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New Trends in Advanced High Strength Steel Developments For Automotive Application

Ohjoon Kwon [a], Kyooyoung Lee[b], Gyosung Kim[c] and Kwang-Geun Chin[d]

Technical Research Laboratories

POSCO

Pohang, Korea 790-785

[a]okwon@posco.com, [b]kylee1@posco.com, [c]gkim@posco.com, [d]chinkg@posco.com

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Abstract. The body design with light weight and enhanced safety is a key issue in the car industry. Corresponding to this trend, POSCO is developing various automotive steel products with advanced performance. Conventional advanced high strength steels such as DP and TRIP steels are now expanding their application since the steels exhibit higher strength and ductility than those of conventional solution and precipitation strengthened high strength steels. Efforts have been made to enhance the mechanical performance of these steels such as ductility, hole expansion ratio, deep drawability, etc. Current research is focused on development of extra- and ultra-AHSS. Extra-AHSS are designed to utilize nano-scale retained austenite embedded in fine bainite and martensite. Ultra-AHSS are designed to have austenite as the major phase, and the ductility is enhanced primarily by continuous strain hardening generated during forming. These steels including extra- and ultra-AHSS are believed to be the next generation automotive steels which will replace the existing high strength steels due to their extremely high strength and ductility combinations.

Introduction

Various steels have been applied to the car body, and R&D is still carried out to develop more advanced automotive steels. The developing trend of these steels is summarized as shown in Fig. 1.

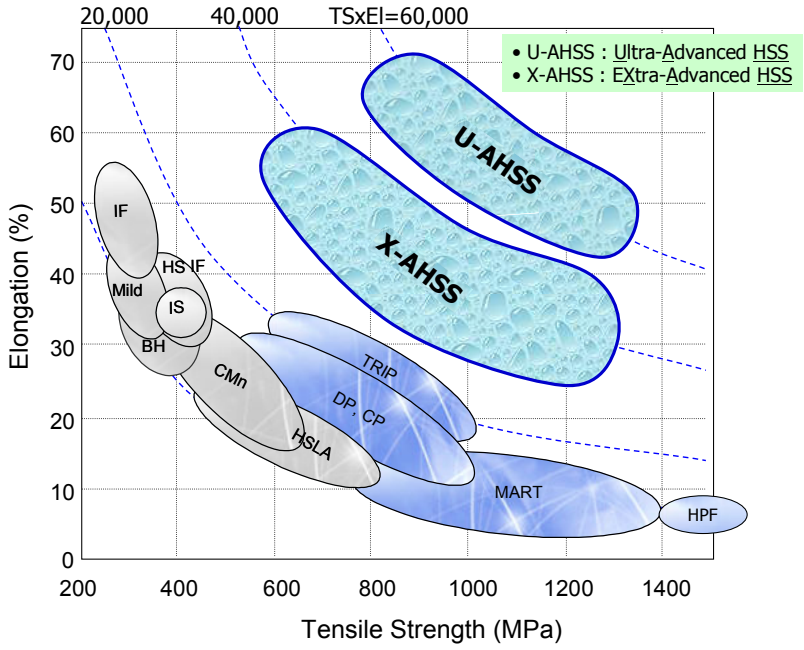

Fig. 1 Relationship between tensile strength and elongation of various steel grades

It is noted that those steels with the product of tensile strength and elongation (TS-El product) lower than 25,000 MPa·% form a banana shape loop. The steels in the banana shape loop include IF steels with or without bake hardenability, HSLA(**h**igh **s**trength **l**ow **a**lloy) steels and conventional AHSS(**a**dvanced **h**igh **s**trength **s**teels) such as DP(**d**ual **p**hase) and TRIP(**tr**ansformation **i**nduced **p**lasticity) steels. Two additional steel groups above the banana loop are shown in Fig. 1; X(e**x**tra)- and U(**u**ltra)-AHSS. These steels have extremely high strength-ductility combinations, and are believed to be the next generation automotive steels which will replace the existing mild, HSLA and conventional AHSS. In the present paper, the salient features of the characteristics of new next generation AHSS are described together with the recent development results of conventional AHSS with enhanced performance.

Conventional AHSS

The conventional AHSS is defined as a group of high strength steels with their TS-El product is lower than 25,000 MPa·%. The typical steels in this group are DP, TRIP and martensite-based complex microstructure steels which are located in the low-right part of the banana loop in Fig. 1. These steels have a long history of R&D[1,2,3,4,5,6] since the oil shock of the 1970s. R&D had been focused on how to utilize the microstructure containing the phase transformation products such as retained austenite, martensite and bainite. In addition, efforts had been made how to design the thermal cycles to generate the desired microstructure. These developments are significantly important in terms of the application of continuous annealing or galvanizing lines. Various cooling technologies have been evaluated since they are of the key tool to produce microstructure needed in AHSS. These steels are the major high strength steels which are currently expanding their application to auto parts manufacture.

