Properties of hot rolled steel strips produced by endless casting-rolling plant

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The plastic formability and the micro-structural features (homogeneity, grain size distribution, crystallographic textures) of structural and micro-alloyed steels produced in a modern endless casting-rolling line have been studied after specific experimental trials performed on the advanced industrial plant working at Arvedi Steel Technology. The investigation has pointed out interesting and outstanding mechanical features associated with the thermo-mechanical process undergone by the rolled steel strips. The obtained results have clearly pointed out that the endless process is not only a more efficient production route, but it allows a control of the operative parameters inducing micro-structural features that optimize the combination of strength and formability properties especially on the micro-alloyed steel grades. Actually, these last steel grades are more sensitive to the nucleation and growth of nano-precipitates induced by the thermal oscillation that are more pronounced and less controlled in a traditional rolling line, if compared to a modern endless casting-rolling system.

Keywords: ESP rolling - Anisotropy - Sheet forming - Crystallographic texture - HSLA

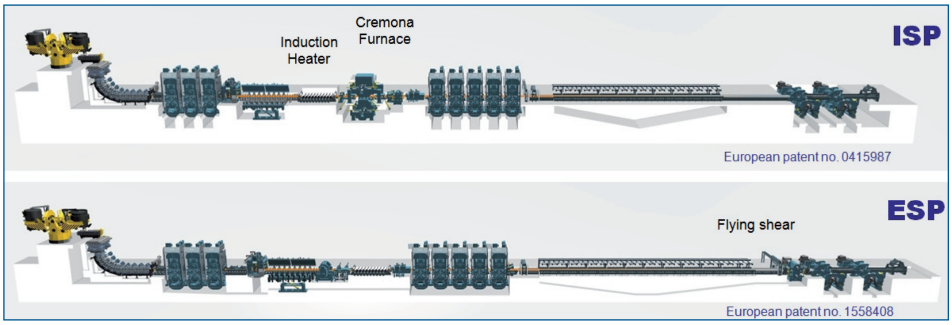

Fig. 1 – ARVEDI ISP and ESP Line layout.

Fig. 1 – Layout di ARVEDI ISP e ESP Line.

INTRODUCTION

Many innovations have been introduced in hot strip mill during the years; they have been due to the technological development in mechanical, electrical, automation knowledge and these innovation represent a key factor to save energy and the associated costs.

These factors have determined the process evolution since the '20s of the XX century and nowadays the most modern plants are endless and semi-endless ones. Since 1989 new generation of hot strip mills have been realized based on thin slab technology. This kind of plant allows to decrease the energy consumption related to re-heat furnace and roughing mill. There are some examples of this kind of plants (compact strip production, flexible thin slab casting) but one of the most innovative is the ISP (in-line strip production). ISP presents some particular plant features: the soft reduction, the in-line rolling of the thin slabs at a slow speed in the high reduction mill, the induction heater, the Cremona furnace. The main advantages of this plant are not only low rolling forces but also a wide range of process parameters to choose from, for medium – high quality products. Moreover, investment and processing costs are low due to the compact line, excellent heat efficiency and stable processing [1].

Based on the ISP technology, a new thin-slab casting process was developed: ESP (endless strip production), unlike the ISP, is an endless process (Fig. 1).

This plant allows to produce two million tons per year of a wide range of steel grades (low carbon, alloy steel, HSLA,IF, DP), with a wide range of strip widths and strip thicknesses from 12 to 0.8mm.The ESP is composed of several sections: thin-slab caster performing soft reduction and the cast rolling, the induction heater, the finishing mill and the cooling line, the high speed shear and the down-coilers. The plant total length is about 190m , this makes the ESP-Arvedi the more compact rolling line among the

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endless and semi-endless process. In addiction, energy saving and cost reduction are guaranteed.
The ESP plant has operated since 2009, only few works are present in the literatures focused on the ESP strip characteristics.
A recent work [2] shows the results of metallographic examinations on thin slabs and strip from low carbon HSLA-steel as well as the numerical simulation of the precipitation of NbC during hot rolling and subsequent cooling for HSLA steel grades produced by ESP technique. The results indicate a very high efficiency in the exploitation of the added micro-alloying elements over conventional steel production processes for producing HSLA-steel grades.
This work is focused on the investigation of the metallographic and mechanical properties of HSLA steel produced by this process and on the verification of the constancy of these features along the strip.

