Development of advanced high strength steels for automotive applications

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The big issues that the automotive industry confronts are those concerned with environment and safety. The lightweighting of the autobody plays one of the key roles for the development of environment-friendly vehicles through the improvement of fuel efficiency and CO_2 reduction. Advanced High Strength Steels (AHSS) are worth noticing as the most promising materials for the weight reduction of autobody with securing the crashworthiness and cost competitiveness still more. Considering such significances of AHSS to both steel makers and car manufacturers, some recent progresses are reviewed on the development of various steel types of AHSS including TWIP steel, hot-dip galvanizing technologies to improve the coating quality, and the issues for AHSS forming technologies by illustrating the noticeable activities.

PROSPECT FOR AHSS DEMANDS

World-wide auto productions is estimated to increase by 6.2% of average annual growth up to 2020 since the economic recession in 2009, so would exceed 100 million cars in 2015 [1].

Regulations for automotive CO_2 emissions and fuel economy will become stricter in the future; the weight reduction of vehicle should be a key issue for auto industry in the conventional as well as eco-friendly cars such as hybrid and electric vehicles. Moreover, the weight implications of hybrid and electric power trains will require the lightweight materials much more. Among the various weight-saving materials including non-ferrous ones, AHSS are expected to expand rapidly as the most promising materials from the technical and economical viewpoints as shown in Fig. 1 [2]. According to that survey, the ratio of AHSS to the total automotive steels would be increased from 7% in 2009 to 28~36% in 2020, especially noticeable in Asian countries. Such a prospect could be accomplished by a progressive advance in steel and galvanizing technologies for AHSS.

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RECENT PROGRESS OF AHSS DEVELOPMENTS

There have been diverse demands for safety, fuel economy, dent resistance and comfort from the automotive industry. To meet such demands, various types of steels have been developed and applied to car bodies, and the intensive researches are still focused on developing more advanced automotive steels, which can be generally classified and categorized as shown in Fig. 2(a).

Steel sheets with TSxEl product lower than 25,000 MPa % are available in the market, such as IF steels, HSLA (High Strength Low Alloy) steels and conventional AHSS including DP (Dual Phase), TRIP (TRansformation Induced Plasticity), CP (Complex Phase), Martensitic and HPF (Hot Press Forming) steels as well. Another two groups are X (eXtra)-AHSS and U (Ultra)-AHSS. Those steels have extremely high strength-ductility balance, so could replace the conventional mild, HSLA and AHSS as next generation automotive steel sheets.

The conventional AHSS have been developed and introduced to the market [3,4,5] as illustrated in Table 1. The core technologies have been how to utilize the microstructure containing the phase transformation products such as the retained austenite, martensite and bainite, and to enhance the weldability and surface qualities for galvanizing and paintability. In addition, the diverse efforts have been made to establish the processing conditions for the desired microstructures in steel mills.
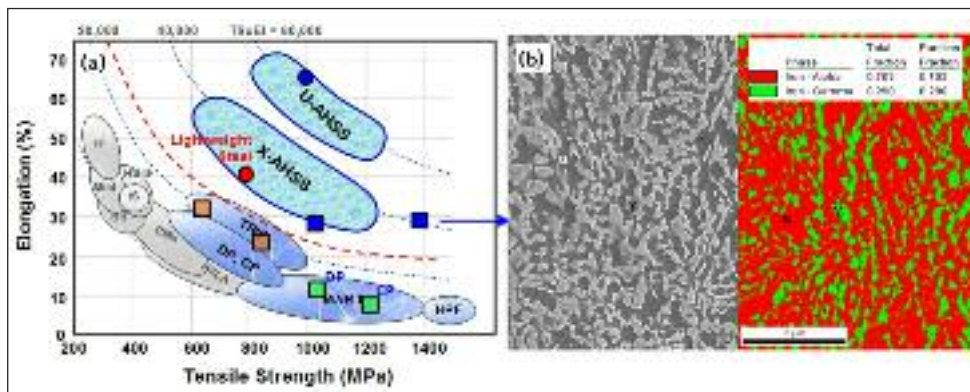
Hot rolled AHSS

