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ISSN 0543-5846
METABK 41 (3) 183 (2002)
UDC - UDK 621.771.23:669-418.016.2=20

PROCESSING OF ADVANCED STRUCTURAL STEELS ON CSP PLANTS

Received - Primljeno: 2001-11-26
Accepted - Prihvaćeno: 2002-04-30
Review Paper - Pregledni rad

Compact Strip Production (CSP) is an process established for the effective manufacture of advanced hot strips. Leading CSP producers put the production emphasis on high-quality grades, and consistently restricting the processing of low-quality grades for competitive reasons. The paper focuses on two major subjects: first: materials processed in CSP plants and examples of application of CSP hot strip are given. After a short overview a closer look to the processing of HSLA grades in CSP plants is taken. These high strength grades with Y. S. up to 600 MPa are manufactured in CSP plants on large scale and with great reliability, second: steel group of interest here - multiphase steels is about to be processed in CSP plants. Requirements on material properties for this new product group are given, which deal with the relationship between microstructure and properties and go over to the metallurgical microstructures. Special focus on DP and TRIP grades is given.

Key words: *compact strip production, structural steels, hot strips*

Prerada modernih strukturnih čelika u CSP tvornicama. Proizvodnja kompaktnih traka (Compact Strip Production - CSP) je process koji služi učinkovitoj proizvodnji modernih toplo-valjanih traka. Vodeći CSP proizvođači daju naglasak na visoko-kvalitetne materijale i prema tomu ograničavaju preradu nisko-kvalitetnih materijala iz kompetitivnih razloga. Članak se fokusira na dva glavna predmeta, prvi: dani su materijali prerađeni u CSP tvornicama i primjeri primjene CSP-toplo-valjanih traka. Nakon kratkog pregleda predočena je prerada HSLA materijala u CSP-tvornicama. Ti materijali visoke čvrstoće (R_E do 600 MPa) proizvode se u CSP tvornicama u velikim serijama visoke pouzdanosti, i drugi: višefazni čelici, grupa čelika koja nas ovdje zanima, proizvodit će se u CSP tvornicama. Dani su zahtjevi na svojstva materijala za tu novu grupu produkata u svezi mikrostrukture i svojstava i potom se prelazi na metalurške mikrostrukture. Posebna se pažnja ukazuje DP i TRIP materijalima.

Ključne riječi: *proizvodnja kompaktnih traka, strukturni čelici, toplo valjana traka*

INTRODUCTION

When about 13 years ago, the first CSP plants were launched on the market, the primary goal of the then new CSP-technology was to process comparatively ordinary tonnage steel into exacting-quality hot strip at high productivity and low cost. The determined equipment and process development led to a second generation of CSP plants featuring even higher productivity, extended process flexibility and a substantially broader CSP product range.

MATERIALS PRESENTLY PROCESSED ON CSP PLANTS

Figure 1. reflects the schematic representation of a CSP plant and provides information on essential CSP process parameters.

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The liquid steel is fed via ladle and tundish into the funnel-shaped CSP mold. Leaving the mold, the thin slab runs through to the secondary cooling zone; it is cut to length by a pendulum shear and then enters the soaking furnace. After descaling, the slab is rolled in the CSP-HSM; the produced hot strip passes the laminar cooling system and is finally coiled. Including a liquid steel supply via EAF- and LMF- melt shop the whole process takes between two and two and a half hours, the productivity of a two strand plant is approximately 2.5 to 3 Mill. to per year, and about 300 - 350 people are involved.

The first two Tables give a survey of the steel groups presently processed on CSP plants, reflect representative grades and indicate examples of application for CSP hot strip. Evidently, the CSP process today covers a very wide product spectrum starting with hot strip of mild low-carbon steel grades through structural and line pipe steels, heat-treatable and spring steels right up to high-carbon tool and wear-resistant steels. In addition to these construc-

