EVOLUTION OF ADVANCED HIGH STRENGTH STEELS (AHSS) FOR AUTOMOTIVE INDUSTRY[1]

Nina Fonstein[2]

Abstract

Aimed at the retention of steel in the car body, steel producers, including ArcelorMittal, are developing ultra high strength steels with tensile strength above 1000 MPa to facilitate weight reduction of critical safety parts while ensuring crash worthiness (high absorbed energy) and high anti-intrusion resistance. In conjunction with ultra high strength, such steels are being designed for high formability including not only high elongation, but also high bendability and high hole expansion. New developments include TRIP (TRansformation Induced Plasticity) assisted dual phase steels, carbide free bainitic steels, medium Mn steels, Q&P (Quenching and Partitioning) steels and fully martensitic steels. This presentation, based on laboratory results of AM as well as on literature review, covers key features of each design, important for effective applications of these new developments.

Key words: Advanced high strength steels; Effect of Nb; TRIP aided DP; Third Generation

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[2] *Professor - Dr.Sci., ArcelorMittal Global R&D scientific advisor - East Chicago, USA.*

1 INTRODUCTION

The initial motivation for increasing the strength of formable automotive materials was aiming exclusively at decreasing car weight and thus enhancing fuel efficiency. Nowadays, the increased strength of automotive sheet materials is the main and sometimes the only way to meet growing requirements for passenger safety, fuel economy and environment protection. In fact, steel and car industries have performed rather revolutionary changes in strength of manufactured/applied steels moving from TS < 350MPa to > 1500 MPa in less than 20 years.

Keeping in mind the existing challenges from car makers and emerging light density materials, the creation of high strength steels with high formability becomes critical for sustainability of steel industry focused on auto market.

AHSS (Advanced High Strength Steels) imply YS > 280 MPa and TS>590 MPa with improved formability. Traditionally they included Dual-Phase (DP) steels, TRIP- and Complex Phase (CP) steels. Growing requirements for formability of AHSS simultaneously with strength increase have brought about new metallurgical approaches such as TRIP-aided DP steels, carbide free bainitic (CFB) steels, Quenching & Partitioning (Q&P) steels. Tensile strength target is continuously changing from 590, 780 and 980 MPa to 1180, 1500 and 2000 MPa.

2 "TRADITIONAL" AHSS

The major group of AHSS is represented by dual-phase steels that demonstrate a combination of high tensile strength and high elongation, high strain- and bake-hardening, increased fatigue resistance and can be produced with a wide range of tensile strength.

For example, DP590/600 was followed by DP780, DP980 and recently by DP1180.

Automotive customers' demands lead also to the development of some special groups of high strength sheet steels, which meet specific requirements for special safety conditions, such as steels with the TRIP- effect, featured with extremely high strain hardening rate, up to the ultimate uniform elongation.

This can ensure extremely high energy absorption at collisions and the so-called "accordion"-type of fracture at higher fatigue limit compared to conventional and DP steels with the same yield strength.(1) The same trend of increase in TS is observed not only for DP steels but for TRIP steels as well. Starting with TRIP590 car makers moved to TRIP780 and now major steel producers are working on TRIP980 and TRIP aided DP 1180.(2-3)

The first decade of the new millennium brought about growing competition of steels against alternative highly formable light materials. Steel industry responded by the most rapid growth in the number of new AHSS that were characterized by original microstructural approach to reach new formability parameters. All steel strengthening mechanisms including solid solution strengthening, grain refinement, transformation strengthening, precipitation hardening and strain ageing were utilized separately or in combination, in addition to using appropriate alloying elements and variation in hardness (carbon content) of martensite.

Table 1 gives an example of a list of AHSS with different structural designs and tensile strength globally produced or in development by AM where TRIP steel group includes TRIP-assisted steels as well.