It is necessary to optimize the chemical composition, rolling condition and cooling rate on ROT (Run Out Table) of hot strip mill
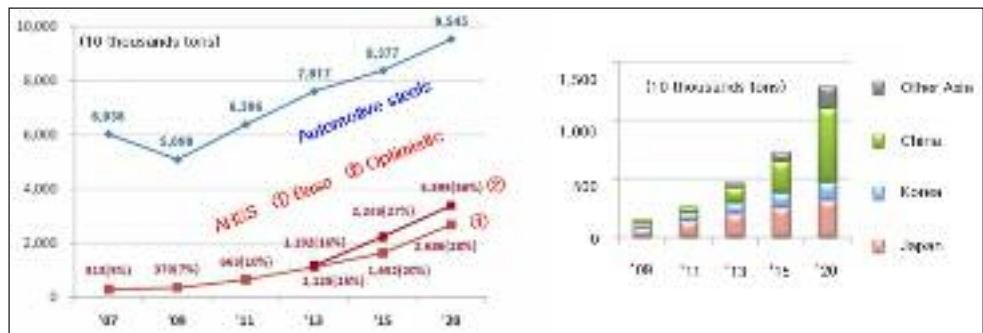
FIG. 1
Prospect of demand for automotive steels and AHSS world-wide and in Asian countries.

Domanda di acciai per l'industria automobilistica e di acciai AHSS nel mondo e nei Paesi asiatici.

FIG. 2
(a) Relationship between TS & El of various steel grades, (b) SEM/EBSD for X-AHSS.

a) Relazione fra resistenza a trazione e allungamento per diversi gradi di acciaio b) SEM/EBSD per l'acciaio X-AHSS.

Steels		■ Production tried, ❑ Commercialized Tensile Strength (Minimum TS guaranteed, MPa)								
		440	490	540	590	690	780	980	1180	1470
DP	CR/Coated	❑	■		■		■	■(L,H YS)		
	HR/PO			❑	■	❑	❑		❑	
TRIP	CR/Coated				■	❑	❑	❑		
	HR/PO						❑			
CP, HPF	CR/Coated								■(CP,HPF)	■(HPF)
	HR/PO								❑(HPF)	■(HPF)
FB	CR/Coated				❑		❑			
	HR/PO	■			■	■	■		❑	

TAB. 1 *Examples of classification and development for conventional AHSS.*

Esempi di classificazione e sviluppo per acciai AHSS convenzionali.

to obtain the proper mechanical properties of DP, FB and TRIP steels. The hot rolling of AHSS is finished above Ar3 temperature and then 2-step cooling is applied. The intermediate cooling temperature, air cooling time and coiling temperature between 100 and 500°C affect the final microstructure of hot-rolled AHSS.

DP steels use the low C-Mn-Si system, so the ferrite and martensite microstructures of 590MPa and 780MPa grades are directly obtained from the extra-low coiling temperature below the martensite transformation start temperature (Ms). For 980MPa grade, the hot strip can be coiled above Ms temperature with low C-Mn-Si-Ti-Nb-Cr system due to the increased hardenability by Cr addition. DP steels are used as wheel disk and members of chassis with a good balance of TS and El, low YR.

FB (Ferrite Bainite) steels used as low arms with a good stretch-flangeability can be produced by reducing C content and the hardness difference between matrix and 2nd phase. The low C-Mn-Nb system of 590MPa grade and low C-Si-Mn-Ti-Nb system of 780MPa / 980MPa grades are coiled below bainite transformation start temperatures (Bs) which suppresses an undesirable 2nd phases.