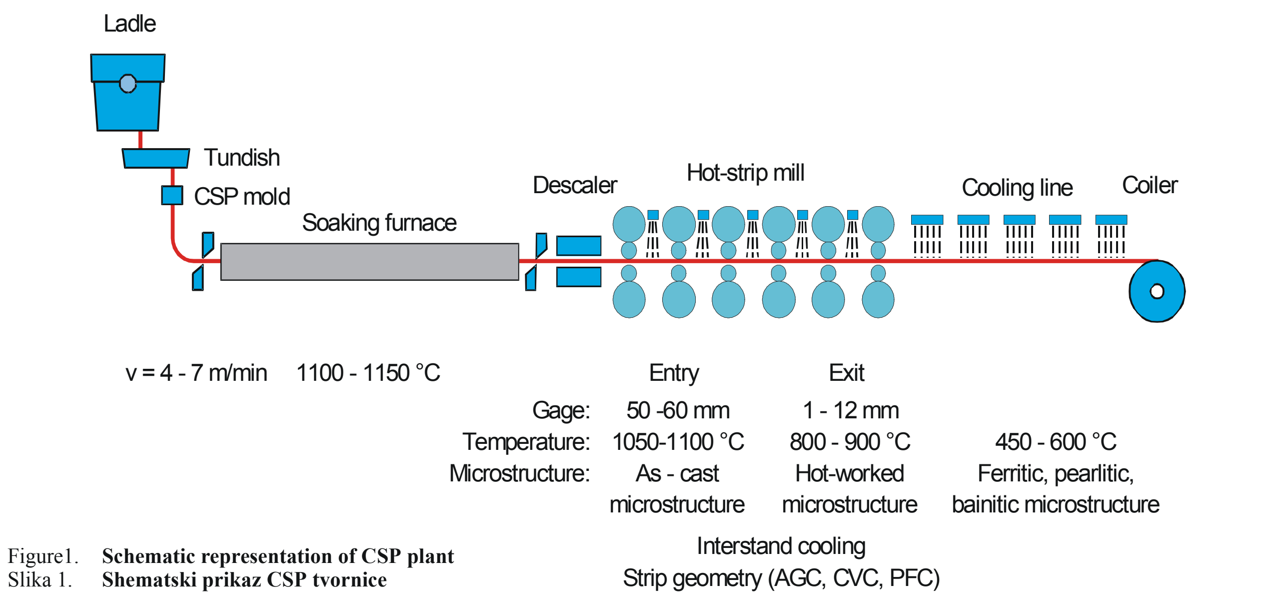


Figure1. **Schematic representation of CSP plant**
Slika 1. **Shematski prikaz CSP tvornice**

Table 1. **CSP hot strip grades, Examples of application**
Tablica 1. **CSP gradacije toplo-valjanih traka, primjeri iz primjene**

No.	Steel group	Representa-tive grade	Example of application
1.	Mild low-carbon grades for		
1.1	cold forming	StW24 (+B)	Longitudinal beams
1.2	rerolling	St24	Strapping material
2.	Structural steels and HSLA		
2.1	Plain carbon grades	St52-3	Structural tubes, oil barrels
2.2	HSLA grades with improved formability	QStE550TM	Wheel rims, shelf elements
2.3	Fine-structural steel. suitable for welding	StE500 WStE420 TStE500 EStE500	Car frame compon. Strapping material Propane gas cylinders
2.4	Weathering steels	WStE52-3	Sheet pilings
2.5	Phosphor alloyed special grades		Reroller
3.	Line pipe steels		
	Line pipe steels	StE480.7 X70	Pipeline construction
4.	Heat - treatable steels		
	C-Steels	Ck50	Strapping, washers
	C-Cr-Steels	41Cr4	Clutch plates
	C-Mn-Steels	28Mn6	Tubings
	C-Mn-B-Steels	(30MnB5)	Stampings, stand construction
	C-Cr-Mo-Steels	42CrMo4	Brake elements (Aeronautical equi.)
	C-Cr-Mo-V-Steels	(30CrMoV4)	Steering column assembly lever

tional materials, functional materials such as silicon-alloyed electro-technical steels as well as corrosion-resis-

Table 2. **CSP hot strip grades, Examples of application**
Tablica 2. **CSP gradacije toplo-valjanih traka, primjeri iz primjene**

No.	Steel group	Representa-tive grade	Example of application
5.	Spring steels		
5.1	Unalloyed spring st.	Ck67	Bending, spiral spr.
5.2	Alloyed spring steel.	50CrV4	Rulers
6.	Tool steels		
6.1	Unalloyed tool steel.	C70W C85W C100W	Knives, shears Plough blades Files
6.2	Alloyed tool steels	75Cr1 56NiCrMoV7 75NiCrMo553	Wood saws Carrier blades for saw teeth Saw blades
7.	Wear-resistant steels		
	Wear-resistant st.	90Mn4	Harrows, cultivators
8.	Electrical quality steels		
8.1 8.2	Electrical quality st. Non-oriented Grain-oriented	Si = 1.2 - 3.2	Reroller Electrical sheet for motors, generators, transformers
9.	Stainless steels		
	Stainless steels		Automotive silencer
9.1	Territic grades	X6Cr17	Catalitic converter castings
9.2	Austenitic grades	X5NiCr18 10	Kitchen utensils

tant ferritic and austenitic grades are processed. That means, CSP hot strip successfully meets a wide range of requirements regarding the mechanical, physical and chemical service behavior.

