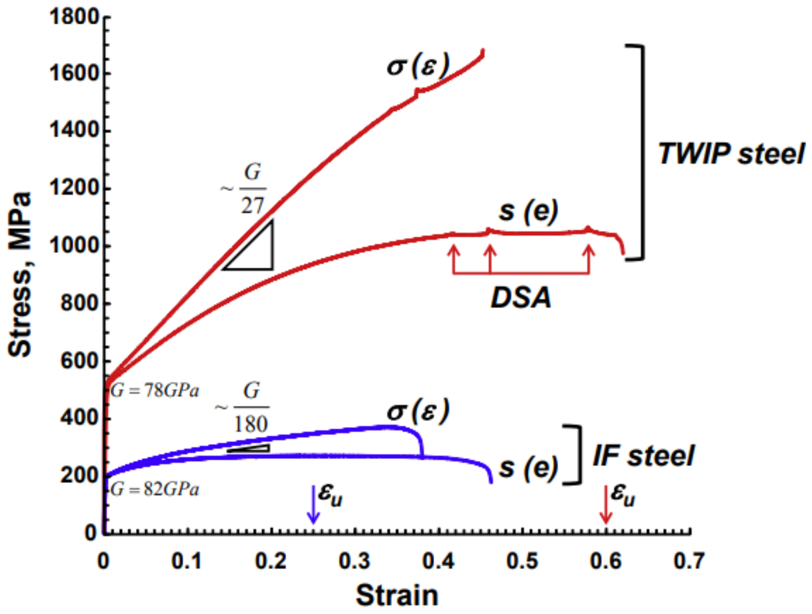


**Fig. 2.** Comparison of the uniaxial tensile stress-strain curves for a Ti-stabilized interstitial-free (IF) ferritic steel (bcc crystal structure) and an austentic Fe-18%Mn-0.6%C-1.5%Al TWIP steel (fcc crystal structure), illustrating a considerable difference in mechanical properties resulting from the more than six times larger strain hardening rate of the TWIP steel as compared to the IF steel.

## Mechanisms of TWIP Effect

The TWIP effect is a fundamental phenomenon that contributes to the exceptional mechanical properties of TWIP steels. This section delves into the mechanisms behind the TWIP effect, focusing on the formation and behavior of deformation twins. The role of deformation twinning in enhancing the material's ductility and strength is explained, along with the interaction between deformation twins and dislocations. The influence of these mechanisms on the material's mechanical properties is thoroughly examined.

## Factors Influencing TWIP Effect

Several factors influence the TWIP effect in steels. This section provides an in-depth analysis of the key factors that contribute to the TWIP effect. The impact of alloy composition on the TWIP effect is explored, with a particular emphasis on the role of specific alloying elements, such as manganese. The influence of microstructural features, including grain size and grain boundaries, on the TWIP effect is discussed. Moreover, the effect of various processing techniques, such as heat treatment and severe plastic deformation, on the TWIP effect is examined.