TRIP steels use the C-Mn-Si-Nb system, and 780MPa grade is coiled below Bs after hot rolling and 2-step cooling. During the ferrite transformation at the intermediate temperature for a few seconds holding, C diffuse out from the ferrites and enrich in the untransformed austenite. If C enrichment were not enough, martensite would form during cooling. TRIP steels show high El due to TRIP effect of retained austenite but are not widely used due to worse weldability than DP steels.
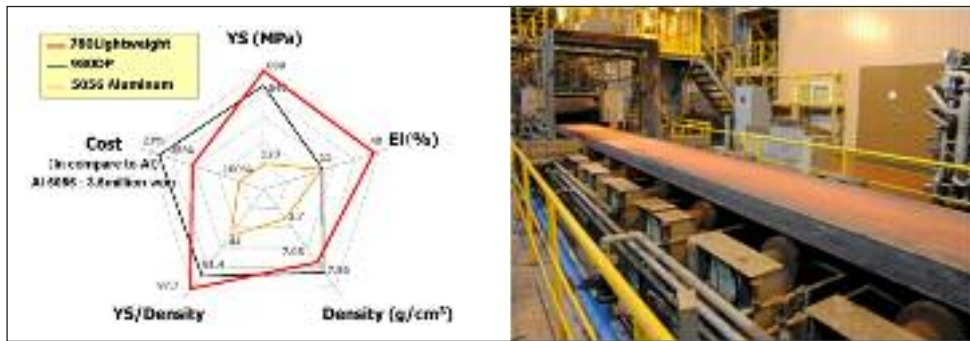
Cold rolled and annealed AHSS
DP steels with a relatively low C content with good weldability are widely used for autobodies. A recent investigation has shown that Si addition enhances El by 6% in DP steel with TS of above 780MPa because Si eliminates Mn-rich band structures of the pearlite in a hot band, and purifies the ferrite by facilitating solute C diffusion from ferrite to austenite [6]. DP steels have a high potential for the exposed panel application, but lower r-value and surface quality restrict the applications for outer and inner panels. High r-value is required for the inner panel, to increase it, Ray and Han et al. discussed how to improve {111} texture [7,8]. High surface quality and dent resistance should be assured for the outer panels, and the control of spring back is indispensable as well. Recently, DP steel with TS of 590MPa was tried for the outer panel, and the sheet thickness could be reduced from 0.7mm to 0.55mm with higher dent resistance than the conventional one. TRIP steel with higher C and Si content exhibits more challenging surface quality, galvanizability and weldability issues despite possessing good ductility. To overcome such problems, various concepts have been proposed such as the substitution of Si with Al, the preoxidation during annealing or alloying elements to retard oxidation or reducing C content. CP steel with TS of 1180MPa grade has been developed to give an improved bendability applied for the reinforcements. The microstructures are consisted of mainly bainite with small amount of ferrite and martensite due to the suppression of ferrite transformation after annealing by the additions of Cr and B. This steel is also designed to exhibit a good spot weldability and galvanizability by reducing C equivalent and Si content.

X-AHSS
There has been increased interest in TRIP steels with TSxEl > 25,000MPa•%, so called X-AHSS, so various metallurgical ap-

proaches have been made in the laboratory [9-13]. All these approaches mainly use the transformation induced plasticity of retained austenite to obtain the superior elongation. Mn and C are added to obtain a sufficient amount of retained austenite and the concept of partial reverse transformation during continuous annealing is adopted. Owing to the partitioning of Mn and C into the austenite during reverse transformation, the stability of austenite is improved. The desired microstructures can be obtained by the precise control of Ac1 and Ac3 temperature, composed of the ferrite and retained austenite grains with the size of 200 ~ 500nm as shown in Fig. 2(b). The amount of retained austenite would be about 20 to 30%, allowing attainment of TS = 1033 ~ 1389MPa, El = 27.5 ~ 28.8% and TSxEl product = 28,408 ~ 40,003MPa ? %.

The primary concept of lightweight steel for automotive steel was studied in Fe-18 ~ 28Mn-9 ~ 12Al-0.7 ~ 1.2C alloying system with higher Al content [14]. The microstructures studied by Frommeyer (Fe-26Mn-11Al-1.15C) called "TRIPLEX" consisted of the austenitic matrix with 6 to 8 vol% of ferrite and nano size κ-carbides, however new steel with lower Mn and Al content is under development whose microstructure is almost similar to the duplex type with 30 ~ 40% of austenite in the ferrite matrix. Owing to the transformation induced plasticity of retained austenite, TS = 780 ~ 830MPa and El of about 40% could be obtained, and TSxEl product was 30,000 ~ 35,000MPa %, belonging to the X-AHSS group. The density reduction reaches to 10% compared with the conventional one as shown in Fig. 3(a). Since the lowest hot ductility of lightweight steel was 67% at the temperature of 600 ~ 1200 , the continuous pilot castings were conducted with sound surface of slabs as shown in Fig. 3(b).