All of these grades are manufactured on CSP plants on large scale, in every-day practice, and with great reliability [1].

PROCESSING OF MULTIPHASE STEELS ON CSP PLANTS

Requirements on material properties - novel product groups

However the development goes on, and the demand for novel hot and cold-strip qualities is raised by different branches of the industry. Especially the automotive industry imposes continuously increasing demands both on the processing behavior of the strip and the service properties of the manufactured car components. To meet this costumer demand the basic goal of the strip producer implies in the optimization of the material behavior, improving in particular the relationship between strength and formability (Table 3.).

Table 3. **Mechanical material behavior**
Tablica 3. **Mehaničko ponašanje materijala**

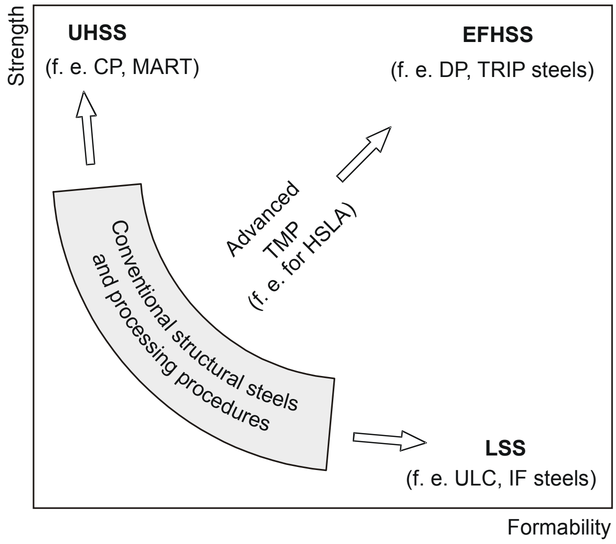
Load	Characteristic data: Strength	Characteristic data: Formability
Tensile test	Yield strength, Tensile strength (R_e / R_m)	Uniform elongation, Elongation at fracture, n - value, r - value
Processing, Formability during manufacture	Stretch formability ← n - value, Deep-drawability ← r - value	
Service properties on the component	Light weight parts, Dent resistance, Fatigue strength, Impact safety	

When taking the tensile test as a basis for judging the material behavior, the strength can be characterized by the yield strength and the tensile strength. With regard to formability the uniform elongation, the elongation at fracture, the n- and r-value are applied frequently.

If talking about processing - the work-hardening coefficient "n" is a good measure of the formability under stretch forming conditions and the r-value characterizes the deep-drawing behavior [2]. From a physical point of view, a higher n-value stands for greater work hardening and results in a more uniform strain distribution in the component [3].

The service properties characterize the behavior of the component in the finished product. If we stay with the car industry, there is a strong interest in the manufacture of lightweight parts showing high dent resistance, fatigue strength and excellent impact safety. Depending on the service conditions of the particular part, an optimal combination of strength and formability has to be set in each case.

When we start our discussion about improving the mechanical properties with conventional structural steels, so we have to mention in particular three novel product groups (Figure 2.):



TRIP - Steels with Transformation Induced Plasticity
EFHSS - Extra Forming High Strength Steels **DP** - Dual Phase
UHSS - Ultra HighStrength Steels **IF** - Interstitial Free
CP - Complex Phase Steels **MART** - Martensite Steels
LSS - Low Strength Steels **ULC** - Ultra Low Carbon

Figure 2. **Relationship between strength and formabiltity**
Slika 2. **Povezanost čvrstoće i zadržavanja oblika (formabilnosti)**

Ultra high-strength steels - UHSS,
Extra forming high-strength steels - EFHSS and
Low-strength (soft) steels - LSS.

Hot strip of UHSS features high yield strengths > 100 ksi (> 690 MPa); examples are CP (complex phase steels) and MART (martensite steels).