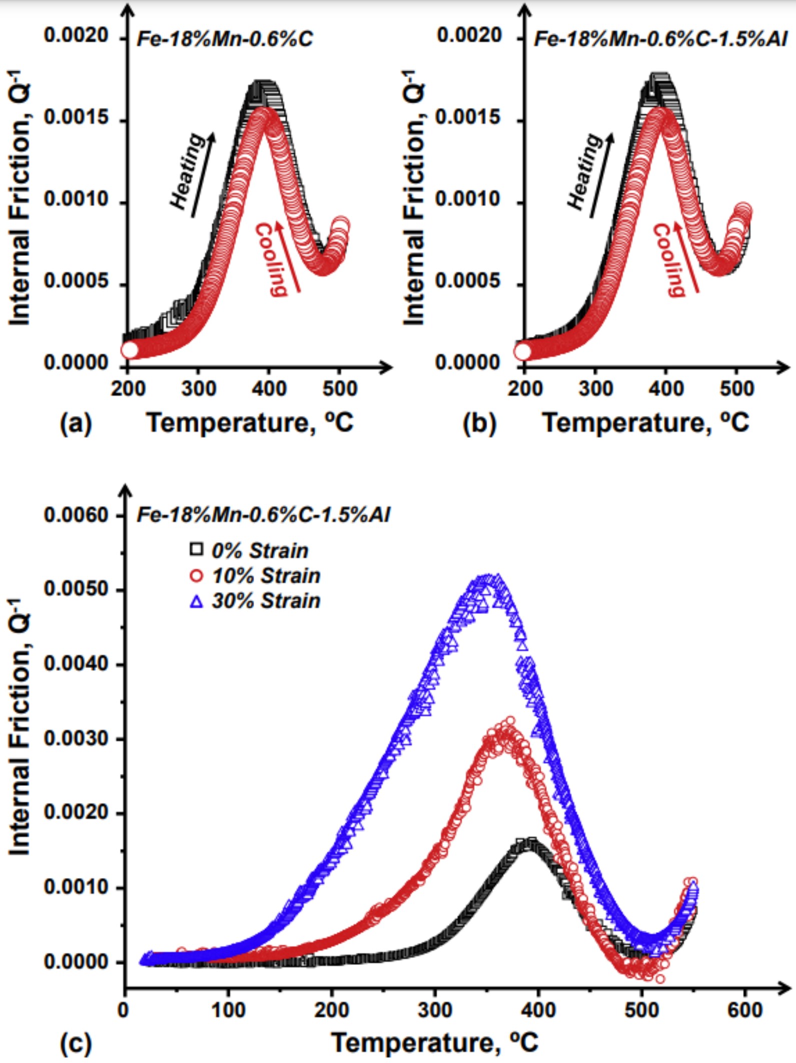


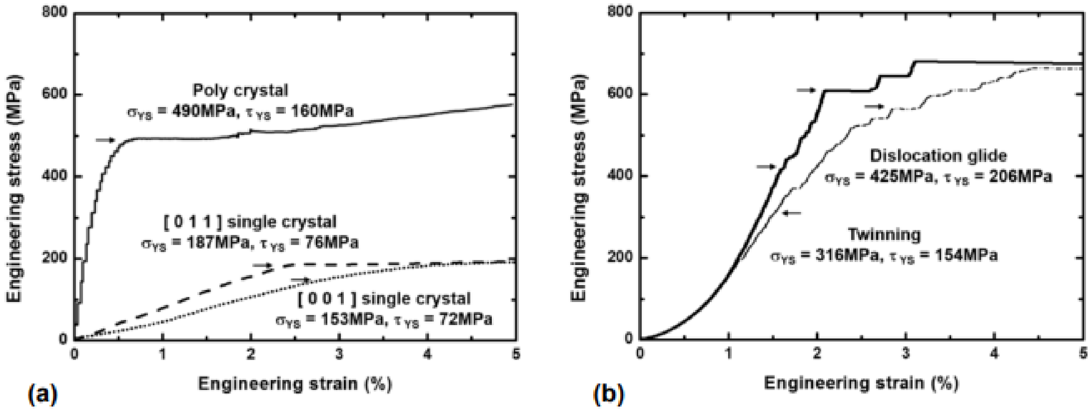
**Fig. 12.** Internal friction spectrum of TWIP steels [65]. (a) FR relaxation peak in Fe-18%Mn-0.6%C; (b) FR relaxation peak in Fe-18%Mn-0.6%C-1.5%Al at the measurement frequency of about 1 kHz; (c) Enhancement of the FR peak height for Fe-18%Mn-0.6%C-1.5%Al by straining.

## Fabrication Techniques

The fabrication of TWIP steels involves specific techniques aimed at optimizing their microstructure and properties. This section provides an overview of the different fabrication techniques employed for TWIP steels. Conventional methods, such as hot rolling and annealing, are discussed, focusing on their impact on the microstructure and mechanical properties of TWIP steels. Advanced techniques, including severe plastic deformation and additive manufacturing, are introduced, highlighting their potential for tailoring the properties of TWIP steels to meet specific application requirements.

## Mechanical Properties

Understanding the mechanical properties of TWIP steels is essential for their successful application in various industries. This section thoroughly examines the mechanical properties of TWIP steels, including their tensile properties, such as strength, ductility, and strain hardening behavior. The influence of different factors, such as strain rate, temperature, and loading conditions, on the mechanical behavior of TWIP steels is discussed. The exceptional combination of strength and ductility in TWIP steels makes them attractive for lightweight structural applications that require both high strength and energy absorption capabilities.



