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RECENT PROGRESS IN HIGH STRENGTH LOW CARBON STEELS

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Advanced High Strength (AHS) steels, among them especially Dual Phase (DP) steels, Transformation Induced Plasticity (TRIP) steels, Complex Phase (CP) steels, Partially Martensite (PM) steels, feature promising results in the field. Their extraordinary mechanical properties can be tailored and adjusted by alloying and processing. The introduction of steels with a microstructure consisting at least of two different components has led to the enlargement of the strength level without a deterioration of ductility. Furthermore, the development of ultra fine-grained AHS steels and their service performance are reviewed and new techniques are introduced. Various projects have been devoted to develop new materials for flat and long steel products for structural applications. The main stream line is High Strength, in order to match the weight lightening requirements that concern the whole class of load bearing structures and/or steel components and one of the most investigated topics is grain refinement.

***Key words**: high strength steels, phases, microstructure, mechanical properties, formability*

Najnoviji napredak kod visokočvrstih niskougljičnih čelika. Progresivni visokočvrsti čelici (AHS), među njima osobito dvofazni čelici (DP), čelici s plastičnošću induciranom transformacijom (TRIP), čelici sa složenom fazom (CP), čelici s djelomičnim udjelom martenzita (PM), daju na tom polju obećavajuće rezultate. Njihova izvanredna mehanička svojstva mogu se programirati i prilagoditi legiranjem i obradom. Uvođenjem čelika čija se mikrostruktura sastoji od barem dvije različite komponente dovelo je do povećanja razine čvrstoće a da nije došlo do narušavanja kovkosti. Nadalje, daje se pregled razvoja ultra sitnozrnih progresivno visokočvrstih čelika i njihovih radnih karakteristika te se uvode nove tehnike. Razni projekti su imali zadatak da razviju nove materijale za pljosnate i duge čelične proizvode za konstrukcijsku primjenu. Glavna nakana je da se postigne visoka čvrstoća i tako zadovolje zahtjevi za smanjenjem težine koje se odnose na cijelu klasu opterećenih konstrukcija i/ili čeličnih komponenti, a jedan od najistraživanijih problema je sitnozrnost.

***Ključne riječi:** visokočvrsti čelici, faze, mikrostruktura, mehanička svojstva, oblikovnost*

DEVELOPMENT OF AHSS

Conventional high strength steels were manufactured by adding the alloying elements such as Nb, Ti, V, and/or P in low carbon or IF (interstitial free) steels. These steels can be manufactured under the relatively simple processing conditions and have widely been applied for weight reduction. However, as the demands for weight reduction are further increased, new families of high strength steel have been developed. These new steels grades include DP (dual phase), TRIP (transformation induced plasticity), FB (ferrite-bainite), CP (complex phase) and TWIP (twin induced plasticity) steels. The critical parts of the manufacture of the steels is to control the processing conditions so that the microstructure and, hence, the strength-elongation balance could be optimized. Various high added value products are developed to satisfy increasing customer demands, as shown in Figure 1. [1 - 3].

The terminus high strength steel (HSS) is used for cold formable steels if the minimum yield strength of the respective steel grade is between 210 and 550 MPa. If the minimum yield strength is higher than 550 MPa, these grades are called ultra-high strength steels (UHSS) [2]:

min.R_e HSS 210 – 550 MPa, R_m > 550 MPa

Numerous high strength steels have been developed in the last 25 years. The conventional mechanisms to increase the strengthening steel such as solid solution hardening or precipitation strengthening are accompanied by a noticeably inferior formability.

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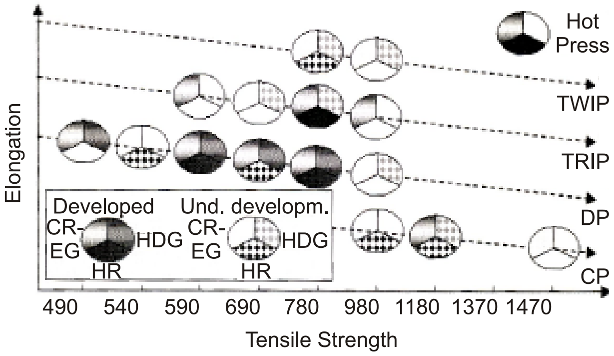

Figure 1. **Various AHS steels developed and under development at POSCO**

Slika 1. **Razni razvijeni AHS čelici i čelici u razvoju uz POSCO**

Conventional high strength steels (HS) in order of increasing strength are listed in Table 1. together with advanced high strength steels (AHS) and high manganese steels (HM). AHS steels is a general term used to describe various families of steels. AHS steels are multiphase which contain phases like martensite, bainite, and retained austenite in sufficient quantities to produce unique mechanical properties. The introduction of a new group of steels with microstructure consisting of at least two different components has led to an enlargement of the strength level without a deterioration of ductility.