EFHSS feature a formability that is superior to that of conventional structural steels; examples are DP (dualphase) and TRIP (transformation induced plasticity) steels.

LSS show a particularly good formability; examples are ULC (ultra-low carbon) and IF (interstitial free) steels.

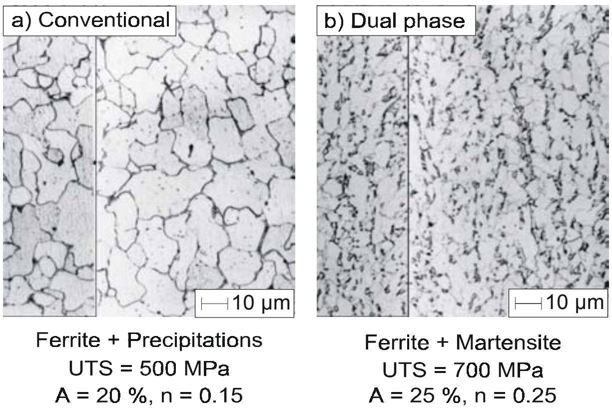
Each of these steel groups meets special costumer demands and needs a separate discussion.

This paper focuses on EFHSS, which is a typical "high tech material". Its characteristic feature is an excellent combination of strength and formability which markedly improves the processing behavior of the strip and the service properties of the manufactured parts. CSP plants are best suited for processing EFHSS.

Relationship between microstructure and properties

Let us now turn to the question how these extremely favorable properties come about. To answer this question, we have to take a look at the causal relationship between the properties of the material and its microstructure.

Typical of conventional structural steels are primarily single phase microstructures with minority phases such as precipitations (Figure 3a.). In this case, the optimization of the relationship between strength and formability is subject to relatively close limits. Normally, an increase in strength means a reduction of formability. In the present case elongations at fracture of 20 - 25 % are achieved, f. e. for HSLA grades through thermo mechanical processing, at a yield strength of approx. 500 MPa, with the mean n-values ranging between 0.10 and 0.15 and the yield strength ratio is approx. 0.9.



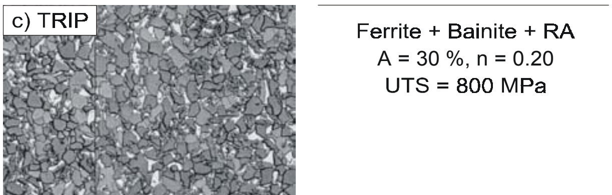


Figure 3. **Microstructure of hot strip for cold forming**
Slika 3. **Mikrostruktura toplo-valjane trake za oblikovanje na hladno**

The situation is totally different when multiphase microstructures with relatively large volume fractions of different phases, so-called majority phases, are set in the strip. Here, the different material properties of the various phases with large volume fractions, such as the high strength of one phase and the great plasticity of another phase, can be reasonably combined with each other; this is a typical case of „microstructure engineering“.

Two examples for multiphase microstructures are shown in Figure 3b. and - Figure 3c.:

Hot strip of DP steel features a microstructure of approx. 80 to 90 % soft ferrite and 20 to 10 % hard martensite (b). Typical tensile strengths are about 700 MPa, the elongation at fracture is approx. 25 %, the mean n-value ranges around 0.25 and the yield-strength ratio is approx. 0.5 [2, 4].

The microstructure of TRIP-steel strip contains approx. 50 % ferrite, 40 % bainite and 10 % residual austenite. The tensile strength comes up to approx. 800 MPa, the elongation at fracture is around. 30 %, and the mean n-value is approx. 0.20; the yield strength ratio comes to approx. 0.7 [4].

These different microstructures and their pertaining stress-strain diagrams are shown in Figure 4. schematically:

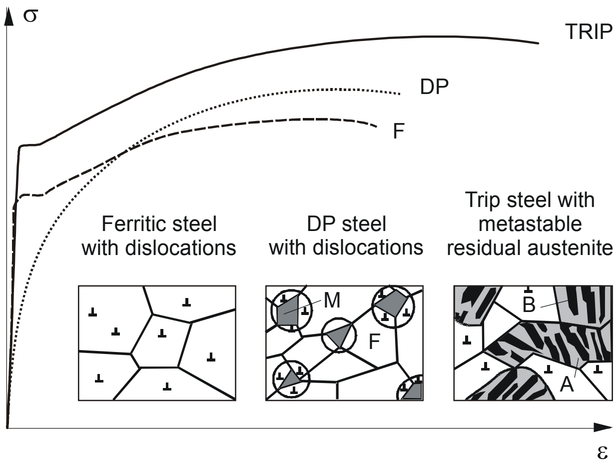


Figure 4. **Schematic stress-strain curves and related microstructures**
Slika 4. **Shematske krivulje: opterećenje-naprezanje i s tim povezane mikrostrukture**

Conventional structural steel features a more or less pronounced yield-strength deformation and subsequent work hardening before fracture.

