KARABUK UNIVERSITY

International Iron & Steel Symposium

APRIL 02-03-04, 2012

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RECENT DEVELOPMENTS IN ADVANCED HIGH STRENGTH SHEET STEELS FOR AUTOMOTIVE APPLICATIONS: AN OVERVIEW

David K. Matlock[a*], John G. Speer[a], Emmanuel De Moor[a], and Paul J. Gibbs[a,]
[a, *] Advanced Steel Processing and Products Research Center, Colorado School of Mines Golden, CO 80401
E-mail: dmatlock@mines.edu, jspeer@mines.edu, edemoor@mines.edu, pgibbs@mines.edu

Abstract

In recent years there has been an increased emphasis on the development of new advanced high strength sheet steels (AHSS), particularly for automotive applications driven by needs for vehicle weight reduction to improve fuel economy and for materials which lead to enhanced crash performance and passenger safety. Steels of current interest involve novel alloying and processing combinations to produce unique microstructural combinations and have been referred to by a variety of identifiers including, among others, DP (dual-phase), TRIP (transformation induced plasticity), HSLA (high strength low alloy), CP (complex phase), TWIP (twinning induced plasticity), and martensitic steels. The properties of these multi-phase steels are derived from appropriate combinations of strengthening mechanisms, the basics of which have been well developed in the steel literature. Continued developments of AHSS steels, designed for specific applications, will require careful microstructure control to optimize the specific strengthening mechanisms responsible for the desirable final properties. In this paper recent AHSS developments are examined, and approaches to produce high strength sheet steels with unique strength/ductility combinations are discussed.

Keywords: AHSS, retained austenite, quenching and partitioning

1. Introduction

Throughout the world there is increasing interest in the development of new Advanced High Strength Steels (AHSS) with enhanced combinations of strength and ductility to provide sheet materials for demanding applications in future vehicles. Correspondingly, research is ongoing at universities, research institutes, and companies to assess different processing routes that have been identified for the production of new sheet steel grades. Significant literature is evolving which describes the fundamentals associated with new steel developments and suggests processing routes to achieve desired properties. In this paper, excerpts from three recently-published papers from the ongoing work at the authors' laboratories are presented to illustrate the status of current AHSS developments. The papers highlighted are:

"Strategies for Third Generation Advanced High Strength Steel Development," reference [1]

"Austenite Stability Effects on Tensile Behavior of Manganese-Enriched-Austenite Transformation-Induced Plasticity Steel," reference [2]

"TRIP Steels - Historical Perspectives and Recent Developments," reference [3]

2. Strategies for Third Generation Advanced High Strength Steel Development [1]

2.1. Historical AHSS Developments

Current commercially applied AHSS steels have evolved from significant early work on Dual-Phase steels in the late 1970's and early 1980's, and Figure 1, a classic figure from the work of Rashid and Rao [4], shows the effects of intercritical annealing followed by quenching on the mechanical properties of a conventional HSLA steel. Data shown include a plain carbon steel, a HSLA steel (SAE 980X), and the same SAE 980X steel after intercritical annealing and quenching to produce a dual-phase steel (referred to as GM980X). In contrast to the HSLA steel, the dual-phase (DP) steel exhibits continuous yielding and a significant increase in elongation with essentially the same ultimate tensile strength.

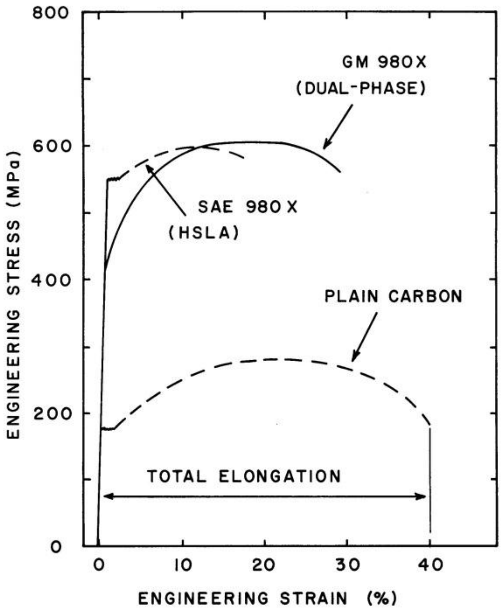


Figure 1. Comparison of the stress strain curve for a dual-phase steel with those for a plain carbon steel and an HSLA steel [4].

