AN OVEREVIEW OF TWIP STEELS AND THEIR SUITABILITY FOR AUTOMOTIVE MANUFACTURING

BERNARD FELIX
University of Miskolc, Department of Machine Tools, Faculty of Mechanical Engineering, and Informatics
3515, Miskolc-Egyetemváros
felix.bernard.khawan@student.uni-miskolc.hu

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Abstract: Twinning-induced plasticity steels have gained significant attention in the automotive industry due to their exceptional blend of high strength and ductility. Extensive research has investigated their alloy composition, microstructure, mechanical properties, and simulations. This article explores the characteristic composition, microstructure, primary deformation and strengthening mechanisms, and distinctive mechanical properties of TWIP steels that make them suitable for automotive manufacturing, drawing from numerous professional publications. Additionally, it examines how key alloying elements, such as aluminum and manganese, impact the microstructure and mechanical performance of TWIP steels. The applications of TWIP steels in automotive components, including body structures, are also discussed.

Keywords: *TWIP Steel, advanced high strength steels, mechanical twinning, stacking fault energy, high manganese steel.*

1. INTRODUCTION

Over the past few decades, twinning-induced plasticity in steels has been a subject of intense interest for both academic and industrial research [1][2][3][4][5][6]. These austenitic steels are characterized by a high manganese content of 22 to 30%, as well as other alloying elements like carbon, silicon, and aluminum. This unique chemical composition results in an exceptional combination of high ultimate tensile strength and excellent ductility.

Among austenitic steels sought for light-weighting purposes, TWIP steels are particularly appealing. Unlike traditional high-strength steels that rely on work-hardening mechanisms such as grain refinement, solid solution, or dispersion strengthening, TWIP steels undergo deformation twinning, which provides an additional deformation mechanism alongside dislocation glide. This deformation twinning process increases the work-hardening rate by impeding the motion of gliding dislocations, allowing TWIP steels to leverage their ability to undergo extensive twinning during plastic deformation and achieve their unique balance of strength and ductility [6].

The high manganese content, along with appropriate amounts of other alloying elements, is critical for stabilizing the austenitic microstructure phase and promoting the TWIP effect in these steels [4]. This high proportion of Mn content also makes the resulting TWIP steels lighter than conventional steels, as the specific weight of Mn is lower than that of Fe, and alloys such as Al and Si. The development and application of these manganese-rich TWIP steels have increasingly attracted attention as the global automotive industry continues its quest for vehicle light-weighting with advanced high-strength steels. The incorporation of additional alloying elements enables the further optimization of TWIP steel composition and microstructure, allowing their properties to be tailored for specific applications. This has spurred a growing body of research investigating, for instance, the effects of aluminum content on the microstructure evolution and mechanical behavior of TWIP steels.

This review article aims to provide an overview of the characteristic features of TWIP steels, including their chemical composition, microstructural characteristics, deformation mechanisms, and mechanical properties, with a particular emphasis on their suitability for automotive manufacturing applications. The paper is structured into seven sections. Section 2 explores the distinctive chemical composition of TWIP steels, focusing on the primary alloying element, manganese, as well as other key alloying additions such as aluminum, silicon, copper, and nitrogen. Section 3 discusses the microstructural features of TWIP steels and how such microstructures are achieved. Section 4 presents the different grades of TWIP steels, their chemical compositions, and their corresponding mechanical properties. Sections 5 and 6 delve into the production processes for TWIP steels and their primary fields of application, respectively. The challenges associated with the development and deployment of TWIP steels are also highlighted in

Section 5, along with practical solutions. Finally, Section 7 examines potential future developments and ongoing research directions in this field, providing a concluding perspective.

2. CHARACTERISTIC COMPOSITION OF TWIP STEELS

The microstructure of TWIP steels is retained at room temperature by means of a high percentage of alloying elements, such as manganese, aluminum, and silicon. In this section, the characteristic chemical composition of TWIP steels is reviewed, with a focus on these key alloying elements and their roles in imparting the unique properties.

2.1. Manganese

Manganese is the primary alloying element in TWIP steels, typically ranging from 22 to 30% [4][6]. Its addition stabilizes the austenite microstructure phase by lowering the transformation temperature and enabling the twinning-induced plasticity effect. However, if its concentration is less than 15 wt%, α0-martensite can form, which can degrade ductility and is generally undesirable. At lower temperatures, α0-martensite forms after ε-martensite. Conversely, if Mn content exceeds 30–32 wt%, brittle β-Mn phase can appear in the microstructure. Thus, at Mn content below 15%, the TRIP effect tends to dominate, while for Mn contents above 22%, the TWIP effect becomes the dominant deformation mechanism.