Table 1. **Conventional HS, AHS and HM steels**

Tablica 1. **Konvencionalni HS, AHS i HM čelici**

HS steel	
BH	bake hardening
IF - HS	high strength IF
P	rephosphorised
IS	isotropic
Cmn	carbon/manganese
HSLA	high strength low alloyed
AHS steels	
DP	dual phase
TRIP	transformation induced plasticity
CP	complex phase
PM	partly martensite
HM steels	
HMS	- TRIP high Mn transformation ind. plasticity
HMS	- TWIP high Mn twinning induced plasticity

Recently, new group of austenitic steels with high manganese contents has been developed for automotive use. These are high manganese steels (HMS) which combine and provide excellent combination of mechanical properties with an alloying concept less expensive than conventional or new high strength austenitic stainless steels. This group is divided into transformation induced plasticity steels (HMS-TRIP) and twinning induced plasticity steels (HMS-TWIP) due to the characteristic phenomena occurring during plastic deformation.

The different steel grades for car body use can be characterised by their microstructure or their alloying concept as shown in Table 2. [1].

Typical mechanical property ranges of these different steels are presented in Figure 2. It can be seen that the strength-ductility relationship of AHS steels is improved compared to HS steels. The recently developed HM steels show extraordinary strength-ductility relationships with a product $R_m \times A_{80}$ up to 40 000 MPa % [4, 5].

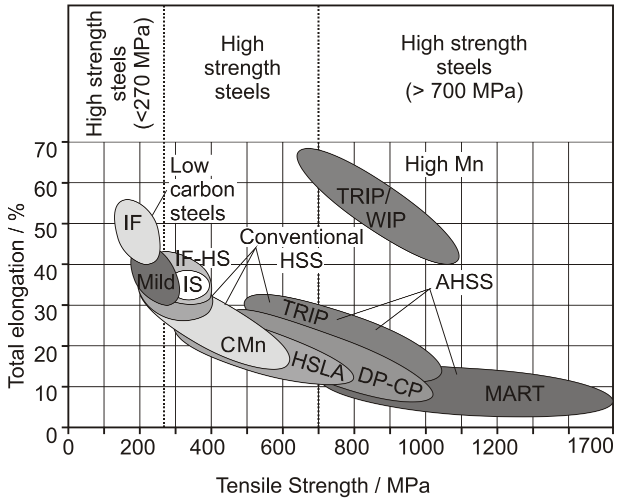

Figure 2. **Ductility-strength relationship of mild and high strength steels**

Slika 2. **Odnos kovkost-čvrstoća kod srednjih i visokočvrstih čelika**

The AHS steels are characterized by the combination of different phases with regard to microstructure description. Smaller constituents like precipitates of microalloying elements are not considered to be isolated phases in this respect.

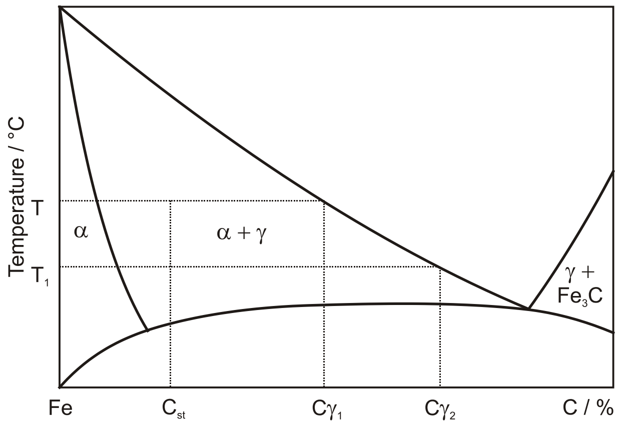

Figure 3. **Pseudo binary Fe(Me)-C diagram illustrating concentration of carbon in austenite as a function of heating in two phase region**

Slika 3. **Pseudo binarni dijagram Fe(Mn)-C koji prikazuje koncentraciju ugljika u austenitu kao funkciju zagrijavanja u dvofaznom području**

While single phase microstructers in mild steels can be simply described by grain size and grain shape, dual

Table 2. **Steels, microstructures and alloying concept of different steel grades**
Tablica 2. **Čelici, mikrostruktura i koncept legiranja različitih kvaliteta čelika**

Steels	Micro-structure	Characteristic features
Mild steels	α	LC: unalloyed Al - killed low carbon steels: EDD grades IF: interstitial free steels; microalloyed EDD grades
HS steels	α	BH: bake hardening steels grades + strengthening during paint bake treatment controlled by C IF: high strength interstitial free steel, strengthened by Mn and P P: P alloyed high strength steels IS: steels with medium YS and isotropic flow behaviour, microalloyed with Ti or Nb CMn: high strength steels with increased C, Mn, Si contents for solid solution strengthening HSLA: high strength low alloy steels, strengthened by microalloying with Nb a Ti
AHS steels	$\alpha + \alpha'$ $\alpha + \alpha_B + \gamma_R$ $\alpha' + \alpha$ $\alpha + \alpha_B + \alpha'$	DP: dual phase steels with a microstructure of ferrite and 5 - 30 % martensite TRIP: transformation induced plasticity steels with microstructure of ferrite, bainite and retained austenite PM: partly or fully martensitic steels CM: complex phase steels with a mixture of strengthened ferrite, bainite and martensite
HM steels	γ or high fraction of γ	HMS - TRIP: steels with alloying concept that strain induced $\gamma \rightarrow \varepsilon \rightarrow \alpha'$ transformation occurs HMS - TWIP: steels with an alloying concept that mechanical twinning occurs during straining

phase, duplex, and multiphase microstructures need additional features for quantification i.e.:
- volume fraction of different phases,
- grain size of each phase,
- hardness ration of the hard and the soft phase,
- local chemical composition,
- mechanical stability of the metastable phase.

