

Perspectives on coated advanced high strength steels for automotive applications

D. Bhattacharya

Advanced High Strength Steels (AHSS) is the fastest growing segment of sheet products in the automotive industry. Coated (galvanized or galvanized) AHSS are the most important of this class of steels. AHSS includes various families of steels, major among them being dual-phase, multi-phase or complex-phase, TRIP and martensitic steels. Recently, Twin Induced Plasticity (TWIP) and Quenching and Partitioning (QP) steels are also becoming popular. Finally, press-hardened steels (PHS) are increasingly becoming a material of choice for many automotive manufacturers. In addition to tensile and yield strength properties, many of these steels are also required to possess other functionalities such as total and uniform elongation, sheared-edge stretch-flangeability, bendability and weldability. To achieve the combination of properties, most of these steels contain significant amounts of various alloying elements. Presence of both the alloying elements as well as the complex microstructures poses a challenge for coatability. These multi-faceted aspects of coated AHSS and their metallurgical challenges will be discussed in this paper. Mechanisms to explain coating behavior will be included as appropriate. Finally, new coatings for improved functionalities and future breakthrough products for automotive applications will also be briefly discussed.

Keywords:

AHSS, automotive, galvanized, galvanized, coatability

INTRODUCTION

Advanced High Strength Steel (AHSS) is the fastest growing segment of sheet products in the automotive industry. Two major drivers for the use of these steels in the automotive industry are fuel efficiency and increased safety performance. Fuel efficiency is mainly a function of weight, which in turn, is controlled by gauge and design. Safety is determined by the energy absorbing capacity of the steel. In addition, one further requirement is sustainability or resistance to corrosion. To meet this need, coated (galvanized or galvanized) AHSS are the most important of this class of steels.

AHSS includes various families of steels, major among them being dual-phase, multi-phase or complex-phase, TRIP and martensitic steels. Recently, Twin Induced Plasticity (TWIP) and Quenching and Partitioning (QP) steels are also becoming popular. Finally, press-hardened steels (PHS) are increasingly becoming a material of choice for many automotive manufacturers. In addition to tensile and yield strength properties, many of these steels are also required to possess other functionalities such as total and uniform elongation, sheared-edge stretch-flangeability, bendability and weldability. Consequently, these steels use various strengthening mechanisms such as solid-solution hardening, grain-refinement, precipitation strengthening, transformation strengthening and consists of a multitude of microstructures. To achieve the combination of properties, most of these steels contain significant amounts of various alloying elements. Presence of both the alloying elements as well as the complex microstructures poses a challenge for coatability.

However, it is almost impossible to discuss all the complex factors which make the production of the newer coated AHSS a challenge in an eight page paper. Therefore some AHSS such as multi-phase or complex phase steels, TWIP steels, Q&P steels, and many other factors (for example the issue of testing, effect of process parameters) have either not been discussed or the discussions are perhaps too short for a complete understanding. The author apologizes for this shortcoming.

In addition, it was not possible to discuss both the substrate aspects as well as details of coating aspects in a brief paper. Since there will be many papers on coatings at this conference, the author chose to concentrate on the substrate for AHSS and thus present the challenge the coaters would face.

AUTOMOTIVE CUSTOMER NEEDS FOR AHSS

Mechanical Properties

For details of the current specification on advanced high strength steels, the reader is referred to the SAE specification J2745. It should be noted, however, that SAE specification J2745 is only a general guideline and all customers have their own specifications. In most cases, they are much more stringent than the general SAE specification.

Strength and Ductility

The first requirement for most grades is mechanical property. AHSS are mostly specified by their tensile strength (TS). Some years ago the highest tensile strength (TS) specified for dual-phase steels was 590 MPa. However, many customers have already specified minimum TS of 780 and 980 MPa for dual phase steels. Now, there is a request to develop a 1180 minimum TS dual-phase or pseudo dual-phase steel. In the case of TRIP steels, the TS requirement has gone up from 590 MPa to 780 MPa minimum and 980 MPa is just around the corner. For the ultra-high strength AHSS such as martensitic steels, tensile strength up to and in-

Debanshu Bhattacharya

ArcelorMittal Global R&D - East Chicago, IN 46312 USA

Opening lecture presented at the 8th Int. Conf. GALVATECH 2011, Genova, 21-25 June 2011

cluding 1500 MPa is available, although interest has been expressed for such steels with as much as 2000 MPa TS. In addition, all the above grades also have a minimum and maximum yield strength (YS) specified.