The deformation mechanisms in TWIP steels strongly depend on stacking fault energy [7][8], which is a function of composition and temperature [9][10]. TWIP steels have an SFE of ~30mJ/m2, which promotes extensive mechanical twinning under plastic deformation. In general, mechanical twinning occurs in alloys with SFE in the range of 20–50mJ/m2, while martensitic transformation governs deformation in materials with SFE below 15mJ/m2 [11][12]. The strengthening mechanism for TRIP steels is based on the deformation-induced transformation of metastable austenite, a face-centered cubic (fcc) c-phase, to martensite, a hexagonal close-packed (hcp) e-phase and/or body-centered cubic (bcc) a0-phase, during the deformation process. The aim of optimizing TWIP steel composition is to promote deformation by twinning and to suppress this martensitic transformation.

To achieve a fully austenitic microstructure, TWIP steels require a sufficient amount of manganese. About 27 wt% Mn is needed to stabilize austenite at room temperature in carbon-free alloys. The $\gamma \rightarrow \varepsilon$ transformation temperatures decrease as the manganese content increases. The primary influence of manganese in TWIP steels is its ability to control the stacking fault energy of mechanical twins. The SFE increases with higher manganese content, leading to a shift in deformation mechanism from TRIP-type (with low SFE values) to TWIP-type (with moderate SFE values).

The high Mn content also contributes to the lower density of TWIP steels compared to conventional steel alloys. However, reducing the manganese content has become a serious practical issue to lower the cost and facilitate the manufacturing of TWIP steels.

2.2. Aluminum

Aluminum is another crucial alloying element in TWIP steels. By increasing the stacking fault energy of the austenitic matrix, aluminum suppresses deformation twinning and promotes dislocation slip as the dominant deformation mechanism. Relatively low aluminum content, around 0.6-1.5 wt%, can produce a duplex microstructure of austenite and ferrite, which exhibits an excellent combination of strength and ductility. Conversely, higher aluminum levels, around 2-3 wt%, promote a fully austenitic microstructure.

Alloying with aluminum weakens dynamic strain aging, which can be explained by the prevailing effect of increasing stacking fault energy that suppresses twinning [13]. The dynamic strain aging mechanism is based on the dynamic interaction between mobile dislocations and diffusing solute atoms [1]. This phenomenon is undesirable for automotive materials because it can lead to strain localization, deteriorating ductility and potentially impeding press forming.

While small additions of aluminum facilitate the TWIP effect, the formation of ε-martensite is effectively suppressed by the addition of 1.5 wt% Al to 15Mn–0.6C TWIP steel. Additions of 1.5% Al to 18Mn–0.6C reduce tensile strength but nearly double the elongation by suppressing cementite precipitation during cooling after hot rolling and during annealing, due to the decrease in both the activity and diffusivity of carbon in austenite [14]. The specific effects of aluminum content on the microstructure and properties of TWIP steels are therefore quite complex, requiring careful balancing of the alloying additions.

2.3. Silicon

Silicon is a common alloying element in TWIP steels, with both beneficial and detrimental effects. Similar to aluminum, silicon can be added to achieve a stable and fully austenitic microstructure with a stacking fault energy in the range of 15–30 mJ/m², which is critical for enabling twinning during deformation. However, silicon can also promote the precipitation of cementite, which can degrade ductility.

The addition of up to 3 wt% silicon has little impact on yield strength, but further increases between 3-6 wt% lead to a significant boost in yield strength. This is due to solid solution strengthening, which refines the ε-martensite plates and increases fracture strength. Higher silicon content tends to stabilize the austenite phase against transformation into ε-martensite, but it also results in a decrease in ductility. The optimal silicon content appears to be around 1-3 wt%, as this can increase the work hardening rate of TWIP steels while balancing the competing effects of silicon.

2.4. Carbon

Depending on the alloy system, the carbon content in TWIP steels can vary, typically ranging from 0.4 to 1.0 wt%. Carbon plays a crucial role in stabilizing the austenitic microstructure and contributing to solid solution strengthening. It also inhibits the formation of ε-martensite by increasing the stacking fault energy and enables the TWIP effect by maintaining the stacking fault energy at suitable levels. However, the carbon content must be carefully balanced, as lower carbon may not provide sufficient austenite stability and twinning behavior, while excessive carbon can lead to the precipitation of detrimental carbides, which can reduce ductility.