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Table 1. "Traditional" cold rolled AHSS

Steels		TS, MPa
DP	HR/PO	590, 690
	CR/EG	590, 780, 980, 1180
	GI/GA	590, 780, 980, 1180
TRIP	CR/EG	590, 780, 980, 1180
	GI/GA	590, 690, 780, 980, 1180
CP	CR/EG	780, 980
	GI/GA	780, 980
FB	HR/PO	540, 590, 780
MS	CR/EG	900, 1100, 1200, 1300, 1500, 1700, 1900

The leading role in solid solution strengthening should be given to Si. First, as shown in **Figure 1**, strengthening by Si increases the strength of ferrite (approximately by 90-120 MPa/%).[4,5] This allows reaching the same strength of DP steel at lower amount of martensite that should lead to higher elongation. Second, substantial increase in the amount of Si reduces the difference in hardness between ferrite and martensite thus facilitating higher HER (Hole Expansion Ratio).[5]

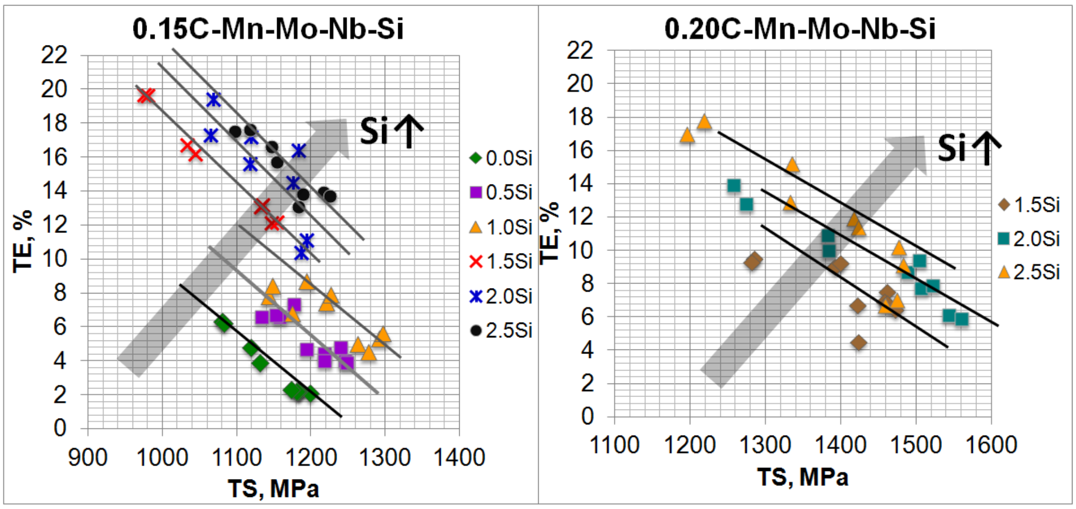
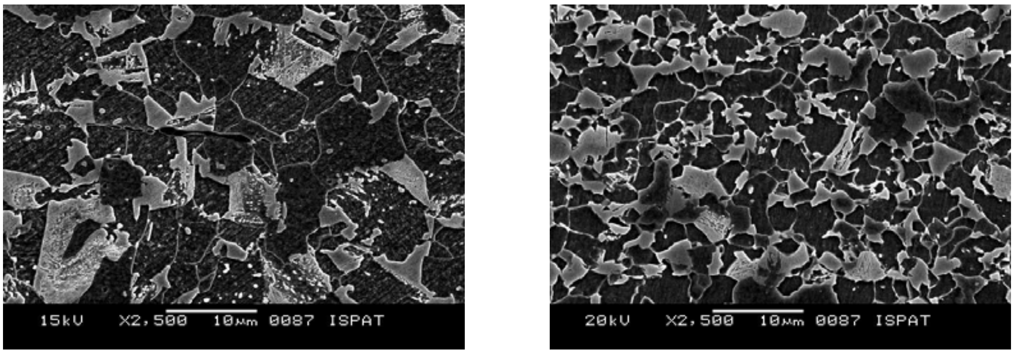


Figure 1. Effect of Si on TS-TE balance of 1.8Mn-0.15Mo-0.02Nb (wt.%) steels with 0.15 and 0.20%C

Figure 2 illustrates the effect of Nb on microstructure of 0.085C-2Mn-0.5Cr (wt.%) DP steel.[6] Substantial strengthening due to the combined effect of precipitation hardening and grain refinement was found. For example, as shown in Table 2, additions of Nb to 0.08C-Mn-Si steel in the amounts of 0.02 and 0.04% significantly affect YS and TS; however, further increase in Nb content to 0.06% produces much weaker effect.



a) b)

Figure 2. Microstructure of DP steels containing 0.085C-2.0Mn-0.5Cr without Nb (a) and with 0.03%Nb.

