Austenite Stability

Subjects: Others

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The austenite stability represents the potential of metastable austenite grains in resisting the martensitic phase transformation under an applied either thermal or mechanical driving force.

Keywords: Austenite ; Martensite ; Martensitic transformation ; Transformation-induced plasticity ; Advanced high strength steels

1. Introduction

Steels have been the working horse for the automotive industry since the 1920s. However, their share in automobiles is decreasing due to the competition from other materials, including Al alloys [1] and even wood [2] . The specific strength of steels may not be as competitive as other structural materials owing to its relatively high density (~7.8 kg/cm^3). Although the density of steels can be effectively reduced by alloying of the lightweight element such as Al, it easily reaches a limit (~13 wt.%) beyond which undesirable brittle intermetallic compound is formed [3] . Nevertheless, the specific strength of steels can be largely increased by elevating their strength through engineering defects, such as boundaries (grain, twin, and interface) [4][5][6] , dislocations [7], and precipitations [8]. However, the introduction of defects frequently deteriorates the ductility, which is known as the trade-off between strength and ductility [9].

Steels can be made strong and ductile by properly utilizing the transformation-induced plasticity (TRIP) effect [10][11]. Moreover, the toughness and formability of steels can also be improved with the assistance of the TRIP effect [12][13]. This TRIP effect plays a pivotal role in developing the advanced high strength steels (AHSSs) [14], including the TRIP-assisted steel [15], maraging TRIP steel [16], medium Mn TRIP steels [17][18], quenching and partitioning (Q&P) steels [19][20], and carbide free bainite (CFB) steels [21] . Austenite is the common phase in the above AHSS and is the source of the TRIP effect. The retained austenite is metastable and could transform to martensite during plastic deformation, leading to the operation of the TRIP effect to enhance the work hardening behavior. Although the hardening induced by the TRIP effect is obvious, the underlying mechanism is still under debate. Generally, there are three possible explanations for the TRIP effect, including the generation of new dislocations [22] , dynamic strain partitioning [23] , and localized stress relaxation [24] . It is reported that the direct contribution of the TRIP effect to the plasticity of steels is expected to be small [25], which may suggest that the timing for the operation of the TRIP effect is pivotal for mechanical properties of steels containing austenite. Both exhaustion of the TRIP effect at small strain and suppression of the TRIP effect at large strain are undesirable for the mechanical properties. The timing for the operation of the TRIP effect is governed by the mechanical stability of austenite grains.

An individual austenite grain is separated from other counterparts by its grain boundaries. The austenite grain interior is distributed with various defects including the interstitial/substitutional atoms, dislocations, and possibly twin boundaries (Figure 1). The above defects including the grain boundaries affect the austenite stability. These defects are inherent to the single austenite grain, intrinsically affecting its stability, and thus could be termed as the intrinsic factors. In contrast, the adjacent grains may also affect the stability of interested austenite grain via stress/strain partitioning, thus the effect associated with the adjacent grains is termed as the extrinsic factors (Figure 1).

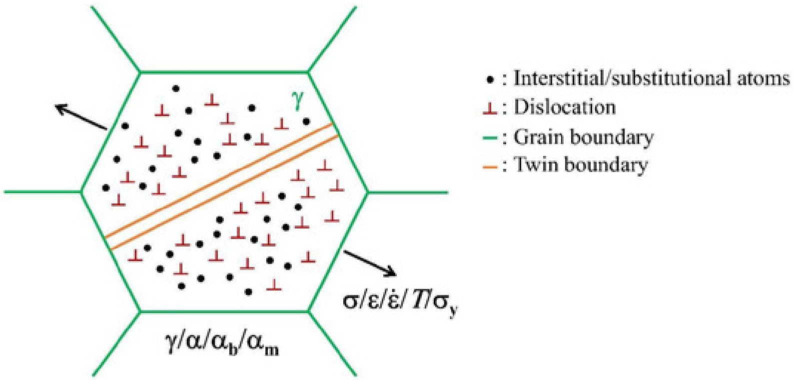

Figure 1. Schematic illustration of the intrinsic and extrinsic factors in governing the austenite stability. *γ*: austenite; *α*: ferrite; α_b: bainite; α_m: martensite; *σ*: stress; *ε*: strain, d*ε/dt*: strain rate; *T*: temperature; σ_y: yield strength.