TWIP steel

TWIP steel is an attractive material for the lightweighting and safety requirements of vehicle parts [15], whose commercial production is recently close at hand. The developed one as denoted in Fig.2(a) represents TS = 980 MPa with El > 60%. The austenite stability is obtained by controlling the content of Mn at 15 ~ 18% and C at 0.5 ~ 0.7%. Twin kinetics can be calculated and optimized by considering stacking fault energy by addition of Al with 1.5 ~ 2.0%. Al is also beneficial element to prevent the carbide formation and to improve the resistance against the hydrogen delayed fracture [16]. The distributions of TS and El were very uniform along the length and width of the coil processed in production mill, which would be attributed by the absence of phase transformation during continuous annealing [17].

The higher Mn content of TWIP steel is well known to give a harmful effect on the hot-dip galvanizing, however, some alloying elements could modify the surface oxide layer and contribute to a remarkable progress in hot-dip galvanizing qualities as shown in Fig. 4. The alloying elements together with the process optimization in CGL help the Fe-Al inhibition layer uniform, so especially the wettability could be greatly improved and the peel-off

of coating was not observed in 0T bending test for the galvanized TWIP steel processed in CGL.

Hot press forming steel

The conventional 22MnB5 steel has been mainly used for hot press forming, which can be substituted by the newly developed one with higher Mn-N content and without Cr. The new type gives advantages in the heating temperature for the austenitization and bake hardenability (BHo) after the hot press forming. The heating temperature can be lowered by more than 50 compared to 22MnB5, and BH0 value of new type heat-treated at 850 reaches up to 160 MPa.

Hot press forming will become more widespread, also the use of Zn-based coatings. However, Zn-based coatings are easily deteriorated by the oxidation or evaporation, and susceptible to the fracture due to a liquid metal embrittlement at a high temperature [18]. A new concept of Zn coating has been proposed to overcome such problems of Zn coating for hot press forming. The main feature of new type is that the rapid and uniform Fe-Zn growth during the heating stage makes Fe-Zn layer stable with little Zn-rich area, which concerns the remarkable improvement of heat resistance during a direct hot press forming as shown in Fig. 5.

## HOT DIP GALVANIZING ON AHSS

AHSS generally contains high Si, Mn and B to obtain the mechanical properties, but such elements deteriorate the wettability due to their selective oxidation [19,20]. Various technologies have been suggested to improve the wettability, and some of them are known to be effective such as the pre-coating, pre-oxidation and dew point control. On the effect of hydrogen content under the annealing condition of DP -40°C, the amorphous S-Mn oxides were observed in N_2+10%H_2 whereas the crystalline Mn oxides were formed in 100%N_2. The annealing in 100%N_2 represented a good wettability in galvanizing, which indicates that Mn oxide is more favorable than Si oxide, because Mn oxide would be reduced easily by aluminothermic reaction during galvanizing [21]. Various type of oxides could be formed during the annealing such as Mn_2SiO_4, SiO_2 and MnO, and the pre-annealing in N_2 or air atmosphere before the annealing in N_2+10%H_2 generated the thick Mn_2SiO_4 and internal oxides, which exhibited a relatively good wettability.