Typical microstructure features of different single and multiphase steels are summarized in Table 5. The DP and TRIP steels are characterized by a medium ferrite grain size which, to some extent, can be refined by a controlled transformation of the super cooled austenite. Both steels contain finely distributed islands of the second phase with extraordinary small island diameters between 1 and 4 μm.

DUAL PHASE STEELS

Among AHS steels, dual phase steels are gaining the widest usage among automakers. This is because they provide an excellent combination of strength and ductility while at the same time they are widely available due to the relative ease of manufacture. The following Table 3. is a summary of the dual phase product property requirements. Requirements for the same product sometimes vary widely; hence only representative property targets are listed.

All the steels developed are based on annealing in the two phase (intercritical) temperature region and the consequent increase in carbon content in austenite comparison with the average carbon content in the steel. Thus, as shown in Figure 3, carbon in austenite at a lower intercritical temperature $C\gamma_2$, is higher than carbon at a higher temperature, $C\gamma_1$, at the same total steel carbon content.

The comparison of CCT diagrams after intercritical annealing with CCT of the same steel after annealing in γ region, i.e. after complete austenitization, displays some critical features of their difference shown in Figure 4. [6]. Higher carbon content in austenite after intercritical annealing results in a significant shift of pearlite transformation towards lower temperature and slower cooling rates. It is clear that the relative fraction of the formed ferrite always increase, and significantly at certain cooling rates. The intercritical annealing is not confined only to higher carbon, in comparison with the fully austenitized condition. The acceleration of "new ferrite" formation due to the presence of pre-existing phase boundaries and corresponding repartitioning of carbon has very important consequences for production of DP and TRIP steels.

Table 3. **Dual Phase steels and their properties**
Tablica 3. **Dvofazni čelici i njihova svojstva**

Product	R_m min / MPa	R_e / MPa	TE min / %
Cold rolled 590 MPa CR 590 DP	590	305 - 450	24
Cold rolled 780 MPa CR 780 DP	780	420 - 550	14
Cold rolled 980 MPa CR 980 DP	980	600 - 720	10
Galvanized 600 MPa GI 600 DP	600	340 - 410	23
Galvanized 780 MPa GI 780 DP	780	420 - 550	14
Galvannealed 590 MPa GA 590 DP	590	300 - 410	23
Galvannealed 780 MPa GA 780 DP	780	440 - 560	12
Galvannealed 980 MPa GA 980 DP	980	600 - 720	10

The cold rolled dual phase steels have been developed using advantages of the water quench continuous annealing. It is clear from Figure 3. the closer to A_{c1} the annealing temperatures are, the higher carbon content is in austenite ($C\gamma$) and higher its hardenability. Thus, effect of annealing temperature (T_{an}) and cooling rate are interrelated. The lower the T_{an} in the $\alpha + \gamma$ region is and therefore the higher

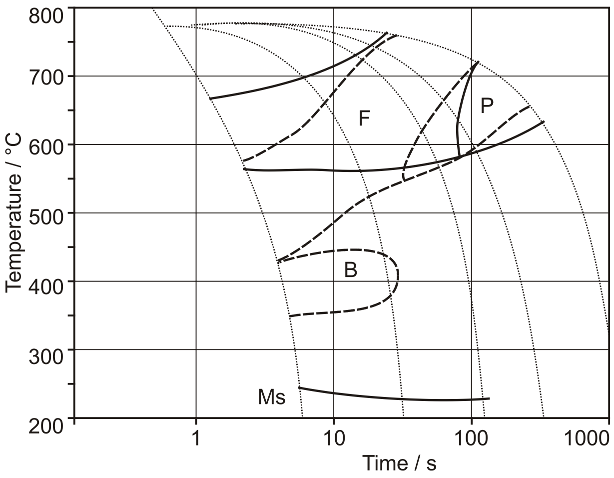

Figure 4. **CCT diagram for a steel of 0.14C-0.3Cr-1.2Mn-0.5Si-0.002B cooled from intercritical temperature range and from γ region (dashed lines)**

Slika 4. **Dijagram CCT za čelik 0.14C-0.3Cr-1.2Mn-0.5Si-0.002B hlađen iz područja interkritične temperature i iz γ područja (isprekidane crte)**