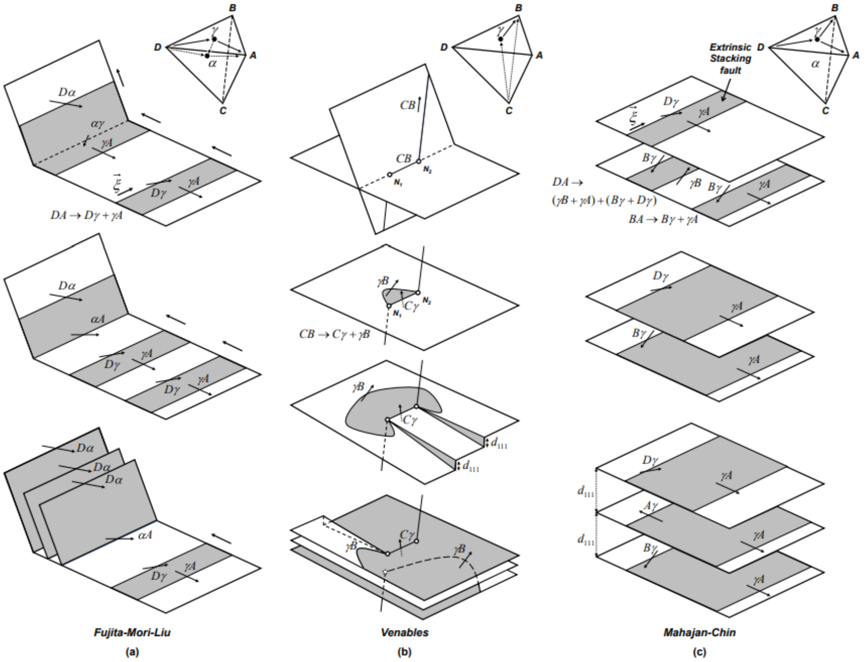
## Potential Applications

The potential applications of TWIP steels extend across multiple industries. This section explores the potential uses of TWIP steels in industries such as automotive and aerospace. The superior mechanical properties of TWIP steels make them suitable for a wide range of components, including safety-critical parts and structural elements. The potential benefits of TWIP steels in terms of improving vehicle safety, fuel efficiency, and overall performance are highlighted.

## Twinning mechanisms in TWIP steels

This section focuses on the models proposed for deformation twinning in twinning-induced plasticity (TWIP) steels. TWIP steels exhibit a combination of dislocation slip and deformation twinning during plastic deformation. Various mechanisms have been proposed to explain the formation of twins in TWIP steels, considering factors such as dislocation density and local stress. The text mentions that dislocations in the boundary plane of grain boundaries can emit twinning partial dislocations, which act as areas where twin embryos are formed. Random grain boundaries may also contain pre-existing multi-layer twin nuclei that can be easily activated at low strains. The deformation in TWIP steel typically starts with dislocation slip, and secondary slip systems are already activated at this early stage. Long stacking faults and secondary slip systems are visible in transmission electron microscopy (TEM). Deformation twins form soon after yielding and at low strains, primarily on the primary twin system. The contribution of secondary twin systems to deformation twinning is limited. Twinning is sensitive to crystal orientation, being more favorable when a grain has a ⟨111⟩ direction or a direction close to the tensile axis on the ⟨111⟩-⟨100⟩ tie line.

Several twinning mechanisms have been proposed, with six models specifically related to deformation twinning in TWIP steels discussed in this section. These models include the Venables pole mechanism, the Cohen-Weertman Frank cross-slip mechanism, the Fujita-Mori stair-rod cross-slip mechanism, the Mahajan-Chin extrinsic fault mechanism, the Miura-Takamura-Narita Frank primary slip mechanism, and the Copley-Kear-Byun partial dislocation breakaway mechanism. These models share the requirement of achieving a high dislocation density and local stress to initiate twin nucleation and growth. The text provides schematics illustrating the key aspects of these deformation twinning mechanisms reported in relation to TWIP steels. It should be noted that while classical models for deformation twinning exist in the literature, new twinning mechanisms have been proposed, particularly for ultrafine-grained and nanocrystalline materials with high stacking-fault energies. Overall, this section offers an overview of the models proposed to explain deformation twinning in TWIP steels, emphasizing their compatibility with TEM analysis and the factors influencing twin nucleation and growth.