Pre-oxidation for 590 TRIP Steel

TRIP steel with 0.08C-1.6Mn-1.5Si (TS 590MPa) was processed in CGL with DFF (Direct Fired Furnace) under an oxidizing atmosphere followed by RTF (Radiant Tube Furnace) under a reducing atmosphere. The uniform Al inhibition layer was observed on the reduce Fe layer attached to Si-Mn oxide in the resultant coating with a good appearance and no bare spots, which was peeled off by 0T bending followed by taping tests [22,23]. Fig. 6 shows XPS depth profiles for the peeled-off interface from the interface of steel and coating layer, which reveals that the exfolia-
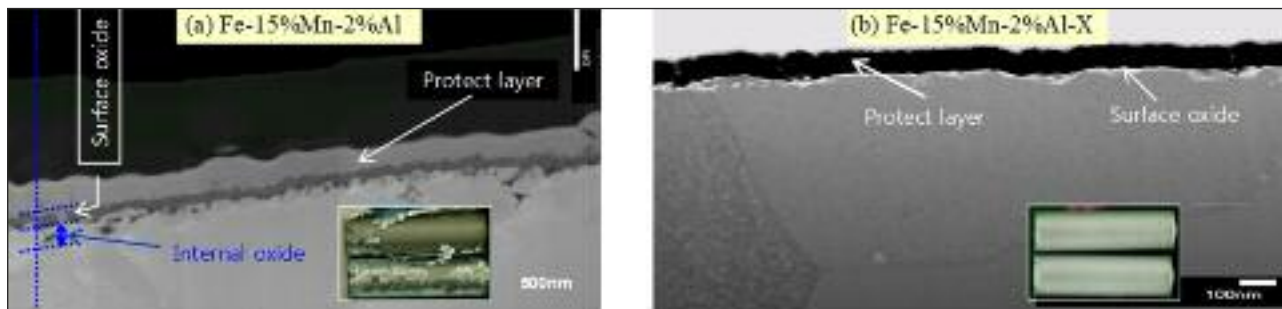
FIG. 4 *Effects of some alloying elements on surface oxide layer and coating adhesion.*

Effetti di alcuni elementi alliganti sullo strato di ossido superficiale e sull'adesione del rivestimento.
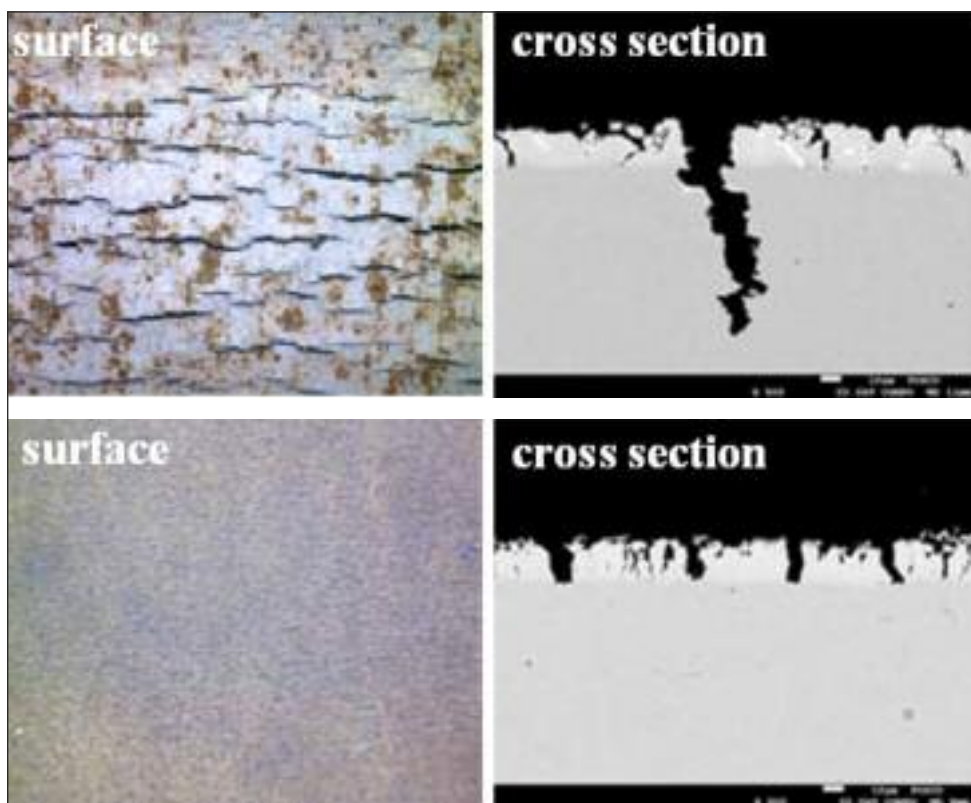
FIG. 5
Comparison of GI coating for the conventional (a) and new type (b) after hot press forming.

