A Review: Production of Third Generation Advance High Strength Steels

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Abstract— To fulfill the requirement for steel with higher strength while retaining its formability, advanced high strength steels (AHSS) was developed. Several authors worked on the first generation AHSS steels with Dual phase structure and successfully achieved high strengths as compared to conventional counter-parts but could not achieve good formability. Several authors worked to overcome this problem and substantially improved the ductility and strength by forming second generation AHSS. However, DP steels were not formed (in second generation). Second generation steels (included ASS, TWIP steels etc.) were dependent on expensive alloy additions and were not cost effective. Authors became successful in achieving good strength and ductility but because of alloying, the weldability suffered. Finally, a few authors have reported their work on third generation AHSS, where first generation dual phase steels have been modified through suitable alloy additions to improve formability, strength and toughness. Work has been reported where carbon has been reduced to improve weldability. There is extremely limited work has been done for production of dual phase multipurpose steels with controlled cooling.

Key words: Inter-critical annealing, Ultra-fast cooling, Upper-critical annealing, Controlled cooling

I. INTRODUCTION

The automotive industry aims at the production of vehicles with low weight, fulfilling high requirements concerning safety improvement, reduced fuel consumption and limitation of emission of harmful exhaust gases. In order to meet these demands, improvements in the known materials and searching new materials with high ratio of strength to weight and good suitability for metal forming operations are still being carried out (Meng *et al*., 2009). The special groups of interest are steels of multiphase structure. They exhibit superior strength-ductility balance compared to conventional steels and also the required formability. These are sheets of the ferritic / martensitic structure or ferritic / bainitic structure (Dual Phase-DP), ferritic / bainitic structure with retained austenite showing TRIP effect (TRIP steels) and complex multiphase structure (Complex Phase-CP). The interest in respect of the suitability for metal forming operations is also connected with high-manganese steels of austenitic structure. To strengthen these steels, mechanical twinning during the technological deformation is used (TWIP effect – Twinning Induced Plasticity). These all steels are called advance high strength steels (AHSS) (Adamczyk and Grajcar, 2006; Bhattacharya, 2006).

II. ADVANCED HIGH STRENGTH STEELS

As urban pollution goes on, petroleum consumption increases and the global climate changes year by year, the demand for automobiles with fewer emissions and higher fuel efficiency never stops. Aside from the development of new power generation system which is costly (i.e. hybrid-electric vehicles), technologies that promise improvements in fuel economy include improved aerodynamics, advanced transmission technologies, tires with lower rolling resistance, and reduction of vehicle weight. Among all other technologies, reduction of vehicle weight is believed to be the most promising technology responsible for significant improvement in fuel economy in the future (Hulka, 2003). For example, 1 percent mass reduction yields up to 0.66 percent improvement in fuel economy. As a result, developing lighter weight vehicles has become more and more important to the automotive industry over the years. Reduction of vehicle weight can be achieved by technology improvements in many ways, such as materials, structural design, as well as the functional efficiency of vehicle systems or components. These aspects have been fulfilled by AHSS but still there is a need of further developments in these steels (Hao, 2011).

A. *Developments in Advanced High Strength Steels*

Early efforts to obtain lighter weight and enhanced crash performance in vehicles were aimed at the development of high strength low alloy (HSLA) steel. This kind of conventional high strength steel (HSS) has a tensile strength of 250 to 800 MPa as shown in Figure 1.1. However, the tradeoff between strength and ductility limited the performance of HSLA steels. To fulfill the requirements for steel with higher strength while retaining its formability, advanced high strength steels (AHSS) were developed during mid-1990. AHSS, as defined by Bhattacharya (2006), refer to steels with 500 MPa or more tensile strength and complex microstructures comprising of phases such as bainite, martensite and retained austenite. The strengthening mechanisms involved in AHSS include solid solution strengthening, precipitation strengthening, grain refinement and phase transformation. There are three generations of AHSS based upon the microstructure of steels (Hao, 2011; Matlock *et al., 2012*).