Cγ, the lower the permissible cooling rate is that allows martensite transformation while avoiding pearlite and/or bainite transformation. Direct quenching from intercritical temperature range allows achieving the steels of very high strength without expensive alloying. By water quenching but without initial slow cooling, any desired volume fraction of martensite, which will be equal to the amount of formed austenite can be obtained [7]. The combination of beneficial features, especially in R_e/R_m ratio and partly in elongation, can be achieved using interrupted cooling cycle involving direct quenching and relatively slow initial cooling. Figure 5. presents effects of quenching temperature T_q and various annealing temperatures on properties of DP steel. Similar results were presented for various amounts of C and Mn in work [8]. As shown, the lower the annealing temperature (higher austenite stability), is the larger plateau of quenching temperature is where there are no hanges in volume fraction of martensite and therefore TS occur. Representative microstructures for two of the steels grades CR 590 DP and CR 980 DP are presented in Figure 6. [19].

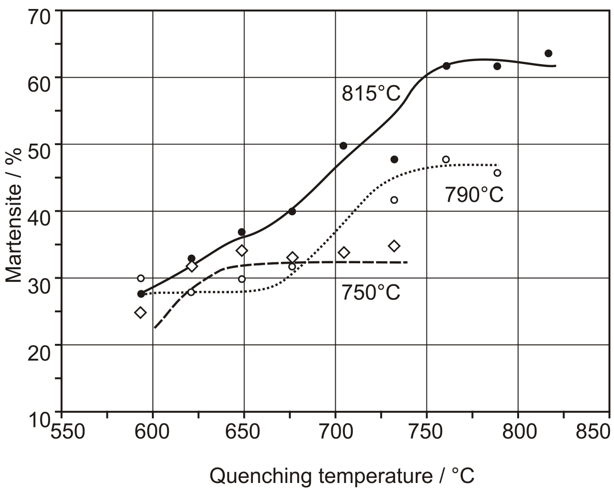

Figure 5. **Volume fraction of martensite as a function of quenching and annealing temperature**

Slika 5. **Volumni udio martenzita kao funkcije valjanja i temperature žarenja**

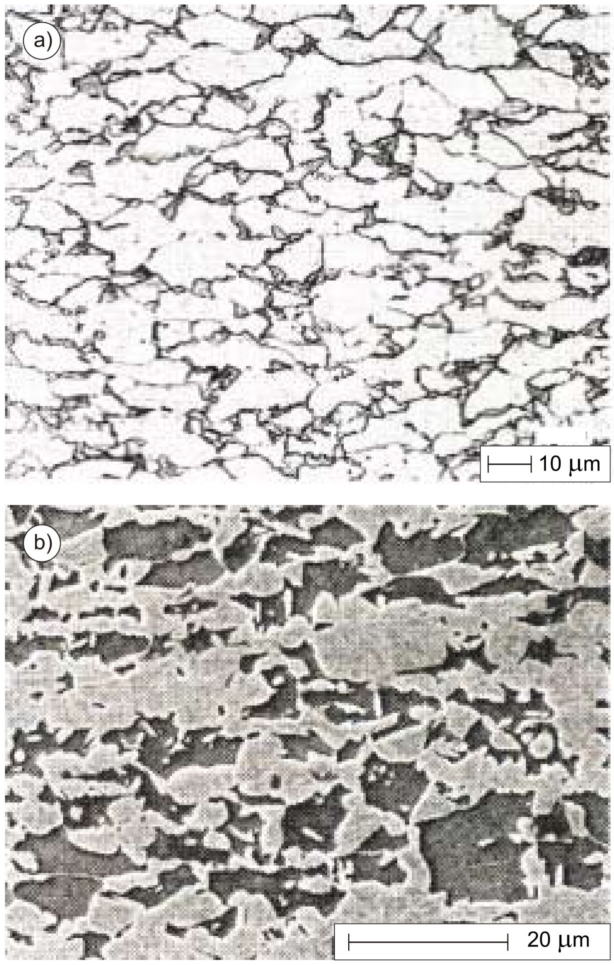

Figure 6. **Microstructure of DP steels annealed at two different temperatures; 0.1C-1.4Mn steel**

Slika 6. **Mikrostruktura DP čelika žarenog na dvije različite temperature; 0.1C-1.4Mn steel**

A scheme of the metallurgical concept of obtaining dual phase steel structure after galvannealing is presented in Figure 7. Intercritical annealing can be used to obtain austenite enriched by carbon. The basic idea is to have such combination of C and Mn content as to ensure a very high stability of gamma phase, sufficient to prevent any decomposition of austenite during galvanizing and/or galvannealing. The final austenite to martensite transformation should take place during final air cooling. However, the higher the galvannealing temperature is, the more are chances that the remaining austenite would decompose partly by bainite reaction prior martensite transformation during final air cooling.