The combination of continuous yielding with an increase in strength while maintaining or improving ductility generated significant interest and extensive research on DP steels [5-7]. One important finding, as illustrated in the data in Figure 2, was the contribution of retained austenite on the deformation behavior of DP steels. Specifically, it was observed [8] that DP steels contain retained austenite and that the ductility of DP steels increased with an increase in retained austenite content. The data in Figures 1 and 2 illustrate the basis on which new developments in AHSS for automotive applications, particularly transformation induced plasticity (TRIP) steels, are based.

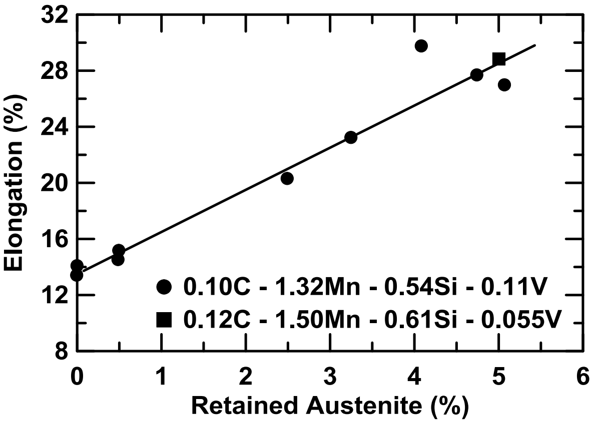


Figure 2. The effects of retained austenite on the ductility of two low carbon dual-phase steels [8].

2.2. Current AHSS Grades [1]

The importance of AHSS is highlighted by the growth of the use of AHSS in North American vehicles illustrated in Figure 3 which shows the amount (both actual and projected) of AHSS in vehicles for the period of 1975 to 2020 [9]. The use of AHSS increased to approximately 8 % in 2011 and is projected to increase to approximately 15 % of the total vehicle weight by 2020. The significant increase in the use of AHSS reflects economic design improvements to enhance both safety and fuel economy.

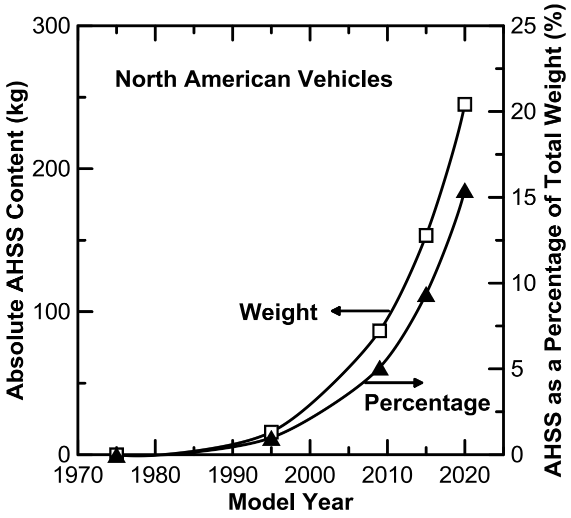


Figure 3. Actual and projected changes in the absolute amount and percentage of the total weight in North American vehicles [9].

In addition to DP steels, AHSS grades that are currently being applied or are under increased investigation by steel suppliers, include Complex Phase (CP) and TRansformation Induced Plasticity (TRIP) steels. These three steel grades are referred to as “first generation” AHSS. The austenitic stainless steels, Twinning Induced Plasticity (TWIP) steels, lightweight steels with induced plasticity (L-IP) and shear band strengthened steels (SIP) are referred to as “second generation” AHSS. An overview of representative tensile properties, compared to those exhibited by conventional steel grades, is shown in Figure 4 [10,11]. The first generation AHSS concepts were developed in fairly lean compositions and are primarily ferritic-based multi-phase microstructures. DP steels are currently the most applied AHSS grades. Interest in DP steels results from improved strength and formability, good weldability, relative ease of processing, and availability [12].