Table 2. Strengthening of 0.08C-Mn-Si steel by microalloying with Nb

% Nb	YS, MPa				TS, MPa			
	CT: 500°C		CT:620°C		CT:500°C		CT:620°C	
	0Ti	0.025%Ti	0Ti	0.025%Ti	0Ti	0.025%Ti	0Ti	0.025%Ti
0	641	667	645	644	979	1001	971	976
0.02	905	905	852	795	1169	1155	1118	1075
0.04	978	964	937	842	1221	1200	1180	1116
0.06	1001	998	934	900	1217	1222	1174	1121

As a result, a very important advantage of using strengthening by Nb in DP steels is the possibility to reach the specified level of TS at a smaller fraction of martensite (that leads to higher ductility) and/or at a lower amount of carbon in steel that improves weldability.

Finally, additions of Nb improve the TS - TE balance of DP steels as shown in Figure 3.[6]

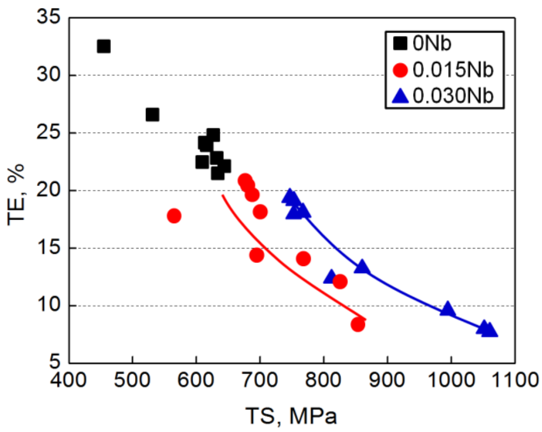


Figure 3. Effect of Nb on TS-TE balance of 0.085-2Mn-0.5Cr DP steel.

Similar effect of Nb additions was found at investigations of TRIP 780 grade.

By comparing DP steels of TS > 965 and 980 MPa with 0.145 and 0.10%C, respectively, it was found that at the same strength the lower carbon martensite has noticeably higher post-necking elongation that results in better bendability and hole expansion.[7]

In the first decade of 2000s, high Mn austenitic TWIP steels with unique combination of TS~1000MPa and TE~50% were developed.(8-10) By far, these steels have become the highest benchmarking of strength and ductility balance and are regarded as new, "second" generation of AHSS.

Formability as a material characteristic imposes different requirements depending on the forming operations. High elongation is critical for stretchability. However, higher strength increases the propensity of steels to edge cut cracking, poorer bending or insufficient flangeability/hole expansion, therefore these properties are gaining great importance.

Numerous investigations revealed the better hole expansion by replacing martensite, at least partially, with bainite.(11-13) New compositions and processing routes (Figure 4) have been explored that have led to the development of TRIP-assisted DP steels and steels with the dominant structure of Carbide-Free Bainite (CFB). These steels are featured by high Si content to prevent carbide formation in bainite and ignited a series of new developments.(13,14)

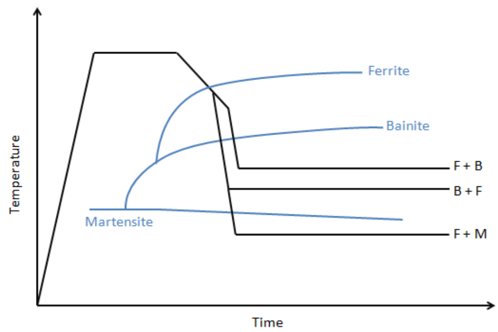


Figure 4. Cooling schemes for obtaining different microstructures.

Since high ductility of TRIP steels is related to the amount and stability of retained austenite, a new processing, the so-called Q&P (quenching and partitioning), has been proposed in which preliminary partial quenching to the temperature below Ms followed by partitioning of carbon from martensite into the remaining austenite during holding at temperatures above Ms that resulted in larger amount of retained austenite and its higher stability.(15,16)

The overall trend is to replace the existing HSS or AHSS grades with those of higher strength but with the same level of formability. For example, steels with TS-590/600 should be replaced with steels of 980 MPa tensile strength with comparable formability (TE>21%). Same is true with respect to replacing the 780 grades with TS>1180 MPa steels at TE>14%.