For all AHSS except the martensitic steels, a minimum elongation and n value are in the specification. Total elongation requirements vary from 10% for dual-phase steels to as much as 30% for TRIP steels.

Sheared Edge Flangeability and Bendability

Many customers are increasingly interested in sheared edge stretchability or flangeability, as measured by the hole expansion ratio. They vary from 55% to 85% minimum for hot rolled steels in J2745.

Selected customers also have the requirement of meeting a certain bendability standard, in conjunction with strength and elongation.

Property Variability

In addition to target properties, SAE specifications have upper and lower limits for yield strength.

But more importantly, all customers have allowable ranges for strength as well as elongation. These are increasingly becoming narrower and hence more difficult to meet.

Weldability

The most important property need of the customer, after meeting mechanical property requirements, is weldability, since almost all the parts manufactured from these steels are welded.

The most commonly used weldability equation, based on Carbon Equivalent, is:

$$Ceq = C + Mn/6 + (Cr+Mo+V)/5 + (Ni+Cu)/15$$

Generally, Ceq should be less than 0.44 for good weldability.

Recently, however, weldability requirements have become more stringent. Many customers are now demanding a Carbon Equivalent of ≤ 0.24 based on the equation:

$$Ceq = C + Mn/20 + Si/30 + 4S + 2P$$

In addition some customers also want less than 0.10% C.

The implications of this requirement will be discussed later.

Coatability

For galvanized and galvanized steels, the quality of the coating

is extremely important. Uncoated spots and another common defect known as “wood-grain pattern” are unacceptable. In addition, the coating should have adequate adherence and powdering characteristics. Some manufacturers also ask for specific coating phase distribution and this adds another challenge to the development of these steels.

Dimension and cost

Driven by the need to reduce weight, manufacturers are demanding thinner and thinner gauges.

Furthermore, to achieve reduced cost through part consolidation, wider steel products are also needed. Both of these needs are more difficult to meet with the higher strength AHSS.

Finally, all of the above requirements must be made with a product that is cost effective with competitive materials. This is very important since otherwise the product will be a technical success but not a commercial success.

AHSS SUBSTRATE METALLURGICAL DESIGN

Metallurgical challenges faced to develop products meeting all the customer needs is complex and depends on the microstructure being employed to achieve the AHSS. Since dual-phase steels are, and, in the foreseeable future, will be the workhorse of the industry, the majority of the discussion will be on dual-phase steels. Shorter discussions will be presented on TRIP and Martensitic steels as well.

Strength and Ductility

Dual-phase Steels

Higher strength, by itself, can be achieved rather easily by either increasing the C, Mn or other alloying elements such as Nb, B or Mo or by changing the microstructure with higher martensite fraction, up to 100% fully martensitic steel. For example, the effect of C and Mn on the TS and YS of a cold rolled dual-phase steel has been reported [1]. It is clear that both TS and YS are increased by addition of C or Mn in this steel. Similarly, the effect of alloying elements such as Nb and B on strength properties [2] shows again both TS and YS increase with addition of these alloys.

The problem is not strength but simultaneously meeting strength, elongation and hole expansion requirements, in particular when the customer need is for higher and higher strength in combination with increased ductility. The relationship between strength and ductility is very complex and depends not only on the relative amounts of each alloying element but also on the microstructure of the steel.