A primary advantage of DP steels compared to TRIP steels is in weldability. This is attributed to the relatively low carbon content. Another advantage of DP steels is surface quality of galvanized strips. In TRIP steels where the content of Si is high, Si promotes oxidation during high temperature processing and deteriorates surface quality of galvanized strips. New technologies have been developed to improve surface quality of Zn coated TRIP steels; substitution of Si with Al, preoxidation before annealing or special alloying to retard oxide formation during annealing. The major advantage of TRIP steels lies in their enhanced tensile properties. Ductility of TRIP steels is greater than that of DP steels when two steels are compared at the same strength level. Auto parts with complicated shapes are often manufactured by using electro-galvanized TRIP steels because the surface quality problem can be avoided when electro-galvanizing is applied.

DP steels have the high potential for the exposed panel application due to lower yield strength and excellent bake hardenability. However, the lower r value of DP steel restricts the application to the outer and inner panels. It is well known that high r values are obtained through the development of strong ND//<111> texture components and, thereby, through scavenging solute carbons in the matrix[7]. According to Han et al.[8], the elaborate control of overall processes from melting to final annealing is necessary to obtain high r values. The formation of Mo carbides before recrystallization was found beneficial since the treatment insured the {111} texture component development by reducing the carbon content.

Multi-phase bake hardenable (MP-BH) steel is a type of DP steels with greater bake hardenability (≥ 70MPa) compared with ordinary DP steels[9]. This new steel incorporates a synergy of two distinct hardening mechanisms: (i) blocking of free dislocations by diffusion of interstitial atoms and (ii) hardening by second phase particles. The typical mechanical properties of MP-BH steel displays YS 355MPa, TS 592MPa, El 26% and BH 76MPa.

The addition of Si has been known to increase the elongation of DP steel[10]. Si eliminates the Mn-rich band structure of pearlite in a hot band and, thereby, induces the uniform distribution of martensite after annealing. Moreover, Si purifies ferrite by facilitating solute carbon diffusion from ferrite to austenite. Recent investigation has shown that Si addition enhanced elongation by 6% in a TS 780 DP steel.

AHSS with higher hole expansion ratio vaules has been developed to enhance stretch flangeability and bendability. This can be realized by minimizing the strength difference between the ferrite matrix and the 2^{nd} phase, and controlling the 2^{nd} phase to be finely dispersed. AHSS with bainite microstructure reveals excellent stretch flangeability together with good weldability due to lower carbon contents. However, relatively low ducitility of this type of steels compared with TRIP and DP steels restricts their use into wheel systems.

Extra-AHSS

There have recently been growing interests in TRIP steels with TS x El > 25,000 MPa·%. This group of steels are categorized as the so called X-AHSS. To meet demands of both extra high strength and enhanced formability, many investigations have been made with various metallurgical approaches in the laboratory[11,12,13,14,15,16,17].

M-TRIP(**m**artensite based **TRIP**) steel is defined as the TRIP steel with martensitic matrix. The typical process to produce this steel is the Q&P process proposed by Speer et al[11, 12]. In the Q&P process, austenite is formed at high temperature either by full austenitization or by intercritical heat treatment, which is followed by rapid cooling to a temperature between M_s and M_f to control the fraction of martensite and retained austenite. Carbon partitioning takes place to enrich the austenite with carbon during the process. The typical TS-El product value is slightly greater than 25,000 when conventional TRIP steels with lean alloying elements are Q&P processed. Annealed martensite based TRIP steels have been investigated by Sugimoto et al.[13,14]. The microstructure consists of uniformly distributed annealed martensite matrix and retained austenite. Since an extra process needs to introduce the martensite phase before final annealing, the steel would have limitation to the commercial application.

As a new concept, Bhadeshia et al.[15] proposed SB-TRIP(**S**uper **B**ainite **TRIP**) steel where nano-sized bainitic microstructure is embedded with retained austenite. In the new process, high carbon TRIP steels are heat treated at low temperature. The critical disadvantage of this process is that bainitic transformation is very sluggish due to high carbon contents and very low transformation temperature. To accelerate this sluggish transformation, Lee et al.[16, 17] investigated the effect of alloying elements on the kinetics of bainitic transformation. This steel was found to have tensile strength 1187MPa and elongation 39%. The typical fine microstructure of SB-TRIP is shown in Fig. 2.

Reverse transformation in hot rolling and batch annealing has been studied in high Mn TRIP steels since 1970s[18, 19, 20, 21, 22]. The aim of these studies is partitioning of Mn into austenite during reverse transformation and, thereby to increase the stability of austenite. Development of these steels under the continuous annealing process has recently been made[23]. The desired microstructure is obtained by precise control of the A_{c1} and A_{c3} temperature. The tensile properties of the developed steel are shown to have TS of 1100MPa and El of 29%. The TS-El product of the steel is 31,900 MPa·%, belonging to the X-AHSS group.