TWIP steels with high carbon content such as Fe–12Mn–1C Hadfield steel (>0.6 wt%), can achieve martensite-free austenitic microstructures even at relatively low manganese levels of 12 wt%. Carbon plays a significant role in the plastic deformation of such alloys, affecting both the work hardening behavior and, more importantly, dislocation mobility.

As demonstrated by Allain et al., higher carbon content in TWIP steels corresponds to lower activation energy required for dislocation glides, a crucial mechanism contributing to ductility [12]. In general, the carbon content in TWIP steels is maintained between 0.4-0.6 wt% to strike a balance between austenite stability, twinning behavior, and ductility. TWIP steels with low carbon content tend to have a yield strength close to 250 MPa, while those with 0.6% carbon can reach 400–600 MPa.

2.5. Nitrogen

Nitrogen is another key alloying element that can be added to TWIP steels in small amounts. This helps to further stabilize the austenitic microstructure and suppress detrimental dynamic strain aging effects, while maintaining a low overall alloy density. According to De Cooman et al., adding less than 0.3 wt-% nitrogen has a similar effect to aluminum in that it can increase the stacking fault energy and austenite stability [15]. Similarly, Jin and Lee reported that nitrogen was found to suppress dynamic strain aging and serrations [14]. Nitrogen is an efficient austenite strengthening element, as seen when adding nitrogen to a Fe–16.5Mn alloy, which lowered the martensite start temperature and reduced the volume fraction of ε-martensite.

In conclusion, the mechanical properties of TWIP steels result from a complex interplay between the various alloying elements and their influence on the microstructure. An important advantage of the Fe-Mn-Al-Si concept of TWIP steels is the relatively low density of these main alloying elements, which is directly related to their composition. For example, the largest component, Mn, is 5.5% less dense than Fe. Typical alloying elements are even less dense, with Al being 66% and Si 70% less dense than Fe. This lower density contributes to the lightweight advantage of TWIP steels compared to conventional steels and other advanced high-strength steels. Additionally, Fe–Mn–C-based TWIP steels exhibit a very high strain hardening rate due to the formation of a high fraction of deformation twins [16].

3. MICROSTRUCTURE/CONSTITUTION OF TWIP STEELS

In this section, the evolution of the microstructure of TWIP steels during deformation and its implications on mechanical properties are discussed.

3.1. Microstructure of TWIP Steels

TWIP steel microstructures consist of a fully austenitic single-phase with coarse grains often containing wide annealing twins. These twins are highly symmetrical discontinuities in the crystal structure, where two crystalline regions are structurally mirror images of each other, appearing as thin plates or dark lines within the austenite matrix. Mechanical twins form due to deformation in body-centered cubic (bcc) and hexagonal close-packed (hcp) metals, while annealing twins form in face-centered cubic (fcc) metals following deformation [17]. The amount of plastic deformation from twinning is small compared to that from dislocation slip.

The plastic deformation in TWIP steels is governed by several mechanisms, including dislocation glide, martensitic phase transformations, and mechanical twinning. The metallurgical parameter that determines the predominant mechanism is the stacking fault energy. A stacking fault arises when there is a disruption in the stacking sequence of the close-packed planes in the crystal structure of metals. This disruption creates a change in the energy field around it, known as the stacking fault energy, measured in units of mJ/m^2. As mentioned previously, the stacking fault energy can be influenced by the alloy composition and deformation temperature, and its magnitude dictates the ease of dislocation glide and the activation of deformation mechanisms in these steels.

As the stacking fault energy decreases while other conditions remain constant during deformation, a higher density of strain-induced mechanical twins forms. These twins act as barriers to dislocation glide, a phenomenon known as the "Dynamic Hall–Petch effect", which causes very high strain hardening in TWIP steels [18]. Previous studies have shown that the TWIP effect can only be activated within a well-defined range of stacking fault energies [19][20]. When the stacking fault energy falls below approximately 20 mJ/m^2, the steel exhibits Transformation-Induced Plasticity behavior, involving the formation of hexagonal close-packed ε-martensite and body-centered cubic α-martensite. Conversely, above a certain stacking fault energy threshold, deformation by dislocation glide prevails.

Grain size has a significant influence on the TWIP effect in these steels. Coarse-grained materials exhibit a greater TWIP effect, as the number of deformation twins increases with increasing grain size [21]. Conversely, fine grain sizes can completely inhibit the formation of twins and martensite in low stacking fault energy materials. The initiation of twinning requires a critical buildup of dislocation density, meaning the twins only start to form after a certain level of plastic strain has been achieved through dislocation glide. Microstructural observations suggest that planar dislocation pile-ups are necessary to trigger mechanical twinning, and that grain refinement suppresses this twinning mechanism.