3 CANDIDATES TO 3RD GENERATION OF AHSS

New requirements for HSHF (High Strength High Formability) steels cannot be achieved using existing type of dominant microstructure of DP or TRIP steels and requires entirely new approaches. These steels imply not only the extremely high elongation values that approach the area encircled in the diagram presented by D. Matlock (Figure 5),(17) but simultaneously significantly high hole expansion of 50 and 30 % for steels with TS>980 and >1180 MPa, respectively. Development of similar steels according to automotive demands has significant importance for the sustainability of steel in the cars of the future.

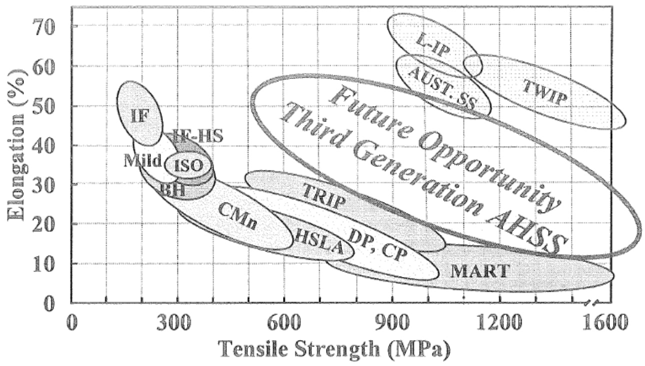


Figure 5. Elongation - tensile strength balance diagram for both existing varieties of formable steels and prospective so-called "Third generation" grades.[18]

There are a few prospective candidates that demonstrate extremely high combinations of strength and formability and deserve the same attention of car and steel industries as that they have received from researchers.

3.1 Medium Mn steels

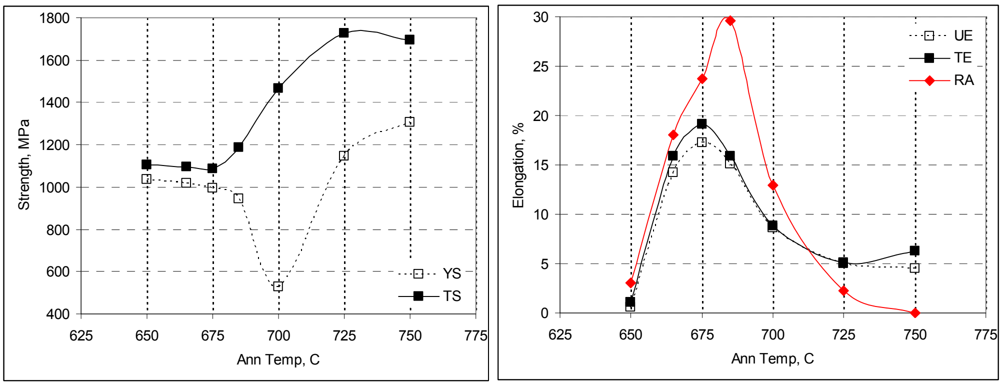
One of the most promising composition systems that satisfy the combination of properties of "The Third generation" are steels with "medium" content of Mn (typically 4-10%). These steels are not yet commercially available but have already become subjects of numerous publications and presentations at leading conferences.[19-23] Besides Mn, these low carbon steels can contain certain amount of Si/Al and microalloying elements as Nb. After the most common treatment using inter-critical annealing cycle microstructure of these steels contains ferrite, austenite and some fraction of martensite.