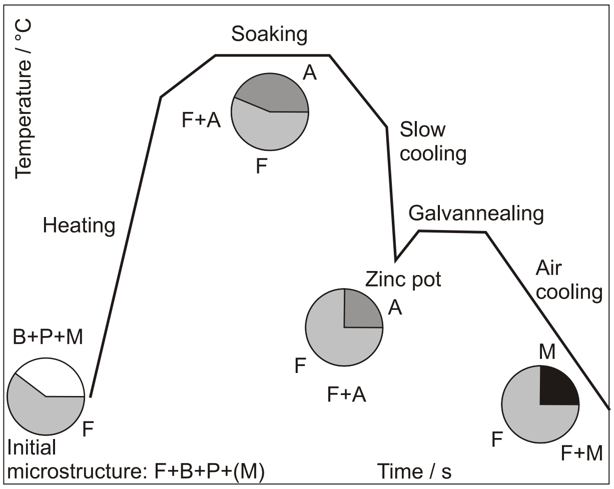

Figure 7. **Schedule for obtaning dual phase steel during the galvannealing process**
Slika 7. **Plan za dobivanje dvofaznog čelika za vrijeme procesa galvaniziranog žarenja**

Additional contribution to enrichment of austenite by carbon takes place during the initial slow cooling from galvannealing temperature, when "new ferrite" formation initiates from austenite at sufficiently high temperatures. At slow cooling a near-equilibrium carbon redistribution from ferrite to remaining austenite can be achieved. This phenomenon has some important practical consequences such as significant decreasing the sensitivity of the final structure and properties to annealing temperature [9]. In fact, the higher the annealing temperature and higher the amount of initial austenite, is the lower is its stability due to its lower carbon content and the greater the amount of "new ferrite" formation. The typical microstructure of coated dual phase steels is presented in Figure 8.a [19].

Concerning galvanized steels (GI in Table 3.) the dual phase structure can be obtained using the same concept shown in Figure 7. The key factor of this approach is sufficient, rather high steel alloying (> 2 % Mn and/or additions of Cr, Mo, V, which are ferrite stabilizers). On the other side, such alloying can result in welding problems. At the same time, the contribution to strengthening by Si addition provides the same product strength at less martensite volume fraction and also gives an additional option to decrease the content of carbon or alloying elements that could negatively affect carbon equivalent and, therefore, weldability of steel [10]. Typical microstructure of GI steels contains a dominant portion of martensite with a very small portion of bainite as strengthening phase in ferrite matrix is presented in Figure 8.b [19].

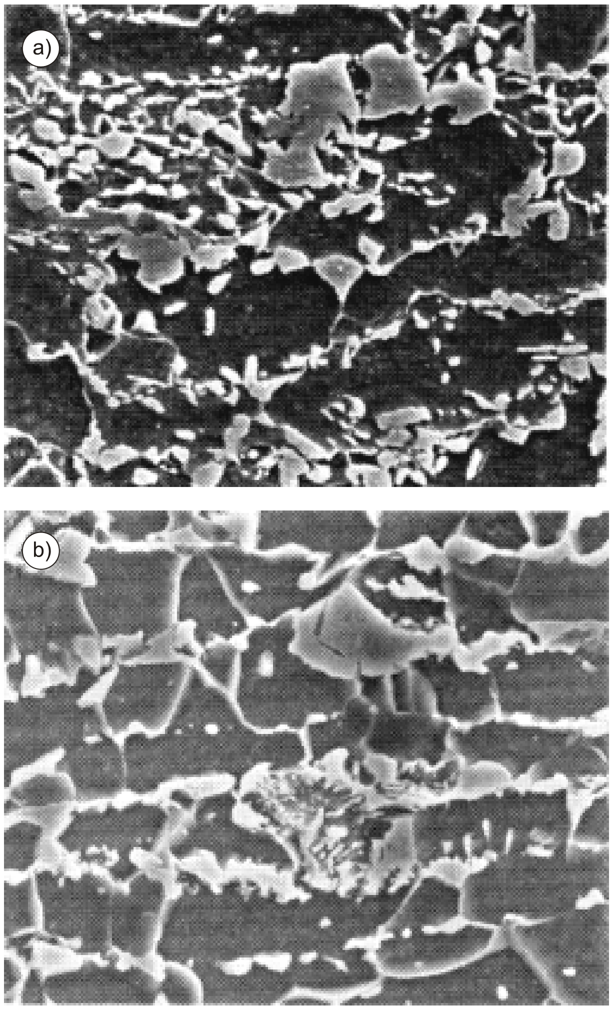

Figure 8. **Microstructure dual phase steels; a) GA 590 DP and b) GI 600 DP**
Slika 8. **Mikrostruktura dvofaznog čelika: a) GA 590 DP and b) GI 600 DP**

MULTIPHASE STEELS

Multiphase steels, also referred to as complex phase steels, provide higher level of yield strength at the same comparable tensile strength levels of dual phase steels. To obtain the high YS/TS ratio, different metallurgical principles need to be used for cold rolled and for galvannealed products. For cold rolled steels, achievement of

Table 4. **Properties of multiphase steels**
Tablica 4. **Svojstva višefaznih čelika**

Product	R_m / MPa	R_e / MPa	TE / %
CR 590 HY	690	515	23
CR 980 HY	1005	795	15
GA 590HY	620	505	26