Confronto fra rivestimento GI per acciai convenzionali (a) e di nuovo tipo (b), dopo pressoformatura a caldo.

tion occurs at the interface of Si-Mn oxide and the reduced Fe layer. The pre-oxidation is not enough to secure the galvanizing quality for high Si-containing TRIP steel, so further study would be required to improve the coating adherence.

Effect of micro-alloying elements
Recently some researches have been focused on the oxide structures and formation affected by the trace elements in steel such as P, B, Sn, Sb and etc. [24,25]. Such elements could influence on the short-cut diffusion through the precipitation at the grain boundaries and metal surface, which would be used to control the surface oxidation. P in the grain boundaries could repulse, and suppresses the short-cut diffusion of Si through the grain boundaries. P is assumed to promote the rough Mn-P composite oxide and suppress the formation of SiO_2 on the steel surface.
The oxidation of B is very fast compared with other elements in the steelmatrix, and B is depleted in the depth of 50~100 um from the surface during annealing. Most of B near the surface is consumed for oxidation. The melting point of B_2O_3 is relatively low around 450 , and the melting point of Mn-Si-B composite oxides would be also decreased with increasing B_2O_3. The addition of B

below 10 ppm would be recommended in utilizing B for AHSS formulation, since the high content of B could arouse the poor surface quality and bare spots in galvanizing. In CGL production of 590 DP steel with 7 ppm of B, the coating quality was comparable. Sb can easily precipitate on the surface and grain boundaries, which gives the oxidation control potential for AHSS during the annealing [26]. The surface oxides were decreased and became fine and uniform by the addition of Sb.
SiO_2 and Mn_2SiO_4 formed on TRIP steel during annealing result in a poor wettability with molten Zn [27,28]. TEM images near the surface region are compared in Fig. 7 for the annealed specimens (DP -50) with the different Al content in TRIP steel (0.08C-1.7Mn-1.6Si-Al). The surface oxides were composed of SiO_2 and Mn-Si complex oxides (i.e. $xMnO\ SiO_2$) for the trace Al level, whereas only thin Mn-Si complex oxides on the surface and the internal oxides at the sub-surface were observed for medium Al level. The internal oxides were identified as Mn-Al-Si complex oxides by means of EDS. It was considered that the internal oxides formed at the sub-surface layer contributed to the reduction of external oxides, especially SiO_2 on the surface. In case of high Al level, thick $xMnO\ Al_2O_3$ and $xMnO\ SiO_2$ complex oxides were formed on the
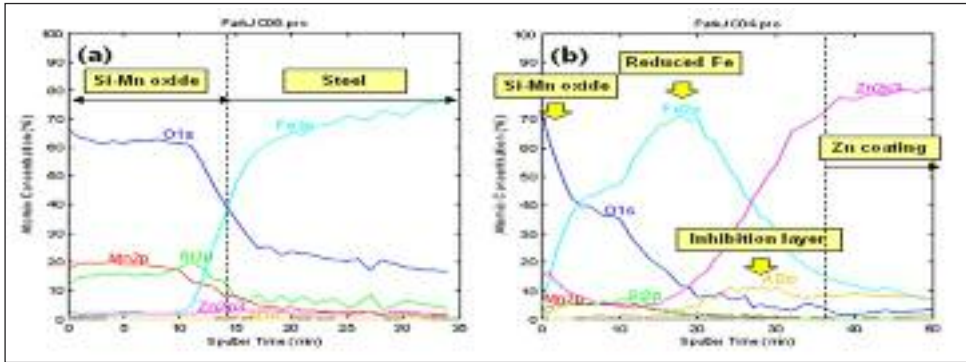
FIG. 6
XPS depth profiles for (a) steel surface side and (b) Zn coating side after peeling-off.