Effect of annealing temperature (AT) on mechanical properties of 0.16C-4Mn-0.5Si-0.05Nb (wt.%) steel is presented in Figure 6. The volume fraction of retained austenite based on XRD measurements is also shown. Both strength and ductility appear to be very sensitive to the annealing temperature which is indicative of very narrow processing window. The tensile strength varies from 1000 to 1800MPa, but changes most significantly in the temperature range of 675-700^{o}C. The total elongation has a peak of 19% at the annealing temperature of 675 ^{o}C and is about 16 % in the range of 665-685 ^{o}C at TS of 1100-1200 MPa. The amount of retained austenite in ferrite – austenite mixture increases up to ~30 % at the annealing temperature of 685 ^{o}C and then decreases with AT. The best combination of TS=1084 MPa and TE=19% is obtained at 675 ^{o}C. [22]

It is worth mentioning that the ductility of steels does not have direct correlation with the total amount of RA, but also depends on its stability. This is because the unstable portion of RA, as well as very stable film type RA, do not contribute to the TRIP effect [23].

Tensile testing of samples annealed in the temperature range of interest (665-685 ^{0}C) revealed decreasing amount of RA after deformation, which confirms the occurrence of TRIP phenomena. On the other hand, the different stability of austenite was found based on the ratio of transformed RA fraction to initial RA fraction: 0.52, 0.50 and 0.65 after annealing at 665, 675 and 685 ^{o}C, respectively.

These results are in agreement with the data presented by Gibbs et al.(24) showing that the highest ductility (here – after annealing at 675°C) corresponds to the highest stability of austenite.



(a) (b)

Figure 6. Tensile properties and volume fraction of retained austenite as a function of annealing temperature: (a) yield / tensile strength; (b) uniform / total elongation and volume fraction of retained austenite measured by XRD.(25)

From the presented (as well as the published) data it can be noticed that medium Mn steels have good elongation when the strength is below 1200MPa. With higher strength (above 1200MPa), which can be achieved through a higher fraction of martensite, elongation decreases drastically below 10%.(26-27) In addition to the influence of carbon content in γ-phase on the austenite stability, the austenite grain size is very sensitive to annealing conditions that also affects its stability and greatly influences the final mechanical properties.

As shown in Figure 7, an interesting feature of medium Mn bainitic and martensitic steels is their substantial post uniform elongation, which has never been studied, but can be interpreted as potentially favorable for hole expansion.

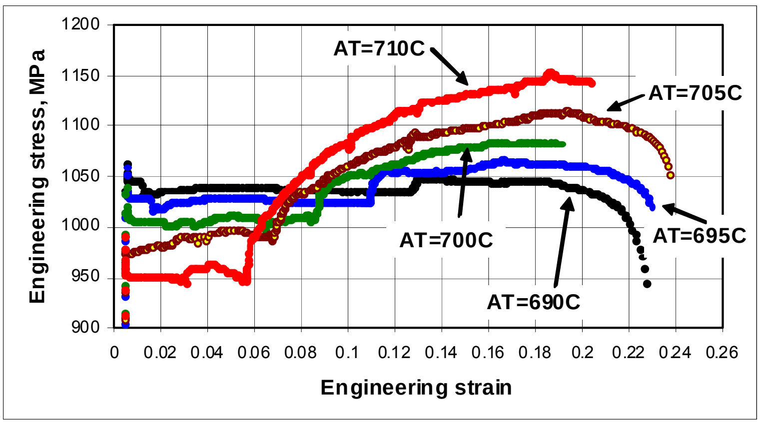


Figure 7. Effect of the annealing temperature on the stress – strain curves of 6.5%Mn steel.

As shown in Figure 8,(27) additions of Nb (they used 0.067%) increase the strength on Mn-Al steels at the same or higher elongation, increasing the product TS x TE.

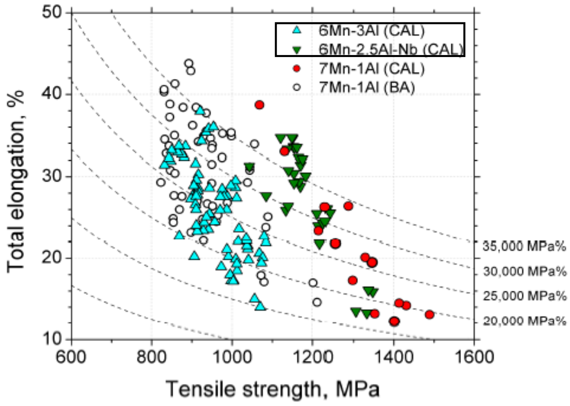


Figure 8. Effect of Nb on the balance TS-TE of medium Mn steels.