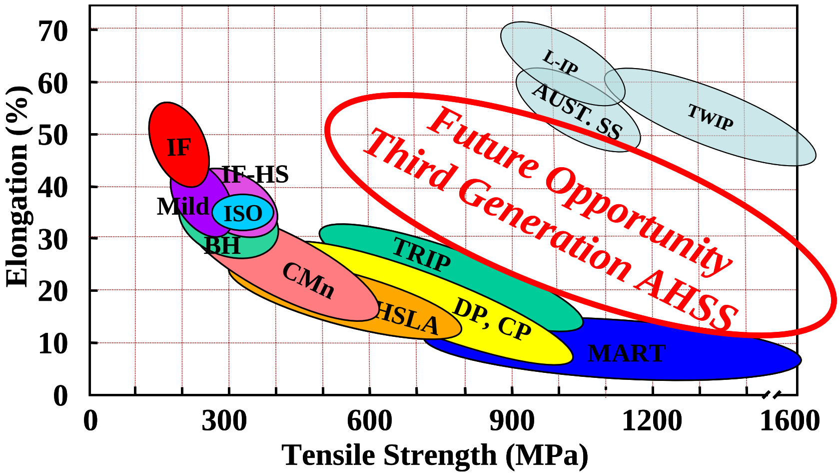


Figure 4. Overview of tensile strength and total elongation combinations for various classes of conventional and advanced high strength sheet steel (AHSS) grades [10,11].

Enhanced strength/elongation combinations are clearly obtained for TRIP steel grades where strain-induced transformation of retained austenite into martensite results in increased strain hardening. The second generation AHSS steels clearly exhibit superior mechanical properties, but these austenitic grades are highly alloyed resulting in a significant cost increase. In addition, industrial processing of these alloys, specifically the TWIP steels with high manganese contents, has shown to be extremely challenging and the TWIP grades have also been shown to be prone to delayed cracking [13]. Recent research indicates that the embrittlement susceptibility can be reduced by aluminum alloying, although the exact mechanism involved is still under investigation [13]. From Figure 4 it is clear that a property gap exists between the currently available AHSS grades of the first and second generations and defines a property band for future “Third Generation” AHSS. Current research is hence focused on filling this property window using modified or novel processing routes where special attention should naturally also be given to industrial feasibility and cost effectiveness [1, 2, 14].

2.3. Design Considerations for Third Generation AHSS

Potential production of third generation AHSS requires a systematic design methodology to identify specific combinations of microstructural constituents that lead to properties within the opportunity band shown in Figure 4. Design considerations for third generation AHSS have been discussed recently using a simplified composite model [10, 15, 16]. Example martensite/ferrite and martensite/austenite microstructures were considered. The results of the calculations obtained by varying the relative phase fractions in hypothetical microstructures are shown in Figure 5 with the individual data points corresponding to fixed relative phase fractions superposed on the property combinations shown in Figure 4. It should be noted that the ductility values obtained from the model are uniform elongations and the model input parameters were obtained from the literature [17-19]. Fully stable austenite was assumed in the results shown in Figure 5, *i.e.* absence of transformation of the austenite during straining. It is clear that the predicted tensile properties for the hypothetical ferrite/martensite microstructures overlap with the properties exhibited by the first generation AHSS. The property band corresponding to the austenite/martensite mixtures is situated between the bands of the first and second generation AHSS, *i.e.* within the desired "third generation" regime.