Profili XPS nello spessore per a) lato della superficie di acciaio e b) lato zincato dopo abrasione.
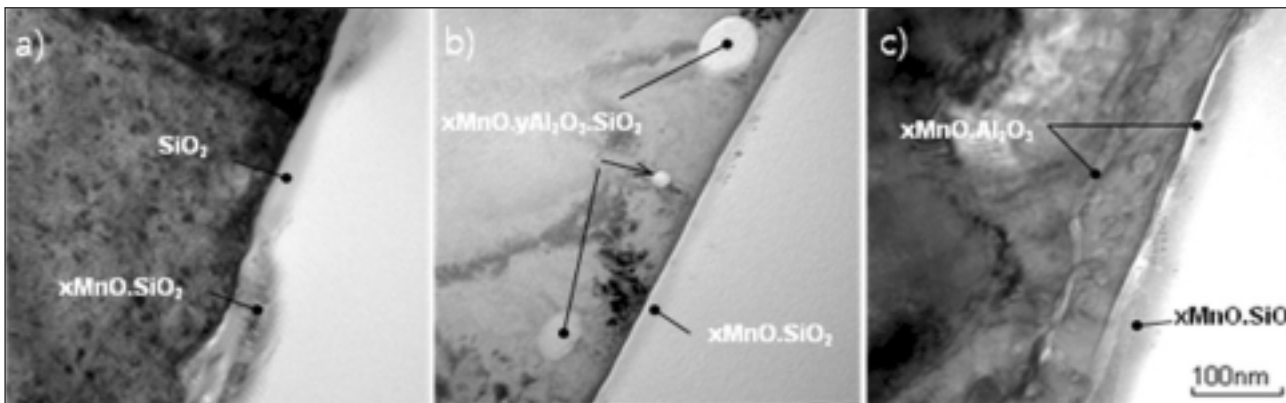
FIG. 7 *Cross-sectiona TEM images for surface oxide morphologies of TRIP steels with different Al contents; a) low level (trace), b) medium level and c) high level.*

Immagini TEM della sezione trasversale della morfologia degli ossidi superficiali degli acciai TRIP con diversi tenori di Al; a) livello basso (tracce), b) livello medio e c) livello alto.

surface, and Mn-Al internal oxides were also observed below the surface. The medium Al level exhibited a good wettability with molten Zn, which means that Mn-Si mixed oxides such as Mn_2SiO_4 and $MnSiO_3$ are more favorable than SiO_2 for hot-dip galvanizing [27].

AHSS FORMING & APPLICATION ISSUES

Some types of AHSS have higher formability than the conventional HSS within the same strength range and other types show very good stretch-flangeability with high strength, which enables to expand the utilization of AHSS for the effective weight reduction of autobody.

Several process requirements should be considered in order to secure AHSS performances, and two major recent concerns for the forming technology are a high level of springback and the occurrence of shear fracture. As many researchers have demonstrated, in general, the springback of AHSS is much greater than that of conventional HSS. Thus, the numerous process techniques such as the die and part designs have been studied to minimize the various modes of springback occurred in AHSS forming [29]. Recently, the shear fracture has started to appear with the adoption of AHSS for automotive parts. It is very difficult to predict the shear fracture on the basis of normal forming limit diagram, because its mechanism is not well understood up to now. Many researches have implemented to establish the accurate prediction of shear fracture for AHSS [30,31].