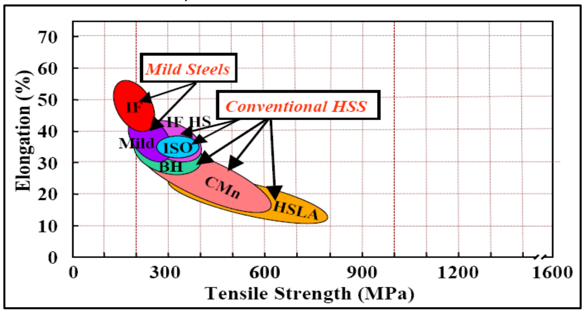

Fig. 1: Tensile strength and elongation data for mild steels and conventional HSS
(Hao, 2011)

B. *First generation AHSS*

The first generation of AHSS are ferrite based steels, including dual-phase (DP) steels, martensitic steels (MS), complex-phase (CP) steels and transformation induced plasticity (TRIP) steels as shown in Figure 1.2. Although the strength level for the first generation of AHSS is far beyond that of the conventional HSS, its limited formability and weldability remained a problem (Hao, 2011; Matlock *et al*., 2012).

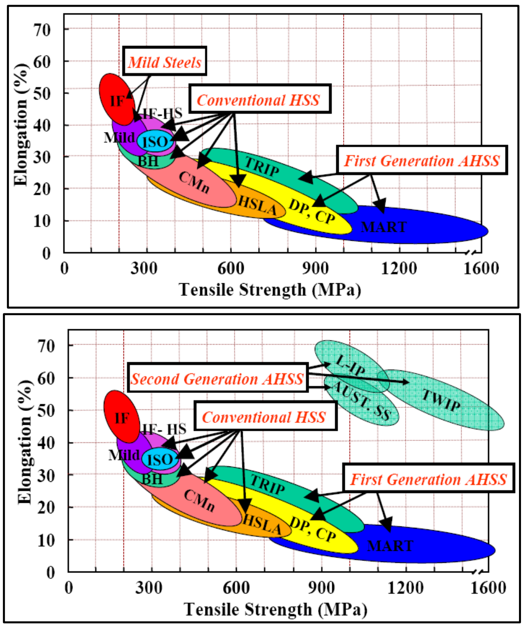

Fig. 2: Tensile strength and elongation for (a) mild steel, conventional HSS and 1stGeneration AHSS (b) various classes of conventional and AHSS (Hao, 2011)

C. Second Generation AHSS

A desire to produce materials with significantly higher strengths has led to the development of a "second generation" of AHSS which are austenitic steels with high manganese contents and are closely related to conventional austenitic stainless steels. During the past few years, a second generation of AHSS has been developed based upon an austenitic microstructure. Twinning-induced plasticity (TWIP) steel, light weight steel with induced plasticity (L-IP) and shear band formation-induced plasticity (SIP) steel are different grades in this category. A ductile austenite matrix provides better formability to the second generation of AHSS than the first generation. However, the high austenite stabilizer content, such as 20 percent manganese and nickel, limits the use of the second generation of AHSS because of its high cost (Hao, 2011). 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. Figure 1.2 summarizes the tensile strength and total elongation data for conventional HSS and the 1st and 2nd generation of AHSS (Hao, 2011; Matlock *et al*., 2012).

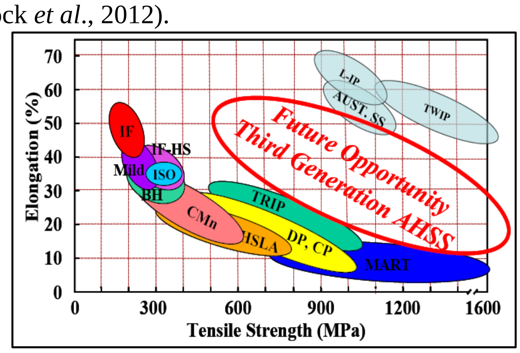

Fig. 3: Tensile strength and elongation for various classes of conventional steels and AHSS (Matlock *et al*., 2012)