DP steel has a low yield strength by comparison. As a result of the partial martensitic transformation, mobile dislocations have formed in the soft ferrite which begin to slide already at low stresses. This specific microstructure results in a continuous transition from the elastic into the plastic area of the stress-strain curve, explains the low yield strength and the lack of yield-strength deformation. When the strain goes up, the stress markedly increases. This is a result not only of the work hardening of the ferrite, but particularly also related to the existing martensite. Besides the martensite volume fraction, the hardness of the martensite islands is playing a decisive role. Anyway, the following becomes apparent: between the beginning of plastic deformation and the failure of the material we have a large stress interval and a sufficiently high elongation at fracture. In other words: a high formability is linked with a high strength. Such a steel absorbs a high energy when exposed to load. This kind of material behavior is of particular interest for instance for crash-relevant components. Moreover, due to the high resistance to crack propagation under vibrating loads it is used, for example, for wheel rims.

In TRIP steel, the existing metastable austenite improves the deformation properties during processing even further. It results from the transformation of metastable residual austenite into martensite under straining. The transformation results in a localized increase of the work hardening coefficient (n) during straining. This delays the start of necking and ultimately leads to a more uniform elongation. Compared to DP steels, this brings about another improvement of the performance.

Metallurgical action principles and their implementation in CSP plants

Metallurgical action principles

The next two figures exhibit the required temperature control in relation to the transformation diagrams of DP- and TRIP-steels, schematically.

The setting of DP microstructure requires the formation of a sufficient amount of soft ferrite, first. Figure 5. shows, that for this purpose the austenite is finish rolled shortly above or right in the range of the beginning polymorphic $\gamma \rightarrow \alpha$ - transformation. If necessary, rolling may be followed by intensive cooling to transformation temperature. The transformation kinetics depend on the undercooling and on the microstructure of the hot-deformed austenite (residual deformation, austenitic grain size, etc.).

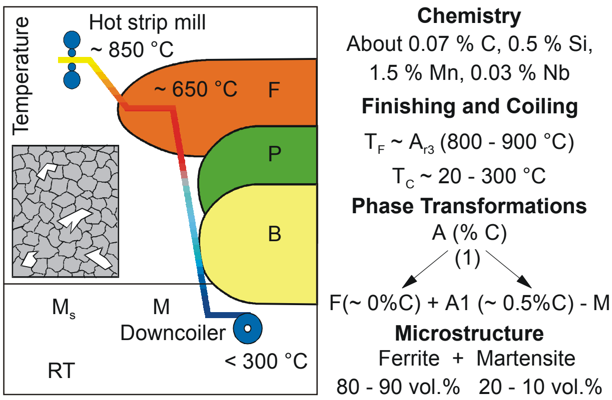


Figure 5. **Dual phase steel - Hot strip production, Metallurgical action principles**
Slika 5. **Dvofazni čelici - proizvodnja toplo-valjanih traka, načela metalurškog djelovanja**

During transformation from austenite into ferrite, carbon is separated between the two solid solutions. Since ferrite dissolves much less carbon, this element is concentrated in the remaining austenite. The austenitic areas are enriched with carbon and may undergo martensitic transformation already at cooling rates of 20 to 30 degrees per second [5]; the hot strip is coiled below the martensite starting temperature (≤ 300 °C). The final microstructure consists of ferrite and martensite.

The production of CSP hot strip showing transformation-induced plasticity (TRIP) calls for metastable (residual) austenite in the finished product (Figure 6.). To achieve this, the martensite temperature must be lowered to below room temperature. Again, this can be done by carbon enrichment, but in this case the carbon concentration must be significantly higher than in DP steel.

Therefore, the initial carbon content is increased to approx. 0.2 % and two enrichment stages in the ferritic and bainitic ranges are introduced (see Figure 6.). In the ferritic range, the carbon concentration in the austenite goes up to approx. 0.5 % and in the bainitic range to approx. 1.2 %.