To promote the adoption of AHSS in autobody, new application technologies have been developed together with OEMs and part manufacturers from the concept design stage of auto body through the early vendor involvement (EVI) activities, from which OEMs can approach properly the optimal material selection for the weight reduction, cost saving or performance improvements.
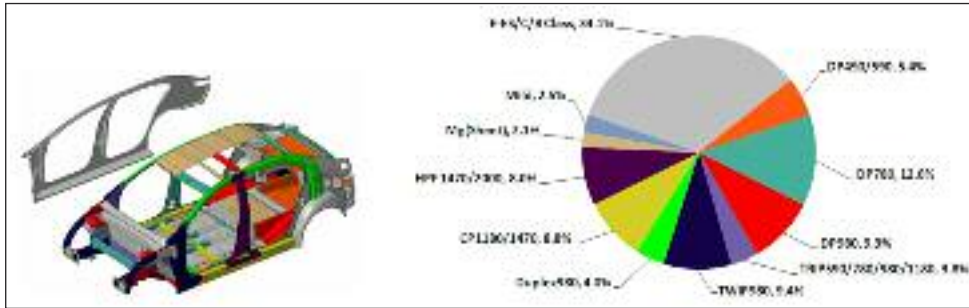
AHSS Usage in Electric Vehicle

Automotive industry is increasingly confronted with the severe requirements for the fuel economy and reduced CO_2 emission. Conventional powertrains alone are not able to cope with these aggressive targets, so automakers are well into the development of advanced powertrains and their vehicles. Recent years, the electric vehicle has become an alternative over the conventional vehicles.

The structural mass reduction of electric vehicle will be more critical than that of the conventional, which can help the battery amount and motor size reduced. The automakers are trying the various materials for the weight reduction, but AHSS is considered to be still a cost-effective material with a higher safety performance. The advantages of AHSS are well known to automotive engineers, and AHSS will allow most auomakers to maintain their tooling equipment with reducing other capital investments. Consequently, AHSS would be incorporated into nearly new electric vehicle design for the mass production. Fig. 8 illustrates the concept of a lightweight steel autobody for a electric vehicle by applying various AHSS grades, which could achieve a weight reduction of 26%.

SUMMARY

Some recent progresses are reviewed on the diverse development of AHSS, hot-dip galvanizing technologies and AHSS forming issues with some examples, which can be summarized as follows:
1. AHSS are expected to expand rapidly as the most promising

FIG. 8
AHSS usage in the autobody concept for the electric vehicle.

Utilizzo degli acciai AHSS nella carrozzeria di veicolo elettrico.

materials, for which technological progress and EVI activities with automakers would become more important in the future.

2. Various types of conventional AHSS with TSxEl< 25,000 MPa % are available in the market. X-AHSS and lightweight steels with good ductility are under development. TWIP steel will be produced commercially in the near future, and the newly-developed HPF steel with Zn-based coating will become favorable for processing conditions and product qualities.

3. Pre-oxidation is not enough to secure acceptable galvanizing quality for high Si-containing steels, therefore further improvement will be required. To utilize the alloying elements would be one of the effective approaches, which will allow remarkable progress in galvanizing TWIP steel.

4. A high level of springback and the occurrence of shear fracture should be overcome to promote the adoption of AHSS. The structural mass reduction with utilizing AHSS will become more requisite in a hybrid or electric vehicle, which benefits for the reduction of battery and motor size.

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Abstract
Sviluppo di acciai avanzati ad alta resistenza per applicazioni automotive

Parole chiave: acciaio, trattamenti superficiali

Fra le grandi questioni che l'industria automobilistica deve affrontare vi sono sicuramente quelle legate all'ambiente e alla sicurezza. Per questo motivo la produzione di componenti più leggere ha un ruolo importate nello sviluppo di veicoli rispettosi dell'ambiente attraverso il miglioramento dell'efficienze del carburante e la riduzione delle emissioni di CO_2. Gli acciai avanzati ad alta resistenza (AHSS) rappresentano la classe di materiali più promettenti per la riduzione del peso delle parti delle autovetture soprattutto per quanto riguarda la resistenza alla collisione e ancor più la competitività economica.

In virtù di queste prerogative degli acciai AHSS, significative sia per i produttori di acciaio che per l'industria automobilistica, viene presentata una rassegna di alcuni dei più recenti progressi ottenuti - per le diverse tipologie di questi acciai, compresi gli acciai TWIP – sia nelle tecnologie di zincatura a caldo, che permettono di migliorare la qualità dei rivestimenti, che nelle tecnologie di formatura, illustrando le attività più degne di nota.