Table 5. **Microstructural features of AHS steels**
Tablica 5. **Mikrostrukturna svojstva AHS čelika**

Micro-structure		DDQ EDDQ	HSLA	DP	TRIP	PM
f / %	α	100	100	70 - 90	50 - 55	0 - 30
d / µ		10 - 40	5 - 10	5 - 20	10 - 20	5 - 10
f / %	α’	0	0	10 - 30	1 - 5	100 - 50
d / µ		0	0	1 - 4	1 - 4	n. d.
f / %	γ_R	0	0	< 7	7 - 15	0
d / µ		0	0	0	1 - 4	0
f / %	α_B	0	0	0	30 - 35	0 - 30
d / µ		0	0	0	5 - 10	n. d.
(f: volume fraction; d: grain diameter; n. d.: not determined)						

higher R_e/R_m ratio of > 0,7 is possible with a higher overage temperature on a appropriate dual phase structure. For galvannealed steels, however, higher R_e cannot be obtained from an initial dual phase structure since in the galvannealing process, martensite is formed only in the final step of air cooling and no further overageing is possible. The only way to gain yield strength in galvannealed multiphase structure is to obtain appropriate mixture of pearlite, bainite as well as ferrite straightened by grain refinement and precipitation strengthening by Nb. Typical mechanical properties of cold rolled and galvannealed multiphase steels are given in Table 5. and structures are displayed in Figure 9. [19].

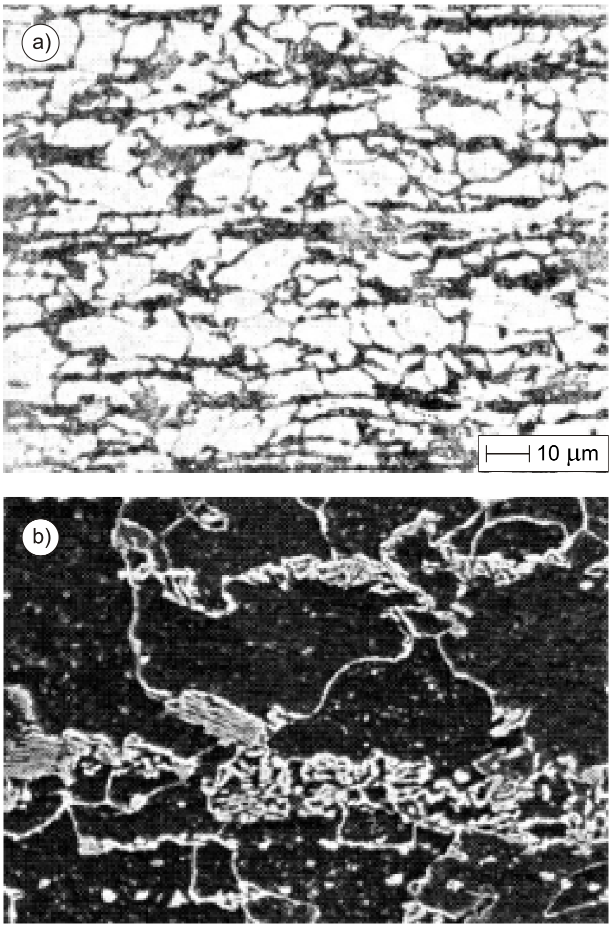

Figure 9. **Microstructure of cold rolled and galvannealed multiphase steels; a) CR 590 HY, b) GA 590 HY**
Slika 9. **Mikrostruktura hladno valjanog i galvanski žarenog višefaznog čelika: a) CR 590 HY, b) GA 590 HY**

A wide range of properties can be obtained with the same chemical composition only by adjusting the volume fraction of the second phases [14, 15]. Steels with ferritic-pearlitic dual phase structure give properties inferior to those having a ferritic-martensitic structure. The general trend is an increase of yield and tensile strength with rising volume fractions of the harder phase.

The microstructure of multiphase steels compared to the single phase microstructures of most cold formable steels requires additional information such as volume fraction, size, distribution, and morphology of the different phases, Figure 10.

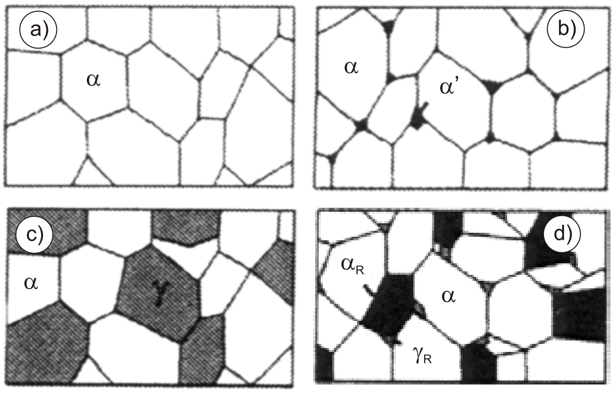

Figure 10. **Characteristic microstructures of multiphase steels; a) single phase steel; b) dual phase steel; c) duplex steel; d) TRIP steel**
Slika 10. **Karakteristike mikrostrukture višefaznog čelika: a) jednofazni čelik; b) dvofazni čelik; c) duplex čelik; d) TRIP čelik**

While single phase microstructures in mild steel can be simply described by grain size and grain shape, multiphase microstructures need additional features for quantification i.e. volume fraction of different phases, grain size of each phase, hardness ratio of the hard and the soft phase, local chemical composition, and mechanical stability of the metastable phases. Concerning individual specific steels, including dual phase, duplex, TRIP, partly martensitic steels and complex steels, the different characteristics of phases the structure consists of are required to define specific role of individual phase in multiphase structure and its contribution to mechanical properties.