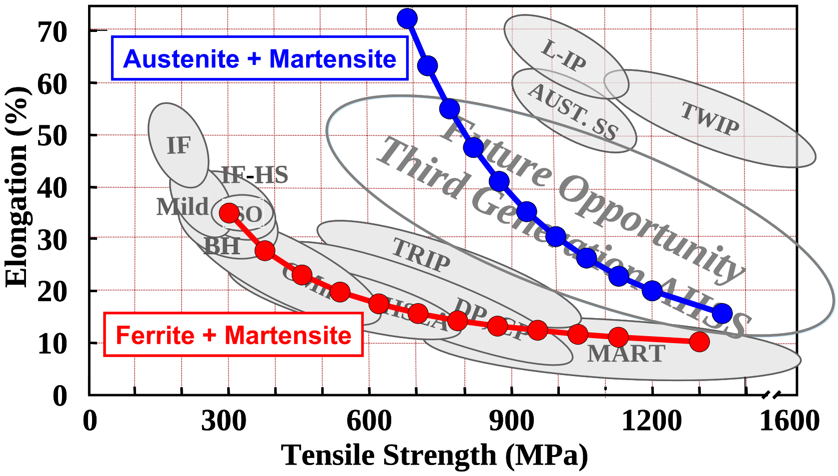
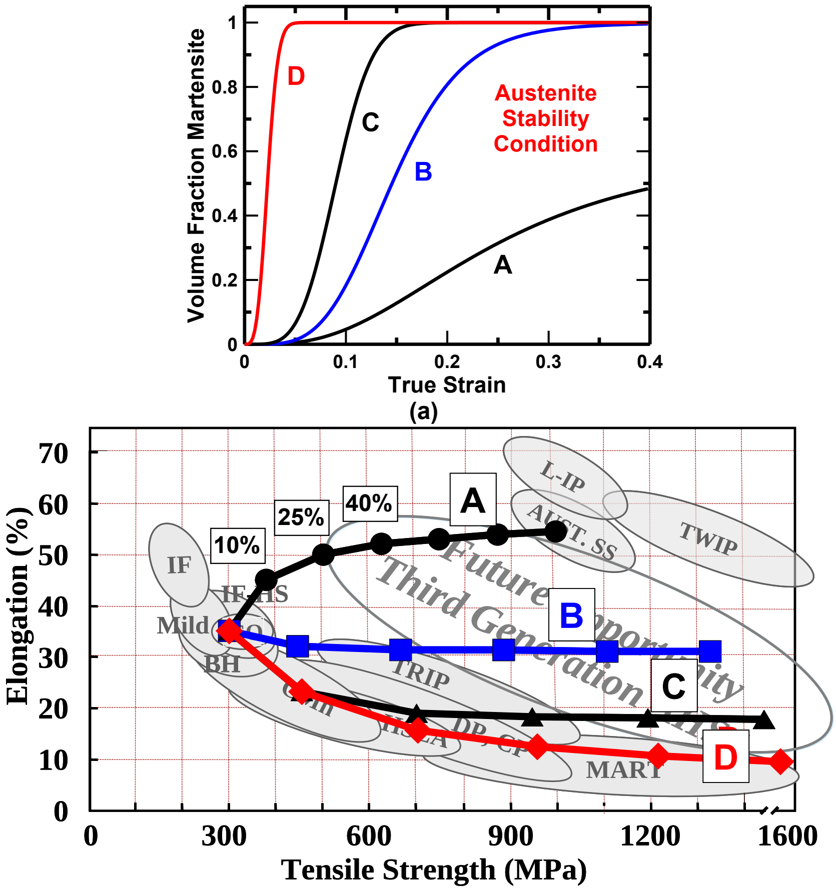


Figure 5. Superposition of predicted strength/ductility combinations of hypothetical ferrite/martensite and austenite/martensite mixtures [10, 15]. The assumed constituent properties (UTS in MPa/uniform strain) were: ferrite, 300/0.3; austenite, 640/0.6; and martensite, 2000/0.08 [17-19].

In a second step of the modeling effort, transformation of metastable austenite with strain was included [15]. Four hypothetical austenite stability conditions were considered as illustrated in Figure 6a. The resulting strength/elongation combination predictions are given in Figure 6b where the different austenite stability conditions are indicated by letters A through D and the individual data points on each curve correspond to different initial austenite contents (assumed to range from 0 to 85%), with the remainder of the microstructure being ferrite.

Austenite stability clearly has a pronounced effect on the predicted properties. The lowest stability (condition D) leads to martensite formation at low strains and properties which overlap with the first generation AHSS band indicating that the austenite does not significantly contribute to improved properties. The best combinations of strength and ductility are predicted for high volume fractions of relatively stable austenite (curve B in Figure 6b). Simplified assumptions were made in this model and additional work is ongoing to develop more refined models [20, 21]. However, this fairly straightforward approach provides an understanding of the contribution of the individual constituents and suggests that, in order to obtain the next generation of AHSS steels, complex microstructures are needed consisting of significant fractions of high strength phases which may be martensite, bainite or ultra fine grained ferrite, in combination with highly-ductile austenite with controlled stability against transformation of austenite to martensite with strain.



(b)

Figure 6. Effect of austenite stability on predicted mechanical property combinations for (a) four different austenite stabilities identified as A through D and (b) predicted mechanical property combinations corresponding to ferrite plus austenite with the different austenite stabilities shown in (a). In (b) each data point on each curve corresponds to an initial austenite fraction, ranging from 0 to 85% [15].