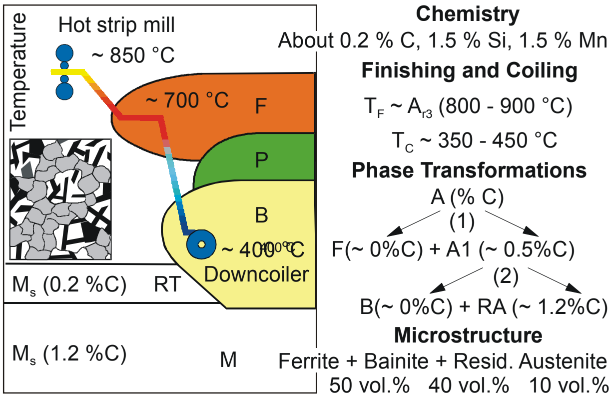


Figure 6. **TRIP - steel - Hot strip production, Metallurgical action principles**
Slika 6. **TRIP - čelik, načela metalurškog djelovanja**

The decisive step for setting the austenite existing at room temperature takes place in the bainitic range. By setting an appropriate holding temperature and time, both an adequate amount of austenite and its required thermodynamic metastability will be set.

The desired specific transformation-behavior of DP and TRIP steels depends on defined chemical compositions.

Table 4. reflects typical alloying concepts applied. First of all it becomes clear, that DP- and TRIP grades represent just a further development of conventional C - Mn structural steels.

Table 4. **Alloying concepts for DP and TRIP steels**
Tablica 4. **Koncepcije legiranja za DP i TRIP čelike**

Material		Chemical composition				
		C	Si	Mn	Al	Other
DP	Basic chemical composition	0.07	0.50	1.50	0.03	Max.: 0.05 % Nb; 0.05 % Ti; 0.80 % Cr; 0.50 % Ni; 0.50 % Mo; 0.08 % P
TRIP		0.20	1.50	1.50	0.03	
Multiphase steel	Alternative chemical composition	0.05	0.01	0.80	0.40	
		0.30	0.20	3.00	2.50	
	N = 30 - 60 ppm, S < 0.010 %					

Carbon is a highly strength-increasing alloying element which in this connection takes adequate effect already at concentrations of approx. 0.07 % for DP- and 0.20 % for TRIP-steels.

Silicon and possible substitutes for it play an important role in multiphase steels. Two effects of Silicon as alloying element are of particular interest in DP- and TRIP- steels:

First, Silicon is a strong ferrite stabilizer and leads to heavy formation of proeutectoid ferrite; typical concentrations of approx. 0.5 % are reported for DP-grades.

Second, Beside of that Silicon suppresses the formation of cementite in the bainitic range; this is especially useful for TRIP grades. Adding approx. 1.5 % Silicon ensures that an adequately high carbon concentration is set in the austenite which prevents its martensitic transformation at room temperature. This way metastable residual austenite is set.

These advantages of silicon as alloying element on one hand face some drawbacks on the other hand:

First, during hot rolling, Silicon leads to the formation of very firmly adhering scale; part of this so-called red scale is rolled in; these strips are relatively hard to pickle and the surface quality is limited.

Second, Si alloyed strip cannot be processed in continuous hot-dip galvanizing lines as the zinc has just a poor wetting effect on these Si-containing steels.

Third, the ferrite formation in Silicon alloyed steels is quite sensitive even to small changes in transformation temperature. Having in mind a stable industrial process, this may result in insufficient reproducibility of the final microstructure and properties.

For this reason substitutes for Silicon were looked for. Most attention is focused on Aluminium and Phosphorous; see Table 4. When Aluminium is used for deoxidation only, typical concentrations range around 0.03 %; using Aluminium as a substitute for silicon requires markedly higher concentrations. Beside of that Phosphorous contents up to about 0.08 % are typical [6]. Both of them Aluminium and Phosphorous are strong ferrite stabilizers inhibiting at the same time the formation of cementite [7]. Moreover, Phosphorous reduces the sensitiveness of the ferrite formation kinetics to changes in the holding temperature [8] and Aluminium markedly increases the adhesion of the Zn-layer in galvanized and galvannealed strip. That means, Aluminium and Phosphorous give the same advantages like Silicon, but without the adverse effects. With regard to multiphase steels Manganese is mainly applied to retarding the pearlitic transformation and to enabling this way the formation of martensite or bainite.