D. Need for Third Generation AHSS

Despite the growing market for AHSS, the trade-off between strength and formability of the AHSS remains the limitation for its application in the automotive industry which requires new vehicle with stylistically and aerodynamically optimized shapes and safety (Bhattacharya, 2006; Hao, 2011; Matlock *et al*., 2012). According to Figure 1.3, the conventional HSS provides steels with total elongation in the range of 10 to 50 percent, but the tensile strength of the steels are all below 800 MPa. Most of the first generation of AHSS has tensile strengths greater than the conventional HSS. However, their ductility drops to as low as 10 percent when the tensile strength reaches approximately 1000 MPa (Hao, 2011). Although the second generation of AHSS solves the problem caused by competition between tensile strength and total elongation (Figure 1.3), the high cost for this solution remains the main obstacle for its broad application. Recently, the need to develop AHSS with a range of properties that give engineers more flexibility in selecting an ideal grade of steel for any given application has raised increasing interest in developing a third generation of AHSS (Hao, 2011; Matlock *et al*., 2012). The design of the third generation of AHSS is intended to produce steels with a better combination of strength and ductility than the first generation of AHSS and at a lower cost than the second generation AHSS. The mechanical properties of the third generation of AHSS are intended to fall within the gap between the first and second generation of AHSS (Figure 1.3), e.g. 1000 MPa tensile strength and 30% elongation. In order to reduce the cost, lean alloy steel compositions will need to be used in developing this generation of AHSS. Because microstructure determines the behavior and performance of AHSS steels, the design and control of the microstructure becomes essential for the third generation of AHSS (Hao, 2011; Matlock *et al*., 2012).

The combination of high strength and ductility that is providing modern AHSS can allow thinner components to be used in the car construction and also to improve the safety due to their high energy absorption capabilities. The better formability of AHSS compared with conventional high strength steels of comparable strength give the automobile designers a high degree of flexibility to optimize the component geometry (Bhattacharya, 2006; Hao, 2011; Matlock *et al*., 2012).

E. Third Generation AHSS

From Figure 1.3 it is clear that a property gap exists between the currently available AHSS grades (first and second generations) and defines a property band for the 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. Third generation AHSS are the extension of first generation steels by improving mechanical properties through grain refinement (Bhattacharya, 2006; Hao, 2011; Matlock *et al*., 2012). Concurrently with the use of micro-alloyed sheet, steels with a microstructure consisting of at-least two different phases can lead to higher strength without deterioration of ductility. These so called multi-phase steels offer attractive combinations of strength and ductility as a result of the different mechanical properties of the microstructural components and their interaction. The ‘‘third-generation’’ AHSS steels should demonstrate the strength–ductility combination significantly better than exhibited by the former (first generation) but need a cost significantly less than required for the latter (second generation). The strategies being pursued for the ‘‘third-generation’’ AHSS steels 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 ultra-rapid heating and cooling; and development of high-Mn content TRIP steels. Among them, most prominent ones are the dual phase (DP) and the TRIP steels (Hulka, 2003; Li *et al*., 2013).

III. TRANSFORMATION-INDUCED- PLASTICITY STEEL

High-strength transformation-induced-plasticity aided multiphase steels (TRIP steels) have received much attention as these steels have excellent combination of strength and ductility due to the martensitic transformation of retained austenite during plastic deformation. This is a much more cost-effective process than the inter-critical annealing process. In TRIP steels, austenite stabilizers are present (mainly carbon and manganese). During cooling, some austenite transforms to ferrite. The remaining retained austenite transforms to martensite / bainite during plastic deformation (Hulka, 2005; Bhattacharya, 2006; Hao, 2011; Matlock *et al*., 2012). Due to their high carbon content, high alloy and manganese content, these steels show limited weldability and formability. So, dual phase steels are a good option for investigation from third generation AHSS (Hulka, 2003; Metlock *et al*., 2012).

IV. DUAL PHASE STEELS

The greatest prospect of application in automotive industry is of DP-type steels. It is predicted, that their total share in a car structure can reach over 50%. These steels usually contain 0.05–0.2% C, 1.2–1.6%Mn, 0.03–0.6%Si and micro additions of V, Nb and Ti upto concentration of 0.1%. DP-type sheets can be produced by a classical heat treatment, consisting in their austenizing at a temperature slightly higher than A_{C1} of the steel followed with water quenching or an energy-saving technology of the thermo mechanical treatment, integrating hot-rolling in the austenitic field or $\alpha + \gamma$ region with direct cooling (Adamczyk and Grajcar, 2006; Bhattacharya, 2006; Lorusso *et al.,* 2012; Mohrbacher, 2013).