2.4. Next Generation AHSS Development Approaches

Ongoing AHSS research is focused on increasing strength and/or ductility to higher levels than exhibited by the first generation AHSS without significantly enriching the alloy compositions, or is aimed at reducing the alloying levels in second generation AHSS grades. An overview of some of the strategies being pursued has been presented [1] and is briefly reviewed here. These strategies include: processing to enhance properties of DP steels; modifications to traditional TRIP steel processing; development of high strength steels with ultrafine bainitic microstructures; implementation of new processing routes including quenching and partitioning (Q&P); and development of high Mn content TRIP steels. The proposed compositions used in the different processing paths compiled from literature are summarized elsewhere [1] and the resulting tensile properties are plotted on a total elongation versus tensile strength diagram in Figure 7a. The solid and dashed lines in the figure are the ferrite-martensite and austenite-martensite property predictions from Figure 5 respectively, shown for reference. It should be recognized that different sample geometries were used in the various studies and thus some care is needed when comparing mechanical properties. The various sample geometries used are also summarized in [1].

In an effort to enable better comparison of the data generated from the disparate sample geometries represented within prior investigations, the tensile ductilities reported in the literature were adjusted according to ISO 2566/1-1984(E) [22] with the Oliver formula [23] so that the normalized properties correspond to a single specimen geometry. The values were converted to correspond to those of the standard ASTM E8 geometry with a 50.8 mm (2 inch) gage length, 12.7 mm (0.5 inch) width and 1 mm thickness. Adjustment of elongations to a single consistent gage length resulted in the strength-ductility map shown in Figure 7b which is significantly different from the one shown in Figure 7a. Many of the samples which displayed high strength/ductility combinations had short and/or circular gage lengths. After adjusting to predict properties characteristic of a standard sample geometry, many of the results coincided with the ranges exhibited by other materials. However, after replotting the data, selected studies clearly show properties at the upper boundary of the property band. The different alloying and heat treating approaches associated with Figure 7 are introduced in the following paragraphs and a complete discussion of each is presented elsewhere [1].

2.4.1. Enhanced DP Steels

An increase in strength of Dual Phase steels can be readily obtained by increasing the martensite volume fraction by altering carbon content and/or intercritical annealing temperature [15]. In this way, DP780 and DP980 have been developed and are currently available commercially. A strength increase has also been obtained by microstructural refinement resulting from special hot deformation practices [24-32], one of which is referred to as Deformation Induced Ferrite Transformation (DIFT) [32].

2.4.2. Modified TRIP Steels

Early TRIP steel research was performed on grades with higher carbon contents than currently used in commercially available grades. Matsumura *et al*. investigated 0.4CMnSi grades [33, 34] and it is apparent from Figure 7 that the high carbon level results in properties that merit consideration in the context of third generation AHSS objectives. Grain refinement of TRIP steels by microalloying has also been investigated [35-37]. Tensile strength levels up to 1 GPa with ductility levels of about 20 % total elongation have been obtained as shown in Figure 7.

2.4.3. Ultrafine Bainite

Recent work has been conducted to create ultrafine bainitic microstructures [38-46]. Theoretical calculations have identified alloys that can be processed at low temperatures leading to interesting strength-ductility combinations. For example low transformation temperatures in the range 125-325 °C were employed in a 0.98C-1.89Mn-1.46Si-1.26Cr-0.26Mo-0.09V alloy (in wt pct) which exhibited 600HV hardness and strength in excess of 2.5 GPa. The microstructure was obtained after a 15 day heat treatment, a time which may be too long for industrial purposes and thus further work has been done on increasing bainite kinetics, reducing heat treatment to hours rather than days by alloying with Al and/or Co [43, 47].

2.4.4. Quenching and Partitioning

Quenching & Partitioning (Q&P) has been proposed recently as a new way of producing martensitic steels containing enhanced levels of retained austenite [48-50]. The process, shown schematically in Figure 8, consists of a two step thermal treatment where the steel is quenched to a predetermined temperature (quench temperature, QT) in the M_s-M_f (i.e. martensite start temperature to martensite finish temperature) range to produce a partially martensitic, partially austenitic microstructure. The second, so-called partitioning step, aims at carbon enrichment of the austenite by (partial) carbon depletion of the martensite and carbon transport to the austenite. Thus, carbon stabilized austenite is retained in the microstructure after final quenching to room temperature. Partitioning can be done at a higher temperature than the QT, so-called two-step Q&P, or by holding at the quench temperature, one-step Q&P. The addition of molybdenum retards bainite transformation kinetics and has been shown to increase the retained austenite volume fraction whereas aluminum substitution for silicon has been found to accelerate the bainite reaction, and reduce the retained austenite fractions [51]. High retained austenite fractions are believed to result in improved strength and ductility as shown in Figure 7 [52-55]. Mechanical properties reported from a recent industrial trial are also shown in Figure 7 [56].