3.2 Carbide-free Bainitic Steels

Bainite concept has been intensively studied to produce HSHF steels with microstructure consisting of carbide-free lath bainite and inter-lath retained austenite. Sufficiently high content of Si allows to have simultaneously high strength and energy absorption due to the absence of fine carbides and the ultrafine size of bainitic ferrite plates, accompanied by the contribution of the TRIP-effect due to the presence of retained austenite.

Extensive investigations of these options based on austempering after fully austenite condition were done by Prof. Sugimoto starting from 2000.[28-30] His studies point at the advantages of ferrite free matrix with martensite and/or bainite depending on holding temperature vs M_s temperature (see Figure 9,a). Similar approach was used by AM Europe who studied the annealed carbide-free bainitic steel with 0.2 – 0.3%C, 2.5%Mn, 1.5%Si and 0.8Cr annealed at 1080°C and isothermally held for 40 min at Ms, Ms+50°C and Ms-50°C temperatures. Depending on holding temperature the microstructure was composed of fully carbide-free bainitic matrix, when holding was above Ms and of tempered martensite when holding below Ms at various fractions of retained austenite and fresh martensite formed during transformation of part of unstable austenite remaining at the end of bainite reaction.[31] Steel with 0.3% C, isothermally held at 450^{o}C demonstrated YS=797 MPa, TS=1400 MPa with TS=19.6%, accounting for 21.5% of retained austenite, and significant TRIP effect at remarkable work hardening and fracture strain up to 60% that suggests an increase in values of hole expansion.

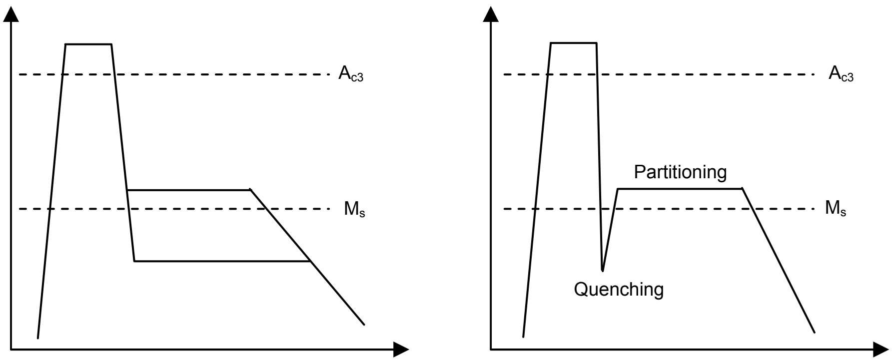


Figure 9. Schemes of annealing cycles used (a) for carbide free bainitic steels and (b) quenching and partitioning.

3.3 Q&P Steels

According to D. Matlock's forecast, the microstructure of the Third Generation steels should consist of the mixture of martensite (bainite) and austenite. This type of microstructure can probably be produced when Q&P process with preliminary pre-quenching for partial martensite transformation is performed from fully austenitic region. Keeping in mind the fairly long isothermal holding to obtain CFB steels described above, it is important that incomplete transformation of austenite to martensite significantly accelerates subsequent bainite reaction.[32]
The Q&P process presented in Figure 9, b aims at stabilizing the retained austenite in martensitic microstructures through carbon partitioning from martensite to austenite. Using the Q&P process, De Moor *et al.* achieved very good combination of strength and ductility of CMnSi steel with 0.2-0.3%C, 3%Mn and 1.6%Si [33-34] The tensile properties demonstrate TS> 1200 and 1500 MPa at TE of 14 and 17% for steels with 0.2 and 0.3%C, respectively.
In contrast to TRIP steels and similarly to med Mn stees, no correlation was found between uniform/total elongation and retained austenite fraction, when steels with very high and very low austenite fraction can exhibit excellent ductility. As was shown earlier [23], a significant portion of retained austenite after Q&P cycle was present as very thin films, which are too stable to contribute to TRIP effect.
However, keeping in mind some controversy regarding the effect of retained austenite on hole expansion, until recently it has been questionable whether Q&P approach is appropriate for production of HSHF steels with enhanced hole expansion. The study by E.De Moor et al.[35] compares Q&P, Q&T and austempering type of annealing of steels with typical TRIP grade compositions after partial (for C-Mn-Al-Si-P steel) and full austentization (for C-Mn-Si grade) at the same final holding temperatures. It shows that Q&P steels demonstrate higher HER at the same strength as Q&T steels but with slightly higher elongation. Summary of those results are presented in Figure 10. Holes for HER testing were prepared by drilling and reaming in all cases, which should result in higher HER values compared to standard practice of testing, but the positive trend is evident.