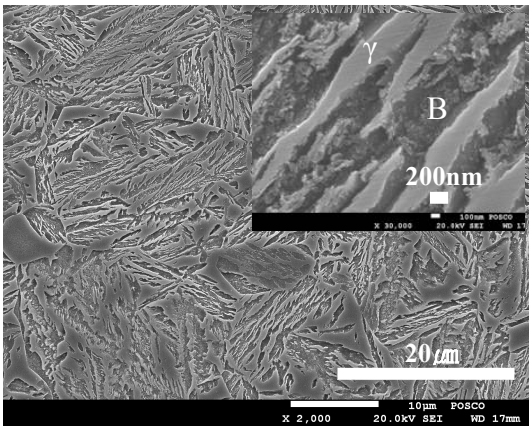

Fig. 2 Fine microstructure of SB TRIP steel only with carbide free bainite and austenite

Ultra-AHSS

In order to enhance the ductility of AHSS, it is desired to have austenite as the matrix phase. For improved ductility, it is also important to utilize transformation hardening pheonomenon and to control the mechanical stability of austenite phase properly[24]. The typical TS-El product of this group of steels is greater than 50,000 MPa·%, and the group is classified here as U-AHSS. The commercial application of the steels has been taking place in a few major steel R&D groups because of the superior strength and ductility combination[25, 26].

TWIP(**tw**inning **i**nduced **p**lasticity) is a potential mechnanism to obtain the superior balance of tensile strength and elongation, and is extensively utilized to develop steels of the U-AHSS class. TWIP steel had successfully been trial-produced at POSCO in early ´90s, but the trial was not extended to commercialization due to limitations in facilities and productivity[27]. Trial productions have also been made in a few steel companies in Europe. These attempts demonstrated the superior mechanical performance of TWIP steels, but turned out to be commercially unsuccessful presumably due to low productivity, high cost and delayed fracture. New approaches to reduce these difficulties are to be made so as to apply the steels to automotive parts manufacturer[28].

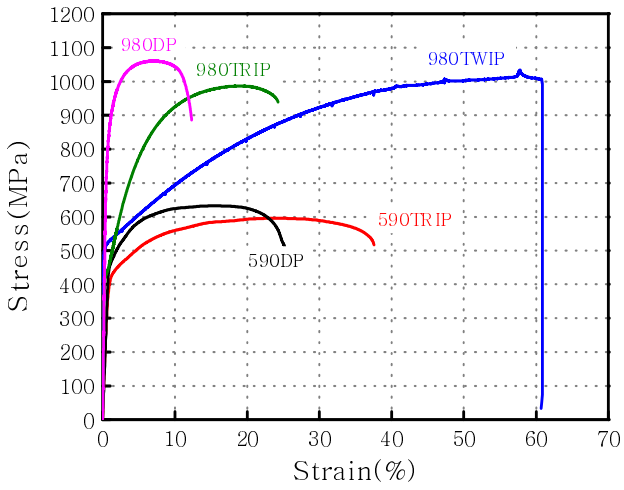

Fig. 3 Stress-strain curve of 980MPa TWIP steel compared to those of conventional advanced high strength steels.

The flow curve of a TWIP steel is shown in Fig. 3 together with the curves of a few typical AHSS. The typical value of tensile TS x El of TWIP steels is about 65,000 MPa·%, more than three times greater than those of conventional AHSS. This superior mechanical performance was obtained by gradual twinning during deformation. The formation of twins partitions austenite grains and induces the continuous strain hardening, resulting in improved ductility. The strain hardening behavior is strongly dependent on the stacking fault energy(SFE), which determines the deformation mechanism of the material. Due to lower stacking fault energy of TWIP steels, the twinning behavior is enhanced during deformation and, thereby, increases ductility.

The developments of U-AHSS with high Mn and Al by using SBIP(**s**hear **b**and **i**nduced **p**lasticity) or MBIP(**m**icro **b**and **i**nduced **p**lasticity) phenomenon have been reported[29, 30]. The SBIP behavior can be promoted by increasing stacking fault energy, which induces planar glides of dislocation without twinning. The role of Al is to increase the stacking fault energy. With the addition of high Al up to more than 5%, weight saving of these steels would be significant. The laboratory results obtaind by Yoo and Park[30] demonstrated that the TS-El product was 84,300 MPa·%.

Concluding Remarks

The importance of high strength steels is becoming more and more widely recognized since steel is the major materails to form the car body and the weight reduction is the prime concern for environmental protection. A popular tool to increase strength is transformation hardening. This is attributed to the fact that both strength and ductility can be improved by utilizing transformation hardening during deformation. Both laboratory investigations and trial productions for commercialization have extensively been made to develop transformation hardened steels for the last 40 years. As a result, application of the conventional AHSS is becoming active nowadays. DP is currently the main steel to be applied to auto parts with limited adaptation of TRIP and martensitic steels. However, the necessity of higher strength steels such as X-AHSS and U-AHSS is growing because of the government policy for greenhouse gas emmision becomes stricter.

A hurdle for commercialization of AHSS is how to secure good enough surface quality. To manufacture strips with good surface quality, the whole production processes should precisely be controlled. Typical surface defects originated from steel refining and continuous casting are sliver, scap, and so on. Extrem care should be taken in order to produce ultra clean slabs expecially for steels for outer panels. Care must also be given to the rolling, annealing and galvanizing processes. This means that integrated efforts to develop production technologies in all processing steps are critical for commercialization.

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