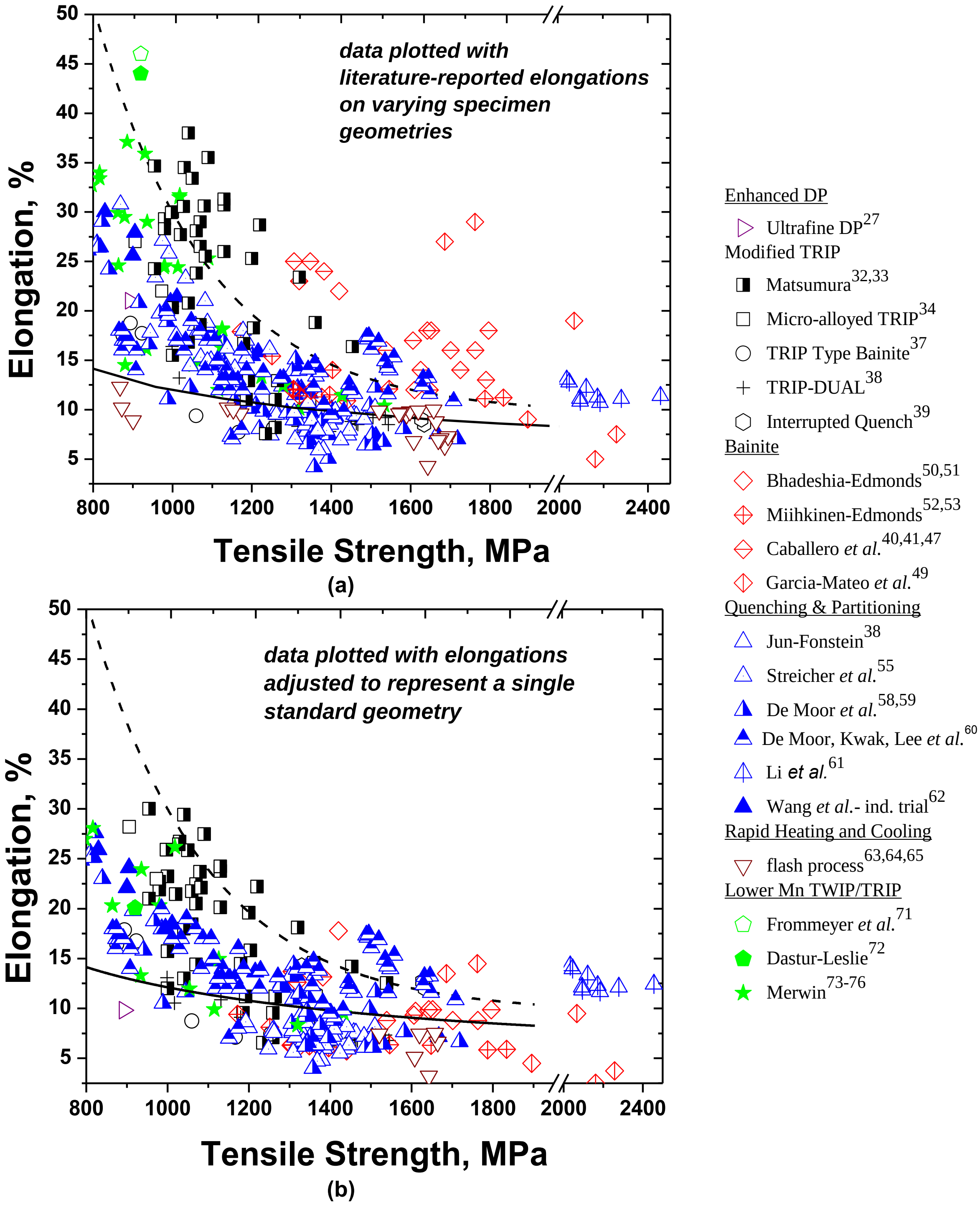


Figure 7. Overview of total elongation and tensile strength combinations obtained by different approaches [1]. a) data as reported and b) same data adjusted to ASTM E8 standard specimen geometry. The predicted uniform elongation results for martensite/ferrite (solid line) and martensite/austenite mixtures (dashed line) from Figure 5 are also shown for reference. The reference citations for the specific data sets in this figure refer to reference numbers found in reference [1].