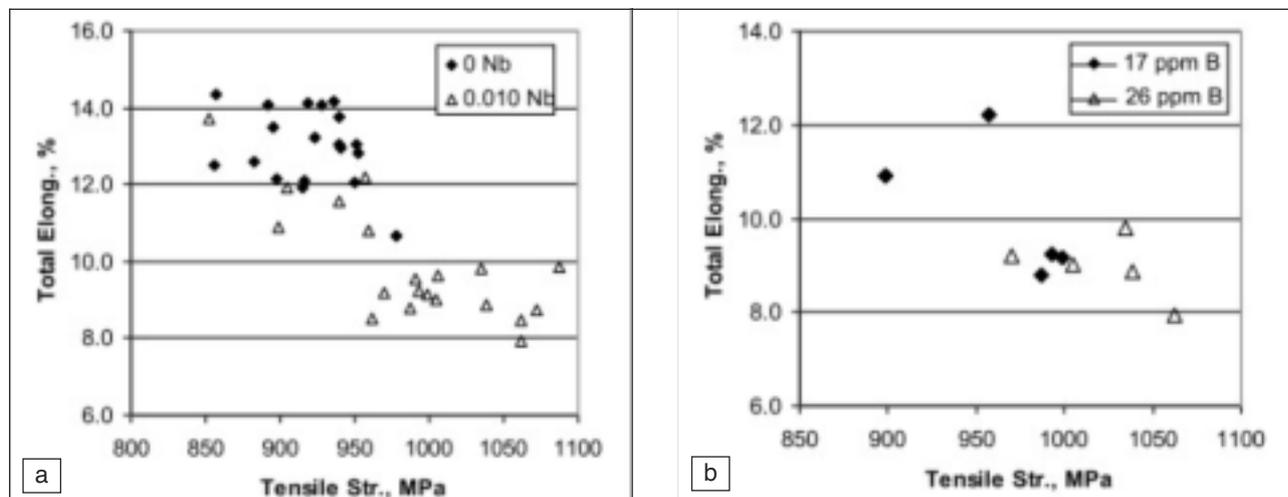


FIG. 1 Effects of (a) Nb and (b) B on the strength –elongation relationship in a cold rolled dual-phase steel.

Effetti di (a) Nb e (b) B sul rapporto carico di rottura - allungamento in un acciaio bifasico laminato a freddo.

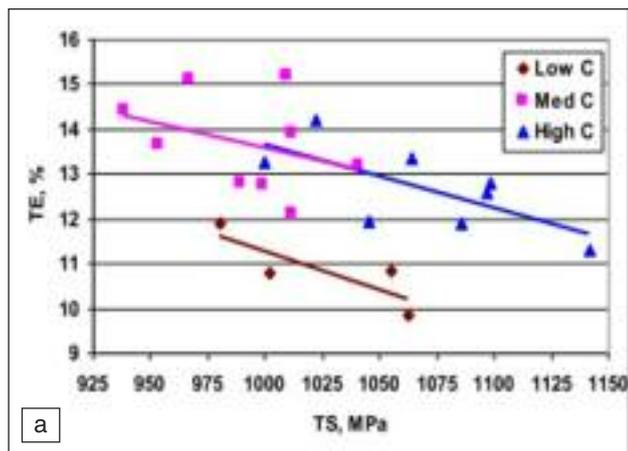


FIG. 2 Relationship between total elongation and tensile strength in cold rolled, dual-phase C-Mn-Si-Al steels.

Rapporto fra allungamento totale e carico di rottura in acciai bifasici C-Mn-Si-Al laminati a freddo.

For simple alloying elements such as Nb or B, the effect is straightforward - decreasing elongation with increasing strength - as seen in Figure 1 [2].

With elements such as C or Mn, however, the effect is complicated. For example, with increasing C, there is an increase in ductility under certain conditions. This is shown in Figure 2 below [3]. At a given tensile strength, the steel with the lowest carbon content exhibits a significantly lower ductility than the two other steels. For instance, at the desired strength level of 1000 MPa, the low carbon steel exhibits a total elongation of 11% while the medium and high carbon containing steels exhibit a total elongation of 13%. The reduction in ductility in the low carbon steel is attributed to the increased volume fraction of martensite that is required to maintain the same level of tensile strength.

This suggests that there is a limit to which the carbon content in the steel can be reduced. The increase in martensite content, beyond a reasonable limit, has a deleterious impact in steel ductility.

The effect of manganese addition on the relationship between total elongation and tensile strength in cold rolled dual phase steels is even more complex. There may be an increase or decrease in elongation with addition of Mn for medium C or high C steels [3]. In comparison to steels with higher levels of carbon, steels with

lower carbon contents have to rely on a greater volume fraction of martensite to meet a given level of tensile strength. At high martensite to ferrite ratios, for a given tensile strength, an increase in the ferrite fraction promotes a higher level of ductility in low carbon steels. This behavior is seen in the low C steel in which the steel with the larger Mn addition exhibits a higher ductility than the steel with the smaller Mn addition at the same tensile strength. At lower martensite to ferrite ratios, for the same tensile strength, the ductility of the ferrite phase, per se, assumes a relatively greater significance. Thus, for a higher C steel at a given tensile strength level, an increase in the Mn content, which strengthens ferrite and reduces its ductility, leads to a decrease in total elongation.