The microstructures of TWIP steels are usually obtained under non-equilibrium conditions due to the method of thermal treatment used in their manufacturing processes. At room temperature, the microstructure of Fe-Mn alloys is characterized by the presence of cubic α-martensite at lower manganese contents and hexagonal ε-martensite at higher manganese contents. The metastable Fe-Mn phase diagram can be used to understand the phases present, and the microstructures produced under the practical nonequilibrium conditions encountered during the processing Fe-Mn steels. Specifically, the Fe-rich side of the Fe–Mn phase diagram exhibits an open γ loop, leading to the potential presence of α0-martensite at lower Mn contents and ε-martensite at higher Mn contents within the 5–25 wt% Mn range [2]. This is reflected in the annealed microstructures of TWIP Fe-30Mn and TWIP Fe-24Mn, as shown in Figure 1.

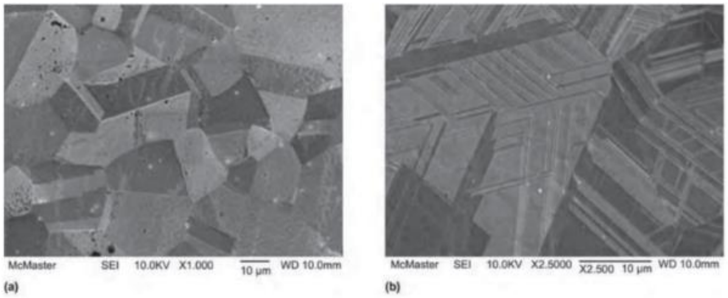

Figure 1: *Microstructure of (a) annealed TWIP Fe-30Mn, and (b) annealed TWIP Fe-24Mn [22].*

Austenite can be stabilized at room temperature with manganese content exceeding 27 wt%, but lower manganese levels of less than 25 wt% can also result in stable austenite at room temperature by incorporating small amounts of carbon to suppress the formation of any type of martensite. However, higher carbon content leads to the formation of Fe3C particles, which are undesirable in welding steels.

3.2. Main Strengthening Mechanisms of TWIP Steels

During the early stages of deformation, dislocation glide is the predominant mechanism in TWIP steels [23]. However, as straining continues, deformation twinning becomes increasingly active after a certain threshold level of strain is reached. Additionally, the transformation from austenite to martensite also becomes more significant with ongoing deformation [17]. The formation of mechanical twins during plastic deformation in TWIP steels acts as barriers to dislocation motion, thereby enhancing the strength of the steel. The degree of deformation twinning can vary depending on factors such as stacking fault energy, grain size, and temperature, but it is typically of the order of 5%.

Refining the microstructure through the formation of numerous fine twins that impede dislocation motion is widely considered the primary explanation for the high strain hardening and tensile strength observed in TWIP steels [24]. In the absence of twinning, TWIP steels exhibit significantly lower work hardening, thus highlighting the critical role of twinning as the predominant strengthening mechanism. Furthermore, the interactions between the twins, martensite, and dislocations also contribute to the enhanced strength of TWIP steels.

Koyama et al. investigated the behavior of two 17Mn steels containing 0.6% and 0.8% carbon to distinguish the respective contributions of ε-martensitic transformation, deformation twinning, and dynamic strain aging to the work hardening rate in carbon-containing TWIP steels [25]. By testing the steels at varying temperatures, the researchers found that the quantitative impact of these mechanisms on work hardening rate could be ranked as follows: ε-martensitic transformation > deformation twinning > dynamic strain aging. The effectiveness of each mechanism was observed to be influenced by the specific temperature ranges and strain rates under which the steel was deformed.

The activation of Twinning Induced Plasticity is strongly dependent on the stacking fault energy in the metal crystal structure. Low SFE is associated with martensitic transformation, while high SFE is associated with dislocation glide. However, within a certain range of intermediate SFE, both twinning and martensitic transformation can occur, leading to the TWIP effect. TWIP behavior is observed in medium SFE steels and is characterized by the formation of deformation twins with nanometer-scale thickness. Adding less than 1 wt% carbon to Fe-Mn alloys can reduce the SFE, but higher carbon content leads to the formation of undesirable Fe3C particles [17]. The strain-hardening mechanism in TWIP steels can be engineered by adjusting the alloying element content, such as manganese, aluminum, and carbon. The alloying composition affects the SFE and determines the dominant deformation mechanism in the steel.