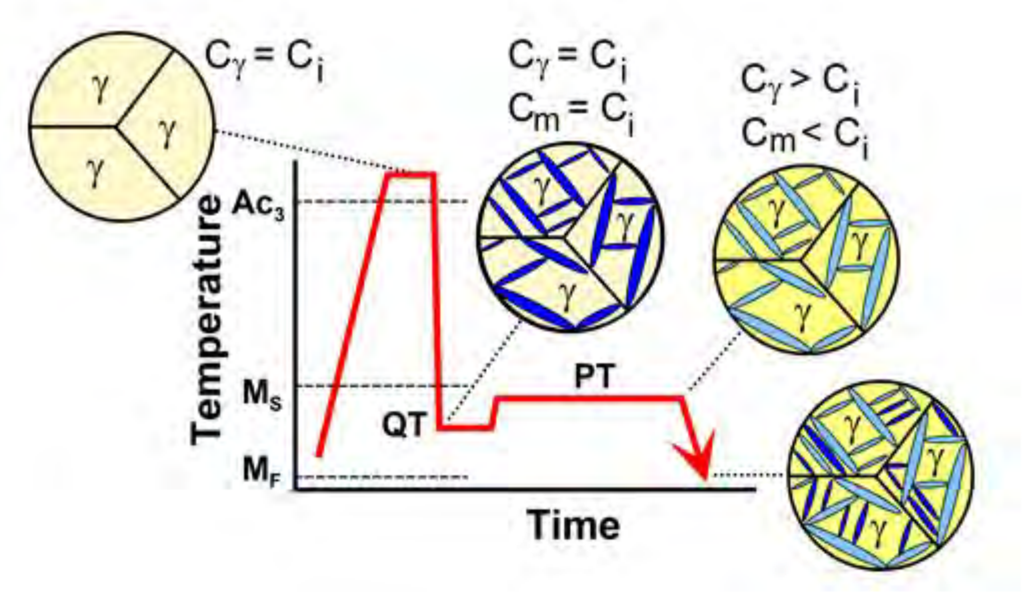


Figure 8. Schematic of the Q&P process for production of austenite-containing microstructures starting with 100% austenite: C_i, C_γ and C_m respectively represent the carbon contents of the initial alloy, austenite, and martensite [50]. Other Q&P heat treatments start with intercritically annealed steel in which the starting microstructure consists of austenite and ferrite [49].