TRIP STEELS

TRIP steels, based on transformation induced plasticity effect, offer the highest combination of strength and elongation, which is measure of high level energy absorption [13]. Simultaneously, TRIP steels display high n-value strengthening coefficient up to the limit of uniform elongation as shown in Figure 11. [14]. In addition, they also show high bake hardening compared to dual phase steels [15].

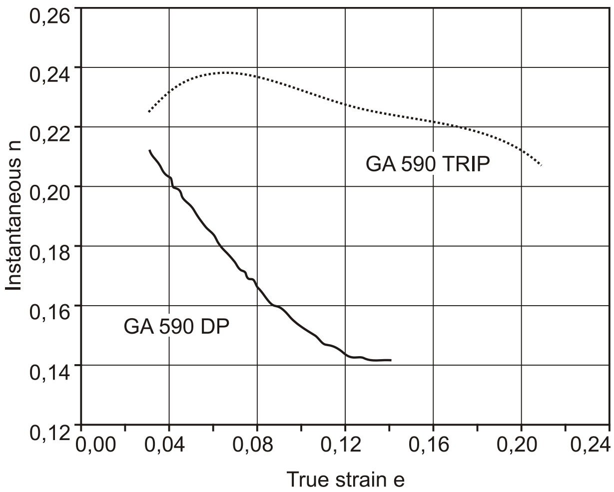

Figure 11. ***n* versus *e* curves for TRIP steel and dual phase steels of the same strength**
Slika 11. ***n* prema *e* krivulja za TRIP čelik i dvofazni čelik jednake vlačne čvrstoće**

These steels belong to AHS group and they are characterised by the combination of different phases with regard to the light optical microstructure description. Smaller constituents like precipitates of microalloying elements are not considered to be isolated phases. The TRIP and DP steels are characterized by medium ferrite grain size which, to some extent, can be refined by a controlled transformation of super cooled austenite. Both steels contain finely distributed small islands of second phase with diameters between 1 and 4 μm.

Among the noticeable microstructural parameters which affect the mechanical properties of TRIP steels are: martensite volume fraction, martensite island diameter, ferrite grain size, retained austenite volume fraction and bainite morphology and packet size. The typical microstructure features of different single and multiphase steels are summarized in Table 5. [14].

Various processing routes for TRIP steels are either already in use or are subject to discussion depending on the product [15]. The use of strip caster for processing of high alloy steels has been put to industrial practice already, while for low alloy multiphase and TRIP steels this is still a matter of current research. Special attention has to be paid to the cooling strategy when producing hot rolled multiphase steels. After solutioning and different steps of rolling in roughing and finishing mill the microstructure and the mechanical properties are finally adjusted in the cooling section. A variation of the cooling intensity and the coiling temperature allows to change the transformation behaviour and to vary the strength level. The temperature-time schedule for the production of hot rolled dual phase and TRIP steels by continuous processing is shown in Figure 12.

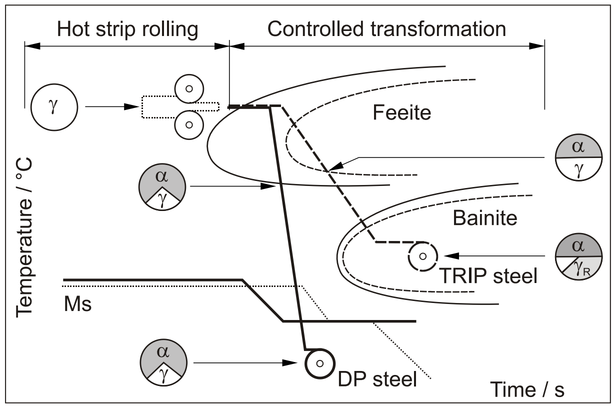

Figure 12. **Temperature-time schedule for hot rolled TRIP and DP steels**
Slika 12. **Plan temperatura-vrijeme za toplo valjani TRIP i DP čelik**

After cold rolling, to developed multiphase structure with TRIP effect in steel, the strip has to undergo a heat treatment that can be realized in continuous annealing lines and hot dip galvanising lines, Figure 13. Low alloy TRIP steels are subjected to a two step heat treatment with critical annealing in the temperature range 780 - 880 °C, fast cooling and another isothermal annealing between 350 - 500 °C and followed by slow cooling to room temperature. The microstructure after intercritical annealing contains