The TWIP effect emerges as the predominant deformation mechanism in high-manganese steels containing at least 15 wt.% Mn, with additions of silicon and aluminum [26]. Owing to the frequent occurrence of deformation twinning, these steels exhibit an exceptional combination of high strength and high ductility. Typically, factors that enhance the strength of a material are detrimental to its ductility, but grain refinement is an exception. Steels with higher manganese content exhibit lower strength, indicating that solid solution strengthening is not a major strengthening mechanism. Instead, strain-induced transformation or twinning is the most significant contributor to the increased strength of these materials.

4. GRADES OF TWIP STEELS

While TWIP steels display remarkably high ultimate tensile strength and uniform elongation, they often suffer from relatively poor yield strength, which can limit their suitability for certain component designs. However, research has shown that the yield strength of TWIP steels can be significantly improved through grain refinement achieved by controlled recrystallization of cold-rolled steels [27]. Additionally, microalloying has been explored as a means to increase yield strength by combining the effects of precipitation hardening, grain refinement, and recrystallization control in cold-rolled TWIP steels [28]. Although the addition of aluminum increases the stacking fault energy and decreases the likelihood of twinning in TWIP steels, it also has a strong positive impact on their yield strength. The probable mechanism for this enhancement of yield strength in TWIP steels through Al addition is believed to be solid solution strengthening [14]. A summary of the compositions of various TWIP steel grades is provided in Table 1 [29].

Table 1: *Compositions of different types of TWIP steels*

TWIP type	Mn (wt%)	Al (wt%)	Si (wt%)	C (wt%)	Cr+Mo (wt%)	Nb (wt%)	Fe (wt%)
TWIP 1	28	1.6	0.28	0.08	<0.01	<0.001	Bal.
TWIP 2	25	1.6	0.24	0.08	<0.01	0.05	Bal.
TWIP 3	27	4.1	0.52	0.08	<0.01	0.05	Bal.
TWIP 4	28.1	0.9	0.54	0.17	<0.01	<0.001	Bal.
TWIP 5	23.9	3.5	0.448	0.11	1.0	<0.001	Bal.

4.1. Characteristic Mechanical Properties of TWIP Steels

TWIP steels exhibit a remarkable capacity for work hardening, enabling them to achieve extremely high tensile strength coupled with exceptional ductility compared to all other steel grades [17]. Their tensile strength ranges from 900 to 1100 MPa (130 to 160ksi), while their ductility spans 55 to 70%. Notably, their strain-hardening exponent increases to 0.4 at 30% strain and then remains constant thereafter. The exceptional characteristics of TWIP steels originate from their fully austenitic microstructure and the twinning deformation mode that dominates their behavior [17]. The mechanical properties of three TRIP steel types referenced in Table 1 are presented in Table 2.

Table 2: *Mechanical properties of various TWIP steel types referenced in Table 1*

TWIP type	Mn, %	Yield stress, MPa (ksi)	Tensile strength MPa (ksi)	Total elongation, %
TWIP 1	28	325 (47)	495 (72)	64
TWIP 2	25	375 (54)	538 (78)	61
TWIP 3	27	383 (56)	548 (69)	61

The extended ductility of TWIP steels originates from their high work-hardening capacity, which delays the onset of plastic instability and localized necking. This elevated work-hardening rate is attributed to the increase in deformation twins with tensile strain, which create additional obstacles to dislocation glides and thereby strengthen the steel [17].

Grain refinement leads to an enhancement in the yield strength and tensile strength of TWIP steels. Conversely, this trend is opposite for elongation. Despite the increase in strength stemming from smaller grain sizes, the product of tensile strength and total elongation declines with decreasing grain size, underscoring the predominant influence of elongation as a critical tensile property in these steels.

5. PRODUCTION OF TWIP STEELS

TWIP steels are manufactured through a hot rolling process akin to the production of other steel varieties. The procedure involves reheating cast steel ingots and then hot rolling them down to the desired thickness. Subsequent coiling and annealing steps are employed to tailor the microstructure and achieve the target mechanical properties. As reported in the literature [30], the grain size of TWIP steels can be refined through a combination of cold rolling and annealing. The cold rolling step introduces a high dislocation density, which then drives recrystallization and grain refinement during the subsequent annealing process.