The effects of Si on the relationships between yield strength and tensile strength and between tensile strength and total elongation in C-Mn-Si-Al steels are illustrated in Figure 3. At equivalent tensile strength, the yield strength of the low silicon steel is higher than those containing higher levels of silicon. This observation could be explained by the solid solution strengthening potential of silicon [4]. Due to significant ferrite strengthening, higher silicon steels need a lower volume fraction of martensite to attain a given level of tensile strength. Lower martensite content, in turn, promotes lower overall yield strength in dual phase steels. The enhancement in ductility with an increase in silicon content, at a given tensile strength, can also be explained on the basis of decreasing volume fraction of martensite in the dual phase steel. Studied effects of aluminum addition on the relationships between yield strength and tensile strength and between tensile strength and total elongation in C-Mn-Si-Al steels show that since unlike manganese and silicon, aluminum is not a potent solid solution strengthener [4], consequently additions of aluminum do not impact the yield and tensile strengths of the steel. All other factors being constant, the strength of aluminum containing dual phase steels is dependent only upon the relative fractions of martensite and ferrite in the matrix. Also, at constant volume fractions of ferrite and martensite, aluminum additions are not expected to influence the relationship between tensile strength and total elongation.

One other alloying addition commonly used is Mo. The effect of Mo on the tensile strength-elongation combination has been studied [2]. Interestingly, Mo is an element which seems to increase both strength and ductility!

TRIP Steels

The strength and ductility of TRIP steels are even more compli-

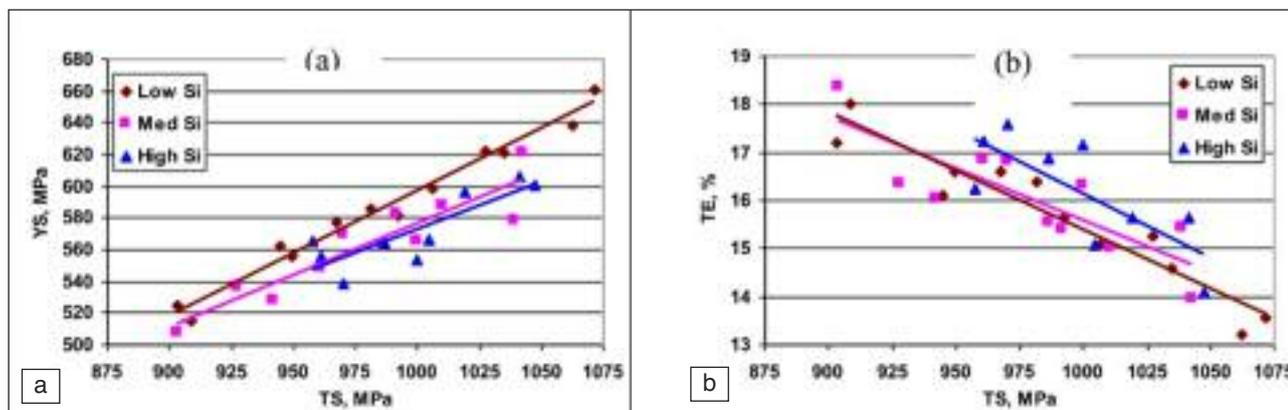


FIG. 3 Relationship between (a) yield strength and tensile strength and (b) total elongation and tensile strength in C-Mn-Si-Al cold rolled dual-phase steels.

Rapporto fra (a) snervamento e carico di rottura e (b) allungamento totale e carico di rottura in acciai bifasici C-Mn-Si-Al laminati a freddo.

cated. This is because the microstructure of these steels are more complex and contain multiple phases of ferrite, bainite, retained austenite and maybe even martensite for the higher strength TRIP steels. Consequently, they contain, in addition to C and Mn, elements such as Si, Al, Mo, Cr and P. While strength can be easily increased by additions of C and Mn, ductility is reduced so that the optimum combination of strength and ductility cannot be obtained by these means. The effect of addition of 0.3% Mo or 0.4% Cr have been studied in a 0.15C-1.5 Mn- 0.35 Si TRIP steel with varying Al addition [5]. It was observed that both Mo and Cr increase tensile strength, the effect of Mo being greater than Cr. However, the total elongation is reduced by the addition of both. Of interest though is the observation that even at about 150 MPa higher strength, the Mo containing steel has the same uniform elongation as the other steels studied. Effects of Al and P on mechanical properties of the base steel show that additions of 0.8%Al or 0.1%P result in quite similar strengthening. However, P-alloyed steel has lower elongation. Si is the most effective method to increase both strength and ductility.