Microstructure of dual phase steels is composed of soft ferrite matrix and 10–40% of hard mastensite or matrensite-austenite (M–A) particles or bainite as the third phase. This type of microstructure allows achieving an ultimate tensile strength in the range of 500–1200 MPa. For some applications, also baintic constituent may also be desirable in the DP steel microstructure. This dual phase type of microstructure can exhibit the following advantageous features over the conventional high strength steels:

The strength of DP steel microstructure is controlled by the amount of and ductility by the size and distribution of martensite phase

- DP steels do not exhibit yield point elongation
- DP steels possess low YS/UTS ratio (around 0.5) and high strain hardening characteristics (high *n* value), especially at the beginning of plastic deformation
- They can be strengthened by static or dynamic strain ageing (BH effect)
- Grades containing low carbon content have been shown to exhibit excellent resistance to fatigue crack propagation

A very important consideration in the development of DP steels is the effect of carbon and other alloying elements. The effect of alloying is summarized in Table 1.1.

The microstructure of DP steels does not allow obtaining a high value of plastic strain ratio value r_m. This means that these steels are not good candidates for applications that require high drawability. They usually exhibit poor hole expansion ratio values. This drawback, however, can be eliminated by adding Ti with the aim of inducing the precipitation strengthening in ferrite to reduce the differences in hardness between the two phases. Alternatively, M-A constituents may be replaced by bainitic phase. Dual phase steels can be welded with all conventional welding methods currently used in the automotive industry (resistance spot welding, laser welding, arc welding). The most important feature influencing mechanical properties of dual-phase microstructure includes shape, size, amount and distribution of ferrite and martensite, the carbon content of martensite, and the volume fraction of retained austenite (Patel *et al.,* 2001; Kuziak *et al.,* 2008).

The mechanical properties of Dual Phase steels are controlled by metallurgical factors, such as the volume fraction of martensite and ferrite phases, the carbon content of martensitic phase, the grain sizes of the martensite (Calcagnotto *et al.,* 2010) and ferrite and the individual resistances of both martensitic and ferritic phases. The resistance factor is also affected by the chemical composition of steel (Lorusso *et* al., 2012).

A. Production of Dual Phase Steels

The development of DP steels has attracted great interest in the automobile industry, because of a potential weight reduction by using inexpensive alloying without sacrificing mechanical properties (Saleh and Priestner, 2001). DP steel mainly consists of two phases viz. ferrite and martensite. But, in addition to martensite, the microstructure may contain small amounts of other phases such as retained austenite, new ferrite, pearlite and bainite, depending on the cooling rate and thermo-mechanical processing route (Saleh and Priestner, 2001; Erdogan and Tekeli, 2002). Some of the authors have produced DP steels by direct quenching from temperature above A_{C1} temperature (i.e. inter-critical temperature). Microstructure produced was ferrite and martensite (Adamczyk and Grajcar, 2006; Demir and Erdogan, 2008).

Alloying element	**Effect of addition**
C	– Austenite stabilizer

(0.06–0.15%)	– Strengthens martensite – Determines the phase distribution
Mn (1.0–2.5%)	– Austenite stabilizer – Solid solution strengtheners of ferrite – Retards ferrite formation
Si (0.005–0.125%)	– Promotes ferritic transformation
Cr, Mo (up to 0.4%)	– Austenite stabilizers – Retards pearlite and bainite formation
V (up to 0.06%)	– Austenite stabilizer – Precipitation strengtheners – Refine microstructure
Nb (up to 0.04%)	– Austenite stabilizer – Reduces M_s temperature – Refine microstructure and promotes ferrite transformation from non-recrystallized austenite

Table 1: Effect of alloying in Dual Phase steel (Kuziak et al., 2008)