Initial research on TWIP steels in the early ‘90s led to attempts to industrially produce variants containing around 22-28% manganese. However, these initial manufacturing attempts encountered some challenges due to limitations in production facilities, low productivity, high costs, and issues with delayed fracture [31]. Through extensive research in Europe and Asia, as well as significant efforts by POSCO, the industrial-scale production of TWIP steels commenced over a decade ago [32]. The first commercial batches of TWIP-980 steel produced by POSCO marked a transition into the industrial testing and commercialization stage for these materials. Further development is ongoing, with reports of TWIP steels with tensile strengths exceeding 1180 MPa being under active research. Ansteel also announced the commercialization of TWIP-980 steel and the development of an even higher 1180 grade [33].

The elevated alloy content of TWIP steels, along with manufacturing complexities, contributes to their high production costs, prompting the exploration of cost-reduction strategies. Research has revealed that partially substituting manganese with microalloying elements such as aluminum, vanadium, or niobium can help lower manufacturing expenses while retaining the high strength and ductility of TWIP steels [34]. Additionally, small additions of chromium, nickel, and copper have been shown to enhance the mechanical properties of these advanced materials [35]. Furthermore, the ongoing development of third-generation advanced high-strength steels offers the potential for achieving comparable performance to TWIP steels at a reduced cost.

6. MAIN APPLICATION FIELD OF TWIP STEELS

Compared to other advanced high-strength steel grades with similar tensile strength, such as TRIP, dual phase, and precipitation-hardened steels, TWIP steels exhibit significantly higher ductility, strain hardening exponent, and more extended formability. This suggests that high-manganese TWIP steels have substantial potential for automotive applications. TWIP steels are primarily targeted for automobile body components due to their exceptional mechanical performance and high strength-to-weight ratio. Their excellent energy absorption capacity and toughness make them well-suited for crash-safety applications.

The lightweight design of vehicles is a key strategy for improving fuel efficiency and reducing emissions, making TWIP steels an attractive choice for automotive components. Some specific automotive applications of TWIP steels include:

- Structural components: Roof rails, side impact beams, A- and B-pillars, door beams, front and rear rails,
- Crash management systems: Bumper beams, energy absorbers, crush cans,
- Chassis components: Suspension arms, control arms, knuckles, shock tower.

In addition to the automotive sector, the excellent mechanical properties of TWIP steels have garnered attention in other industries, opening up a wide range of potential applications for these advanced high-strength steels. The high strength and ductility of TWIP steels also make them suitable for industrial applications such as:

- Pressure vessels and storage tanks,
- Shipbuilding,
- Defense and military equipment.

7. CONCLUSION

TWIP steels emerged as prospective automotive structural materials over a decade ago when the 1991 POSCO patent and subsequent research highlighted their exceptional combination of strength and ductility. Among the advanced high-strength steel grades available for the automotive industry, this class exhibits the highest elongation, reaching up to 50-60%, albeit at strengths not exceeding 900-1100 MPa. Modifications to the steel chemistry have resulted in changes to their properties, which nonetheless remain the most favorable in terms of the ductility range achieved to date, motivating automakers to explore the potential of TWIP steel for vehicle applications.

The desirable characteristics of TWIP steels originate from the twinning-induced plasticity effect, which enhances their work-hardening behavior and formability. To achieve the fully austenitic microstructure required, TWIP steels necessitate a sufficient amount of manganese. Additional elements, such as carbon, silicon, and/or aluminum, are also necessary to ensure high strength and elevated uniform elongation associated with strain-induced twinning. Stacking fault energy is a key factor governing the mechanical properties of high-manganese alloys and plays a crucial role in the occurrence of twinning phenomena and the TWIP effect, with low stacking fault energy being a prerequisite for twinning initiation.

Despite some limitations, such as the high production costs due to the elevated alloy content and low yield strength, TWIP steels have garnered significant attention in the automotive industry due to their exceptional combination of high strength and ductility. These steels are already being employed in the automotive sector and are expected to see increased adoption, particularly in critical safety components like the auto body-in-white, where their unique strength-ductility balance and high energy absorption offer clear performance advantages to enhance passenger protection.

The industrial-scale production of TWIP steels has been realized in the past decade, with POSCO and other steel producers introducing commercial grades like TWIP-980. However, the high alloy content and manufacturing challenges have hindered their widespread adoption, prompting research into cost-reduction strategies, such as partial substitution of manganese. Looking forward, the ongoing development of third-generation advanced high-strength steels may provide comparable performance to TWIP steels at a lower cost, further expanding the application potential of these materials in the automotive sector and beyond.

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