Martensitic Steels

The strength of martensitic steels is controlled by the carbon content. Generally ductility is reduced with higher strength, but in practical terms, because the ductility of these steels is appropriate for operations such as roll forming, the effect is not that significant. To summarize this section, the challenge to obtain both strength and ductility in AHSS is a significant one, in particular when taken in conjunction with the requirements of weldability and coatability.

Sheared Edge Stretch Flangeability (Hole Expansion)

More and more customers are asking for higher sheared edge stretch flangeability, as measured by the hole expansion ratio (HER or γ). Hole expansion is a complex property and is influenced by several factors. The relationship which has been most commonly reported is the relationship between elongation and hole expansion [6, 7, 8]. As elongation increases HER decreases. However this is a general correlation and there are other factors which can cause deviations. Generally homogeneous mono-phase steels have high hole expansion properties while dual phase steels do not. It is accepted that the hole expansion property is controlled by the strength differential between the two phases, martensite and ferrite, in a dual phase steel. It has been shown that as the hardness ratio between martensite and ferrite decreases, HER increases [6, 8, 9]. It follows therefore, that if the strength of the ferrite can be increased to have less differential with the harder martensite phase, HER would be improved. This is indeed shown by the effect of the addition of Si, a known ferrite strengthener. HER is improved at the same time as elongation by the addition of Si [6]. This is shown in Figure 4 from reference 6.

Weldability

As both the equations for weldability given above show, C and Mn increase carbon equivalent.

Alloying elements such as Mo and Cr also increase carbon equivalent. Therefore low C, Mn and other alloying elements are needed to meet the weldability requirements of the customer. Moreover, some customers are specifying actual maximum C allowed. However these are in direct conflict with the desire for higher and higher strength steels for which higher C, Mn and/or alloying elements are needed. In addition, specific equations include P and S to calculate carbon equivalent. Thus, tight controls of P and S are also needed to meet the carbon equivalent requirement. Overall, a major challenge is the development of AHSS with the strength-ductility-HER combination and with excellent weldability.

CHALLENGES IN COATING AHSS

It is clear from the above discussions that the metallurgical design to meet customer needs is a formidable challenge. The steel needs to have low carbon in order to meet the carbon equivalent criterion for weldability. It should contain Mn but up to a certain limit. The steel could contain Mo which enhances both strength and ductility. Al has been added to AHSS, to improve ductility in certain dual-phase steels and particularly in TRIP steels to promote bainitic reaction. P is also added as a strengthening agent but at the cost of ductility. However, as has been shown above, the only element which can be added to AHSS to enhance all the simultaneous customer needs of strength, ductility and particularly stretch-flangeability, is Si.

The paramount importance of coated steels is obvious. Hence, the steel substrate has to be galvanized and therefore, the effect of the above elements, added to produce substrate properties, on galvanizability need to be discussed. At the outset it should be noted that, in general, electro-galvanizing is not a major problem in most cases. The problem is in hot-dip galvanizing or galvannealing. All of the elements listed above have effects on galvanizing. However, the most important element, Si, also is the one which has the most profound effect. Higher silicon containing steels are difficult to hot-dip galvanize and particularly galvanneal, leading to poor coating quality. This has been demonstrated in many instances and accepted by steelmakers. A typical example of the galvanneal coating in a Si bearing TRIP steel as compared to a similar Al-bearing TRIP steel is shown in Figure 5 [4].

Factors affecting the galvanizability of Si containing steels have been studied in detail [10, 11, 12].

General agreement is that it is due to the surface enrichment of Si and subsequent formation of SiO_2 or Mn_2SiO_4 [13]. These oxides affect the wettability of Zn to the steel substrate leading to poor galvanized or galvannealed coating quality [14].