Some authors have produced DP steels by first doing slow (air) cooling upto the desired ferrite transformation from austenite and then quenching for transforming the remaining austenite to martensite (done according to CCT diagram) (Meng *et al*., 2009; Thomas *et al*., 2011).Very limited work has been reported to produce the bainite/ferrite or martensite/ ferrite microstructure of dual phase steels by first doing laminar cooling then ultra-fast cooling upto coiling temperature and then by coil cooling upto room temperature of hot rolled strip (Cornet *et al.*, 2003). Mechanical properties obtained by last method are better than all other methods due to grain refinement of microstructure and proper volume fraction of phases, constituent and properly fits in the region of third generation AHSS as shown in Figure 1.3. But in this method difficulty is to control the rate of ultra-fast cooling (UFC) and also to stop this UFC at the coiling temperature. Also, dual phase steels of ferrite/ martensite microstructure can be produced by doing ultra-fast cooling directly upto room temperature after slow laminar cooling. Mechanical properties (strength and toughness) obtained by this method are better than the properties obtained by direct water quenching (Cornet *et al*., 2003).

V. ULTRA-FAST COOLING

Ultra-fast cooling (UFC) also known as new generation thermo-mechanical controlled processing (NG-TMCP) (Yong *et al*., 2012) consists in spraying the strip with jets of water under a pressure of 4–5 bars. This cooling can be regulated in terms of cooling rate and temperature by means of the water delivery rate and the length sprayed. It allows achieving cooling rates of the order 5–10 times greater than the conventional laminar cooling tables. It is said ultra-fast cooling operation is carried out at cooling rate such that the product of thickness of the strip in mm and cooling rate in ^{o}C/s is greater than 600, and preferably greater than 800. By illustration, the ultra-fast cooling operation is advantageously carried out at a cooling rate greater than 150^{o}C/s on a 4 mm thick strip (Cornet *et al.*, 2003; Yong *et al.*, 2012).

The core concept in NG-TMCP includes:

- Achieving strain accumulation in austenite phase during the continuous rolling at relatively high rolling temperatures
- Ultra-fast cooling after rolling to keep the work hardening of austenite
- Arrest the cooling at a temperature near the transformation temperature
- Cooling route control according to the requirements of microstructure and properties of the steel (Yong *et al*., 2013)

Depending upon the final microstructures of dual-phase steel, the UFC technique has been defined in two ways: (1) early UFC and (2) late UFC. In the early UFC technique, laminar cooling follows UFC, but the strategy is reverse in the case of late UFC. Late UFC is generally achieved by a water spray and air-assisted spray cooling process, and early ultra-fast cooling is studied by air-assisted spray only. The heat transfer analysis on the above cooling processes show that air-assisted spray has an excellent control on the rate of cooling (Mohapatra *et al*., 2012).

VI. SUMMARY AND GAPS IN THE LITERATURE

- Different authors have presented different processing routes for formation of ferrite / martensite dual phase steel structure. Most of the authors have formed DP steels through the route of inter-critical annealing followed by water quenching. There are a few studies in which the dual structure has been obtained from fully austenitic state, followed by slow cooling and finally followed by quenching. Literature lacks in the use of NG-TMCP methods to produce DP steels which offer several advantages viz. fine grain structure, better dispersion of secondary phase etc.
- Several authors worked on the first generation AHSS steels with ferrite/martensite structure and successfully achieved high strengths as compared to conventional counterparts but could not achieve good formability. Several authors worked to overcome this problem and substantially improved the ductility and strength by forming second generation AHSS. However, DP steels were not formed (in second generation). Second generation steels (included ASS, TWIP steels etc.) were dependent on expensive alloy additions and were not cost effective. Authors became successful in achieving good strength and ductility but because of alloying, the weldability suffered. Finally, a few authors have reported their work on third generation AHSS, where first generation dual phase steels have been modified through suitable alloy additions to improve formability, strength and toughness. Work has been reported where carbon has been reduced to improve weldability, however dual phase steels produced still contain alloying elements viz. Ti, N, Mo, V, Cr etc. There is extremely limited literature showing production of dual phase steels with lean chemistry. There is scope of work where dual phase steels can be produced through NG-TMCP without the use of

expensive grain refining elements viz. Ti, Nb, V, Cr etc.

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