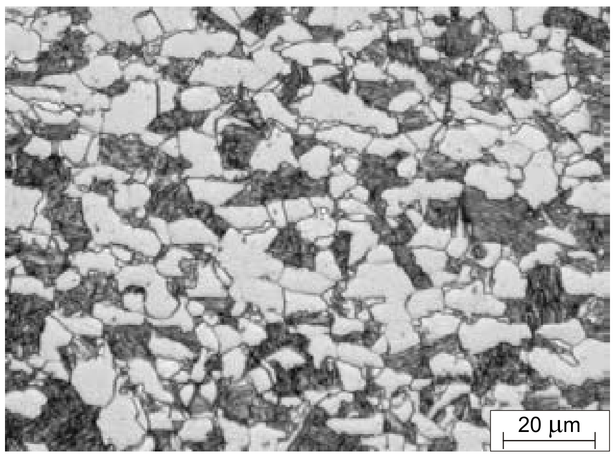

Figure 13.a **Microstructure of TRIP steel using Nital etchant; LOM**
Slika 13.a **Mikrostruktura TRIP čelika (jetkano Nitalom)**

almost identical volume fractions of ferrite and austenite. During the second isothermal holding the austenite is mostly transformed to bainite with final retained austenite volume fraction of 5 to 15 %. Typical microstructures of TRIP steels developed by different etching procedure are presented in Figure 13.a, b.

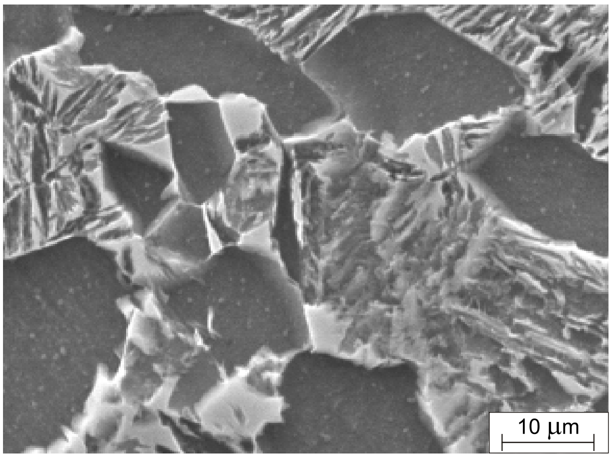

Figure 13.b **SEM microstructure of TRIP steel using LaPera etchant**
Slika 13.b **SEM mikrostruktura TRIP čelika (jetkano LaPera)**

The description of the production process requires the strict control of the process parameters, which is necessary in order to produce the desired microstructure and mechanical properties. TRIP aided steels are developed because of their attractive combination of high strength together with high ductility and remarkable strain hardening [16, 17]. It is the strain hardening behaviour and the temperature sensitivity of these steels which distinguishes TRIP aided steels from conventional cold formable steels. A strong temperature dependence of the strain hardening was observed for all TRIP aided steels [18]. Due to the strain induced formation of martensite the mechanical properties of TRIP steels respond sensitively and change in a wide range if the test temperature is changed. The definition of optimised structure of TRIP steels for different forming operations or forming parameters will need a more thorough and quantitative understanding of the temperature and stress state dependencies and microstructural features responsible for these.

MARTENSITIC STEELS

Using water quenching in a continuous annealing line, steels with 100 % martensite can be produced. These steels offer very high strength although ductility is lower than other AHS steels. The strength of these steel is controlled by the carbon content and complete austenitizing temperature is used to obtain a fully martensitic structure. The selection of martensitic steels in production and their mechanical properties are given in Table 6. Martensitic steels have also been in use for bumpers and door beams for some time now [19].

Table 6. **Mechanical properties of MP steels**
Tablica 6. **Mehanička svojstva MP čelika**

Product	R_m / MPa	R_e / MPa	TE / %
M130	1054	923	5,4
M160	1178	1020	5,1
M190	142	1213	5,1
M220	1585	1350	4,7

CONCLUSION

Advanced high strength steels are defined according to their microstructural features. They offer extraordinary strength-ductility relationship and are thus of prime interest for automotive applications. Matching exact mechanical properties of the intended steel grades the critical forming mode requires an added level of steel suppliers' knowledge. The advance AHS steels have been broadly applied to various automotive parts over the last few years. The advanced dual and multiphase steels are already used in production vehicles starting as early as 2005. Producing companies have developed various hot and cold rolled AHS steels and continue to develope new types of steels in response to automotive demands for additional AHS steels capabilities. The next generation of AHS steels is likely to be a new class of steels based on TWin induced plasticity, called TWIP steels. These offer very high elongations of 60 - 80 % at comparable strength levels. Since the trial of TWIP was successfully produced a decade ago, the productivity improvement for cold and hot rolled strips is now under way. The optimum materials for each automotive part can be efficiently determined with the help of the steel suppliers, since this provides critical tips for successful forming of parts in many cases. As a partner of automaker the steel supplier participates in the full automobile production process, and must be ready to share risks involved in the applications of new steels in combination with advanced forming technologies.

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