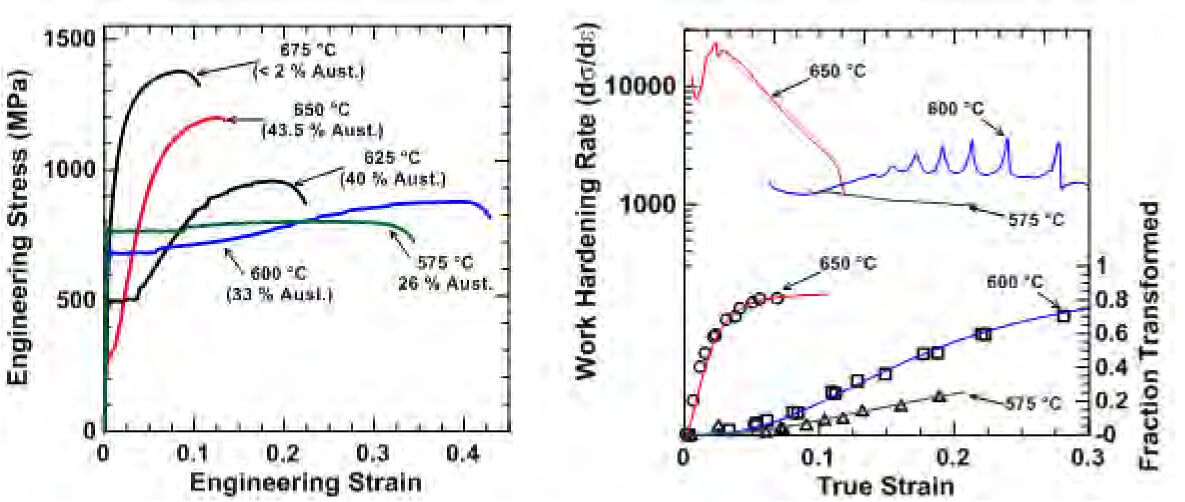
2.4.5. Lower Mn TWIP/TRIP

A variety of compositions have been proposed for the second generation austenitic steel grades, including (in wt pct): 15,20,25,30Mn-2,3,4Si-2,3,4Al-0.01,0.02,0.03,0.04,0.05,0.06C [57], 27Mn-0.02C [58], 30Mn-3Al-3Si [59], and 16,18,19Mn-6,7,8,10Cr-0.25C-0.080,0.100,0.150,0.200N [60]. Some of the current research is focusing on reducing the alloying content in these grades [61]. Some of the resultant properties combinations are also given in Figure 7.

2.4.6. High Mn TRIP

An alternative processing concept has been proposed by Merwin [62-65] based on earlier work by Grange and Miller [66, 67] to produce fine grained or ultra fine grained duplex ferrite-austenite microstructures based on “medium” manganese (5-7 wt pct), low carbon (0.1 wt pct) compositions. Manganese enrichment of austenite during intercritical annealing was recently applied to a cold rolled 0.1-C 7.1-Mn (wt pct) steel to produce a range of microstructures with varying austenite fraction and stability [2, 63]. Based on equilibrium thermodynamic predictions samples of the steel were annealed for 168 hr at temperatures between 575 °C and 675 °C [2, 68]. The long annealing times were employed to facilitate Mn partitioning. The resulting microstructures included between 2 and 43 pct retained austenite in a fine grained ferrite matrix (between 0.9 and 1.5 μm). Ambient temperature tensile properties varied with annealing temperature, shown in Figure 9a, and ranged from high yield strength with limited work hardening (675 °C), to a high ductility steel (600 °C), to a steel with relatively low work hardening (575 °C).

Figure 9b compares the strain induced austenite transformation kinetics, as measured with *in situ* neutron diffraction, to the observed tensile work hardening behavior. There is a strong correlation between the strain dependence of the work hardening rate and austenite transformation behavior, where regions of high work hardening are associated with significant austenite transformation. The sample annealed at 600 °C displayed substantial austenite transformation at strains above approximately 0.1, where martensite formation was able to effectively delay necking and increase elongation. The correlations in Figure 9b illustrate the importance of austenite stability on tensile properties, reinforcing the observed trends discussed in conjunction with Figure 6 above.



(a) **(b)**

Figure 9: (a) Engineering stress-strain curves for a 0.1C, 7.1 Mn (in wt pct) steel annealed for 1 week at indicated temperatures, and (b) fraction of austenite (initial fractions shown in Figure 9a) transformed with strain as observed with in-situ neutron diffraction experiments on samples along with the strain dependence of the work hardening rate; adapted from [2].

3. Summary

This paper has highlighted recent developments leading to the production of the third generation of advanced high strength sheet steels (AHSS) which will be required in future light-weight, fuel-efficient vehicles. The basic principles for these developments were shown to evolve from early dual-phase and TRIP steel research in the late 1970's and early 1980's. The importance of controlling austenite stability and volume fraction in order to produce high-ductility TRIP steels was emphasized as a critical aspect in the growth of new third generation AHSS. Achievement of desired final microstructures in both coated and uncoated products requires control of a large number of variables including alloy content, starting microstructure, annealing temperature prior to cooling, time at temperature, heating and cooling rates, and incorporation of additional thermal cycles. It is important to note that alloy designs have been based primarily on low carbon steels due to welding considerations. Modifications to weld designs or joining processes may allow the use of higher carbon equivalent grades in the future, enabling new process/product concepts that are considered infeasible at present. With the extensive current research activities leading to new AHSS products, the challenges to researchers, steel producers, and designers are to identify and optimize promising alloys and processing routes to minimize the time required for economic implementation of new AHSS products in vehicles of the future.

4. Acknowledgements

The authors gratefully acknowledge the support of the National Science Foundation through award number CMMI-0729114 and the sponsors of the Advanced Steel Processing and Products Research Center, an NSF industry/university cooperative research center at the Colorado School of Mines.

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