In a similar way act Chromium, Nickel, and Molybdenium. They stabilize the austenite, and reduce the critical cooling rate for diffusionless transformation. Microalloying is vital for thermomechanical processing improving that way microstructure and service behaviour of multiphase hot strip.

Implementation on CSP plants

In the integrated steel plants of the market leaders, hot and cold strip with multiphase microstructures represent already today an integral part of the product mix (Table 5.) and the CSP plants are about to include these materials into their product range. The company of Thyssen Krupp in Germany operates the first CSP plant processing multiphase steels.

Table 5. **Processing of multi-phase steels at TKS, Germany - Conventional hot strip production**
Tablica 5. **Prerada višefaznih čelika u TKS, Njemačka. Konvencionalna proizvodnja toplo-valjanih traka**

Product		Steel group				
		DP	TRIP	CP	PM	MS
Hot strip	As - rolled	ORC	ORC	ORC	-	ORC
	ZE	-	UD	ORC	-	ORC
	Z	-	-	UD	UD	UD
Cold rolled strip	As - rolled	ORC	ORC	-	UD	-
	ZE	ORC	ORC	-	UD	-
	Z	ORC	ORC	-	UD	-
	ZF	ORC	ORC	-	UD	-

DP - Dual phase steel
TRIP - Trip steel with Transformation Induced Plastics
CP - Complex phase steel, **PM** - Partial martensitic steel
MS - Martensitic stell, **ORC** - Operational routine conditions
UD - Under development, **Z** - Hot dip galvanized
ZE - Electro galvanized, **ZF** - Galvannealed

It should be emphasized in this conjunction that CSP plants are no doubt much better suited to implement the above described metallurgical action principles than conventional hot strip mills. In particular, the CSP technology offers excellent preconditions:

- for keeping close tolerances with regard to the alloying elements used and
- for ensuring a strictly reproducible temperature control.

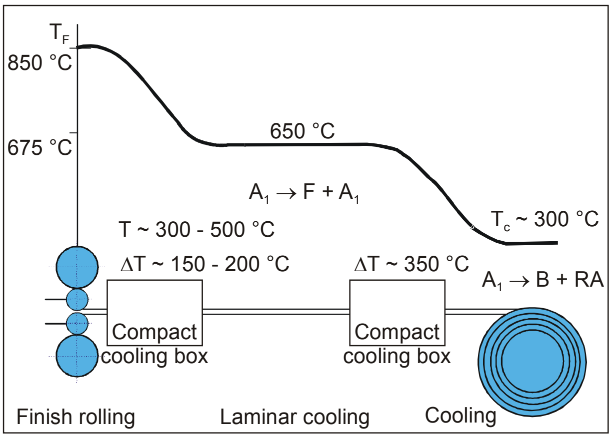


Figure 7. **Cooling pattern for multiphase CSP hot strip**
Slika 7. **Uzorak hlađenja višefaznih CSP toplo-valjanih traka**

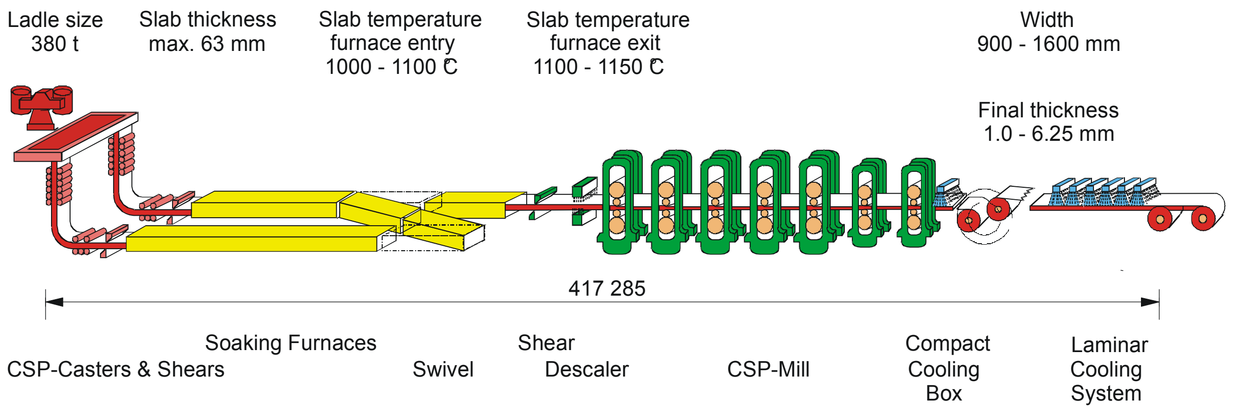


Figure 8. **CSP plant, Thyssen Krupp Stahl AG, Germany**
Slika 8. **CSP tvornica, Thyssen Krupp Stahl AG, Njemačka**