There are essentially three methods to hot dip galvanize Si-bearing steels:

- Oxidation-reduction: In this method, the surface of the steel substrate is first oxidized and then subsequently reduced in order to produce a clean oxide-free surface. This is the most popu-

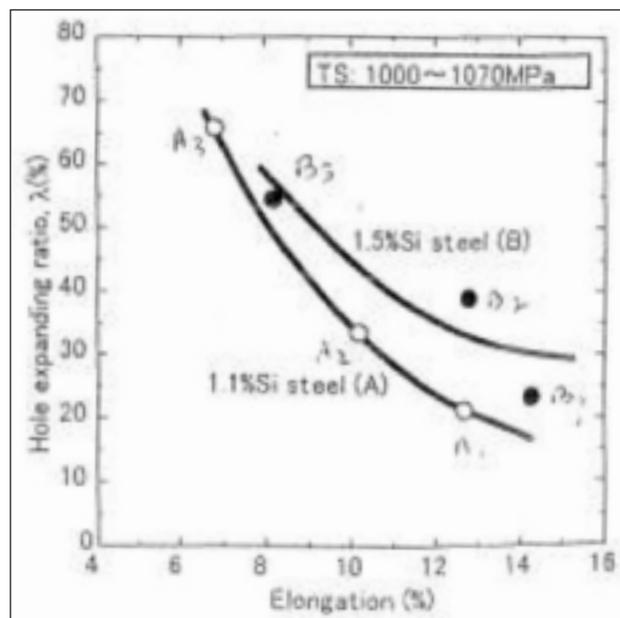


FIG. 4 Relationship between elongation and HER as a function of Si in a dual-phase steel.

Rapporto fra allungamento e HER - Hole Expansion Ratio in funzione di Si in un acciaio bifasico.

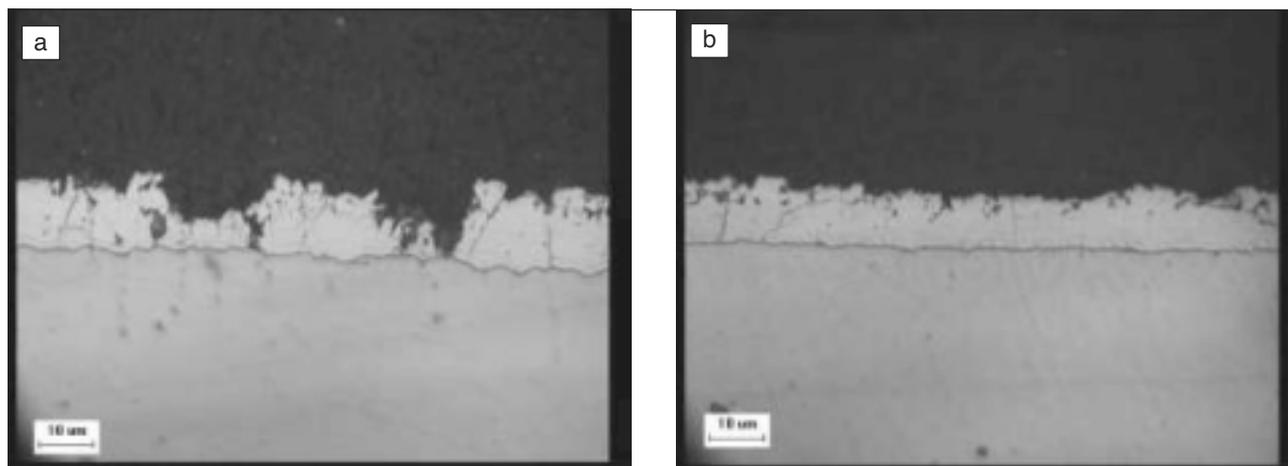


FIG. 5 Galvanneal coating in (a) Si-bearing and (b) Al-bearing TRIP steel.

Rivestimento galvanico trattato termicamente (galvannealed) in acciai TRIP (a) contenenti Si e (b) contenenti Al.

lar method in recent times.

- **Internal oxidation:** In this method, the steel substrate is annealed in conditions such high oxidizing conditions that the oxidation becomes internal such that there are no oxide on the surface.
- **Plating:** In this method a very thin layer of Fe or Ni is applied to the substrate before galvanizing. Since galvanizing occurs on a virgin, clean surface, excellent coatability is obtained.

Other elements mentioned above do not pose as much of a problem. Mo does not exhibit surface enrichment [14] and P, even when oxidized, is readily reduced. Al does produce a layer of surface oxide which does cause issues with uniformity of coatings but does not seem to be as deleterious as Si oxides. Mn can also produce an oxide layer but is again not as harmful.