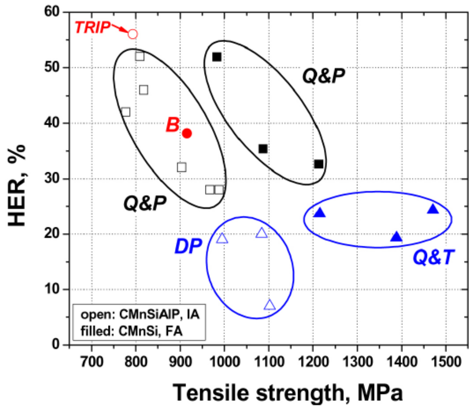


Figure 10. Summary of the measured HER values as a function of tensile strengh of intercritically annealed C-Mn-Al-Si-P (open symbols) and fully austenitized C-Mn-S grade (solid symbols).[35]

According to literature, the high work hardening, controlled by transformation of retained austenite (RA) to martensite, should have a negative effect on HER. This is confirmed by the correlation of YS/TS ratio and HER presented above for Mn steels, as well as by the investigations of DP steels.[36] In the case of steels with substantial RA fraction, the key factor is the morphology of retained austenite that should lead to

its high stability at initial stages of deformation and to proper contribution to work hardening during post necking straining.
It is beneficial, that in Q&P steels all microstructural constituents: tempered martensite, retained austenite and fresh martensite are close in strength so that the steels do not have high internal stresses that usually facilitate crack propagation from the cut edge An example of microstructure of steel after Q&P processing is presented in Figure 11.

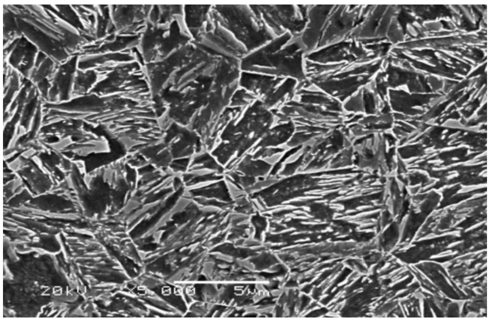


Figure 11. Microstructure of steel after Q&P cycle treatment.

The combinations of properties obtained for C-Mn-Si-Nb-Mo steel after supercritical annealing, pre-quenching at 300-350°C and isothermal holding at 460°C have shown that the target TS>1180MPa at TE>14% and HE>50% (measured on punched hole samples) can be achieved within short times of pseudo-isothermal holding typical for galvanizing lines. This combination of properties has higher HE than the one described in Moor et al.,(35) even with punched holes. This can be probably explained by shorter isothermal holding (60 s vs. 180), somewhat higher isothermal holding temperature (460°C vs. 450°C) and microalloying with Nb that resulted in more refined microstructure.

4 CONCLUSION

Numerous new developments of AHSS based on traditional (DP and TRIP) concepts as well as new promising candidates of the 3rd Generation (carbide free bainitic steels, medium Mn steels, Q&P steels) facilitate weight reduction of critical safety parts while ensuring crash worthiness, high resistance to intrusion and high absorbed energy. In conjunction with ultra high strength, such steels are being designed for exceedingly high formability including not only high elongation, but also high hole expansion.
Microalloying steels by Nb offers important advantages that made this element an integral component of AHSS, promoting their evolution to higher strength and formability. As shown, additions of Nb result in the following:
- increase in YS and TS due to precipitation hardening and grain size decrease that allows achievement of specified strength at lower carbon content and/or alloying
- structure refinement that results in higher strain hardening and therefore uniform elongation facilitating formability improvement and better balance of strength and ductility

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