Here are the reasons why:

Firstly - conditioning of the liquid steel in the ladle furnace prior to thin-slab casting permits the desired chemical composition to be precisely set and ensures an excellent physical and chemical homogeneity of the melt.

Secondly - the high solidification rate, along with soft reduction, contributes to a high constitutional homogeneity over the cross-section of the thin slab.

Thirdly - direct charging and soaking in the tunnel furnace ensure a very uniform temperature over the length, width and thickness of the thin slab and of the hot strip. So we have available excellent conditions for reliable temperature control in the mill and on the runout roller table for setting the required final microstructure in a reproducible manner.

To summarize this: The advanced physical and chemical homogeneity of the CSP-thin slab and -strip offers superiour preconditions for processing multiphase steels.

Figure 7. shows, in schematic manner, the equipment to implement the required temperature control.

Ultra-fast cooling (UFC) boxes are provided to achieve discontinuous cooling curves at comparatively short cooling lines. As a function of strip thickness, such intensive cooling boxes enable cooling rates of approx. 250 °C / s and over. The cooling box right behind the last mill stand serves to cool the material very rapidly from finish-rolling temperature to transformation temperature so that proeutectoid ferrite can form. Normally, the concentration of carbon taking place here enables martensitic transformation of the residual austenite already at cooling rates achieved with conventional laminar cooling lines (20 - 30 °C / s). Therefore, the second ultra-fast cooling box is provided optionally; it makes the cooling line more flexible and enables a more compact design.

Similar approaches may be outlined for the production of other CSP multiphase hot strips. The costumer related design of the cooling line (length, number of UFC boxes, etc.) depends on the intended product mix and the available space.

Figure 8. shows the layout of Thyssen's CSP plant; just one UFC box right behind F7 is followed by a laminar cooling line.

The last Figure 9. exhibits the approx. 7-m long UFC box istalled in Thyssen's CSP plant.

Figure 9. **CSP Technology, Compact strip cooling - Top cooling headers opened**
Slika 9. **CSP tehnologija, Hlađenje kompaktne trake. Rashladni pokrovi su otvoreni**

CONCLUSION

Over the recent years, the range of CSP products has been extended to include practically all materials that are also processed in integrated steel plants.

Newest advanced multiphase steels are about to be processed in CSP plants too, resulting in an even further extension of the CSP product range.

LITERATURE

1. G. Flemming, K. E. Hensger: Present and future CSP technology expands product range, AISE Steel Technology, 2000, Jan., 53-57
2. B. Engl, E. J. Drewes, G. Stich: Eigenschaften und Anwendung von höherfesten Mehrphasenstählen, Stahl und Eisen, 117 (1997), 67-69
3. Werkstoffkunde Stahl, Springer Verlag Berlin,Verlag Stahleisen GmbH, Düsseldorf, 1985
4. H. Kawabe, T. Shimizu, O. Furukimi: Press formability of hot-rolled 1.4 mm thin gauge DP steel sheet with tensile strength of 590 MPa, 32nd ISATA, Advances in Automotive and Transportation Technology and Practices for the 21st Century, Vienna, 1999, 14-18 June, 225-230
5. W. Bleck, R. Kaspar, W. Müschenborn, F. Rakowski: Grundlagen der integrierten Wärmebehandlung, Stahl und Eisen, 117 (1997), 39-45
6. Thyssen Stahl AG: Mehrphasenstahl und Verfahren zu seiner Herstellung, DE 196 10 675 C1, 1996
7. M. De Meyer, B. C. De Cooman, D. Vanderschueren: The influence of Al on the properties of Cold Rolled C-Mn-Si TRIP steels, I&SM, 2000, Febr., 55-63
8. P. Peura: Ferritic-bainitic and TRIP steels for improved combination of strength and ductility, Adv. Hot rolling practice and products. Joint ECSC Steel / NEST Workshop, 2000, 5-6 Oct., 202-209