Finally, a novel approach of using PVD to produce highly corrosion resistant Zn-Mg coating is particularly promising for automotive applications [15, 16].

REFERENCES

- 1) N. POTTORRE, N. FONSTEIN, I. GUPTA AND D. BHATTACHARYA, International Conference on Advanced High Strength Sheets for Automotive Applications, AIST, June (2004), p 119.
- 2) N. POTTORRE, I. GUPTA AND R. PRADHAN, International Symposium on Advanced High Strength Steels for the Ground Transportation Industry, Materials Science and Technology (MS&T) (2006), p 721.
- 3) N. POTTORRE, N. FONSTEIN, I. GUPTA AND D. BHATTACHARYA, Iron & Steel technology, AIST, September, (2006), p 63.
- 4) F.B. PICKERING, High-Strength Low-Alloy Steels - A Decade of Progress, MicroAlloying 75, Union Carbide Corporation, (1977). p 9.
- 5) O. YAKUBOVSKY, N. FONSTEIN, C. CHENG AND D. BHATTACHARYA, GALVATECH 2004, ISS, Chicago, April, (2004), p 547
- 6) N. NAKAMURA, CAMP ISIJ, 13, (2000), p 391
- 7) N. FUJITA et al, SAE 2007-01-0341, p 51
- 8) M. MIURA, M. NAKAYA AND Y. MUKAI, Kobelco Technology Review, No. 28, (2008), p 8
- 9) K. HASEGAWA, K. KAWAMURA, T. URABE AND Y. HOSOYA, ISIJ International, 44, 2004, No. 3, p 603
- 10) T.YASUI, M. NAKAZAWA AND A. MIYASAKA, Proceedings - GALVATECH 2007, Osaka, Japan, p 493
- 11) T. VAN DE PUTTE et al, Proceedings - GALVATECH 2007, Osaka, Japan, p 466
- 12) C. R. SHASTRY, J. A. ROTOLE AND T. W. KAISER, Proceedings-GALVATECH 2007, Osaka, Japan, p 403
- 13) J. MAHIEU et al, Proceedings - GALVATECH 2004, ISS, Chicago, USA, p 529.
- 14) R. BODE et al, Proceedings - GALVATECH 2004, ISS, Chicago, USA, p 107.
- 15) CH. SCHWERDT et al, Proceedings - GALVATECH 2004, ISS Chicago, USA, p 783.
- 16) M. BABBIT, Steel Research International, 77, (2006), p 620.

Abstract

Prospettive future per gli acciai AHSS rivestiti nel settore automobilistico

Parole chiave: trattamenti superficiali, rivestimenti, acciaio, automotive

Gli acciai avanzati ad alta resistenza (AHSS) rappresentano il segmento di prodotti laminati che ha subito la più rapida crescita nel settore automobilistico. Gli acciai AHSS rivestiti - zincati tal quale o con trattamento termico (galvannealed) sono i più importanti acciai di questa classe. Gli acciai AHSS comprendono varie famiglie di acciai, tra le quali le principali sono costituite dagli acciai bifasici, dagli acciai multi-fase o a fasi complesse, dagli acciai TRIP e dai martensitici. Recentemente, gli acciai a plasticità indotta dalla geminazione (TWIP- Twinning Induced Plasticity) e gli acciai (Q&P) stanno diventando molto diffusi. Inoltre, gli acciai Press-Hardened Steels (PHS) stanno diventando materiali sempre più richiesti da molte case automobilistiche. In aggiunta alle tradizionali caratteristiche meccaniche (carico di rottura e limite di snervamento), molti di questi acciai devono anche possedere altre proprietà come allungamento totale e uniforme, la flangibilità (valutata come HER - Hole Expansion Ratio), piegabilità e saldabilità. Per poter possedere una combinazione di proprietà, la maggior parte di questi acciai contiene quantità significative di vari elementi di lega. La presenza di elementi di lega e di microstrutture complesse rappresenta una sfida in termini di rivestibilità. In questo documento si discutono i molteplici aspetti degli acciai AHSS rivestiti e le loro sfide metallurgiche. Saranno compresi i meccanismi per spiegare il comportamento dei vari rivestimenti. Infine saranno brevemente discussi i nuovi rivestimenti per ottenere funzionalità migliorate e prodotti innovativi futuri per le applicazioni nel settore automobilistico.