Fujita-Mori-Liu
(a)

Venables
(b)

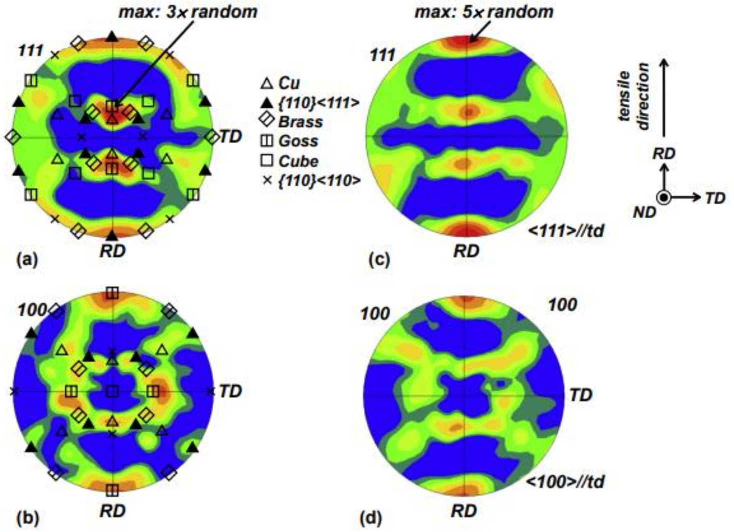
Mahajan-Chin
(c)

This relation has been verified for pure metals [142] and for CuAl alloys [261] by ab initio simulations using the VASPePAW-GGA software. Such analysis has not been applied to TWIP steels as yet. The ‘ideal’ twining stress associated with the homogeneous nucleation of a deformation twin in a defect-free crystal, not involving a heterogeneous twin nucleus such as a three-layer twin nucleus, can be computed using calculated generalized planar fault energy (GPFE) curves [140,142]. The relevant equation reads

$$\tau_T = \frac{\pi}{b_P}\cdot\left(\gamma_{utf} - 2\cdot\gamma_{tsf}\right) \approx \frac{\pi}{b_P}\cdot\left(\gamma_{usf} - \frac{\gamma_{isf}}{2}\right)$$

TWIP steels undergo a transition from a Cu-type texture to a Brass-type texture when both octahedral slip and deformation twinning are active mechanisms. The Brass-type texture is characterized by the predominance of Brass-{110}⟨112⟩ and Goss-{110}⟨001⟩ texture components, with a minor fraction of Cu-{112}⟨111⟩ and S-{123}⟨634⟩ components. Studies on the texture evolution of TWIP steels during uniaxial tensile testing and cold rolling primarily focus on the volume fraction of deformation twins, which is relatively small. The contribution of twinning to texture development is not expected to be a volume effect but rather an indirect effect on conventional {111}⟨110⟩-type slip. Models for crystallographic texture development in TWIP steel, such as during rolling, should not rely on a large volume fraction of deformation twins. Under uniaxial tensile deformation, TWIP steels with a weak initial texture exhibit a double fiber orientation, ⟨111⟩//td and ⟨100⟩//td, with pronounced mechanical twinning occurring in grains close to the ⟨111⟩//td fiber. Grains with a ⟨111⟩//td orientation develop a high density of deformation twins, while only a small fraction of grains with a ⟨100⟩//td orientation undergo deformation twinning. Grains with a ⟨110⟩//td orientation show intermediate twinning behavior and are characterized by reorientation during straining.

In the classical response of single crystals with an fcc crystal structure, the tensile axis rotates to the primary slip direction until both the primary and conjugate slip systems are equally activated. This rotation leads to a stable final orientation. In low gisf fcc materials like TWIP steels, the tensile axis may continue to rotate into the conjugate triangle before the conjugate slip starts, causing latent hardening. Deformation twins belonging to the primary twinning system act as barriers to the dislocations of the conjugate slip system, suppressing multiple slip and favoring the Cu-type texture generated by standard {111}⟨110⟩ slip.



## Conclusion

In conclusion, this report provides a comprehensive and detailed overview of TWIP steels, covering their mechanisms, fabrication techniques, and potential applications. The understanding of TWIP steels' unique properties and the factors influencing their behavior is crucial for further advancements and applications of these materials. The report serves as a valuable resource for researchers, engineers, and materials scientists interested in understanding and utilizing TWIP steels in diverse fields.