2. The Factors Govern Austenite Stability

The austenite stability can be separated into the thermal stability and mechanical stability, defined based on the external driving force (cooling or stress). Here, thermal stability and mechanical stability of austenite are not differentiated because they can be equivalent to each other on the aspect of energy. Moreover, both thermal and mechanical stability can be affected by intrinsic and extrinsic factors. The extrinsic factors such as the stress from adjacent grains owing to varied thermal expansion ratio may affect the thermal stability of austenite during the cooling process [26] . The intrinsic factors are related to the austenite grain domain defined by its grain boundaries, including interstitial/substitutional atoms (chemical composition), dislocations, and grain boundaries (grain size/morphology) (Figure 1). The extrinsic factors are those applied by adjacent grains, involving the stress/strain partitioning, strength of the matrix, stress state (i.e., hydrostatic pressure), grain orientation, and strain rate (i.e., adiabatic heating) (Figure 1).

3. Prospect

The austenite stability in steels is governed by intrinsic and extrinsic factors. The deformation twins, which are observed in the austenite grains with proper stacking fault energy [27] , can be classified as the intrinsic factors affecting the austenite stability. However, the influence of the deformation twins on the austenite stability is not clear yet. It is reported that the intersection of two deformation twins acts as the nucleation site of martensite [28][27][29]. From this aspect, the deformation twins are expected to facilitate the nucleation of martensite. However, the deformation twins may inhibit the growth of the martensite by acting as barriers for the glissile austenite/martensite interface, which is similar to the mechanical stabilization of austenite controlled by the dislocations [30] . It has been postulated that the growth of martensite could be advanced by generation and coalescence of new embryos [31] . In this case, the nucleation rather than the growth dominates the martensitic transformation kinetics. However, the detailed mechanism of the effect of the deformation twins on the austenite stability should be substantiated by the systematic experiments and modeling works.

The combined effect of intrinsic and extrinsic factors on the austenite stability is systematically evaluated by experiments on different steel grades. However, the corresponding modeling work is still lacking in general. By incorporating the influence of chemical composition and deformation temperature in terms of free energy on the martensitic transformation, the evolution of austenite volume fraction to plastic strain can be predicted by a mathematical model [32]. Nevertheless, the other governing factors such as the morphology and stress partitioning are difficult to incorporate in this mathematical model. The numerical method that considers the geometry of grains may be useful to capture the effect of varied factors on the austenite stability. The phase-field modeling may advance the understanding of the growth of martensite [33][34]. The crystal plasticity finite element method (CPFEM) has been demonstrated to be capable of investigating the influence of austenite kinematic stability on the transformation and deformation of duplex stainless steel [35]. It is believed that the micromechanical modeling or the CPFEM may be helpful to identify the effect of austenite stability on the mechanical behavior of the third AHSS, although the development of an appropriate constitutive law in capturing the austenite stability is generally challenging currently. The integration of phase-field modeling and CPFEM may bring insights into the understanding of the effect of different factors on the austenite stability.

The governing factors on austenite stability are separated into intrinsic and extrinsic factors, which successfully rationalizes the observation that, the stronger, the more ductile in certain alloys with grain refinement and high dislocation density. In other words, the competition between the intrinsic factors and extrinsic factors in affecting the austenite stability can be utilized to overcome the strength–ductility trade-off in steels containing metastable austenite grains. Although a few experimental works have been performed to use the synergy of dislocations and grain size in affecting the austenite stability, the application of this novel alloy design strategy should be extended to improve the mechanical properties of the third AHSS. Besides, the modeling work on the synergy of the defects in affecting the austenite stability, and thus the mechanical properties of steels, can provide insights into thermal-mechanical processing to answer the questions such as, what is the optimal dislocation density or grain size to reveal the potential of austenite stability in achieving the best properties for engineering applications. Such an effort is meaningful as it fully utilizes the defects without resorting to the additional alloying, enabling high-performance steels for applications in resource-limited earth.

4. Conclusions

The factors governing austenite stability are separated into intrinsic and extrinsic factors based on the domain of individual austenite grains. The intrinsic factors include the chemical compositions, dislocations, grain size, and morphology, while the extrinsic factors include the stress/strain partitioning, stress state, strength of the matrix, orientation, and strain rate. The effectiveness of these factors in affecting the austenite stability is discussed and can be evaluated by different techniques (i.e., tensile test, nanoindentation test, dilatometry test, magnetization test, and in situ techniques). A new alloy design strategy that involves the competition between the intrinsic and extrinsic factors through the same microstructural features such as grain size and dislocations in affecting the austenite stability is proposed. It is suggested that the design of the AHSS containing austenite should consider these intrinsic and extrinsic factors to fully optimize the austenite stability to enable the great potential of the TRIP effect in enhancing the mechanical properties.

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