EXPERIMENTAL PROCEDURE

Different HSLA grades were investigated, with different minimum yield strength. The chemical composition and main process parameters are reported in Table 1. The final sheet thickness is 2 mm.

	V_cast	Slab th.	Coil th.		C	Mn	Si	P	S	Al tot.	Nb	V
	m/min	mm	Mm		max	max	max	max	max	min	max	max
S355MC	5,6	85	2		0,08	1,00	0,25	0,015	0,005	0,015	0,05	0,04
S420MC	5,6	85	2		0,08	1,4	0,25	0,015	0,005	0,015	0,06	0,05
S460MC	5,6	85	2		0,08	1,7	0,50	0,015	0,005	0,015	0,08	0,08

Tab. 1 - Chemical Analysis (% wt) and main process parameters.

Tab. 1 - Analisi chimica (% wt) e principali parametri di processo.

The steel sheets have undergone the same manufacturing route in endless mode: thanks to the reliability of ESP plant and its possibility to control the process parameters, the casting speed and consequently the beginning and final rolling speed are the same.
The tested specimens were prepared by mechanical polishing and chemical metallographic etching (Nital 2% 10s). These steels were analyzed along the rolling and the transverse direction, to evaluate the microstructural differences. This was carried out through a light microscope. More detailed investigations about the microstructure was done through SEM and EBSD.
The tensile tests were carried out by the test machine MTS Alliance RT/100®. The tests were performed according with european standard EN 10002-1, in the direction 0°, 45°, 90° respect to the rolling one. Tests were conducted in different strip region: head, center and end. The r-values were calculated at 12% strain. The collected mechanical properties were: Yield Stress (YS), Strain Hardening Coefficient (n), Tensile Strength (TS), Total Elongation at fracture (A%).
The plastic strain ratio or r-coefficient:

$$r=\frac{\varepsilon_w}{\varepsilon_t}=\frac{\ln(w/w_0)}{\ln(t/t_0)} \qquad (1)$$

was determined as prescribed by standard from tensile specimens sampled along 0°, 45°, 90° respect to rolling direction. The average r-coefficient (normal anisotropy ratio) was calculated using the following equation:

$$r_m=(r_0 + 2r_{45} + r_{90})/4 \qquad (2)$$

The possibility and the characteristics of the earing phenomenon were evaluated through the determination of the coefficient of planar anisotropy which is defined as

$$\Delta r = (r_0 - 2r_{45} + r_{90})/2 \qquad (3)$$

Bend tests were also carried out.

RESULTS AND DISCUSSION

The metallographic analyses were performed along the rolling direction. Samples were taken from different region of the strips for all analyzed steel grade. The microstructures of S460MC, S420MC and S355MC are reported in Figure 2, Figure 3 and Figure 4.
The microstructural analysis shows, in all the samples, very fine grains and even ferrite and a few content of perlitic islands. The surface is characterized by a slightly finer grain respect of the center of the plate; the grain size is very homogeneous and the difference on the different position in the coil (head, center, end) is negligible. In Table 2 the measured value of grain size are reported. In any case no abnormal ferritic grain growth is detected proximal to the surface: this suggests that austenitic rolling could be performed in endless operation, as in Arvedi ESP plant, with the temperature ranges required to obtain high quality steel grade, i.e for automotive.

Steel Grade	Position	Surface	Tickness
S460MC	Head	13,5	13
	Center	13,5	13
	End	13,5	13
S420MC	Head	12,5	12
	Center	12,5	12
	End	12,5	12
S355MC	Head	12,5	12
	Center	12,5	12
	End	12,5	12

Tab. 2 – Grain Size (ASTM E 112-10).

Tab. 2 – Dimensione del grano (ASTM E 112-10).

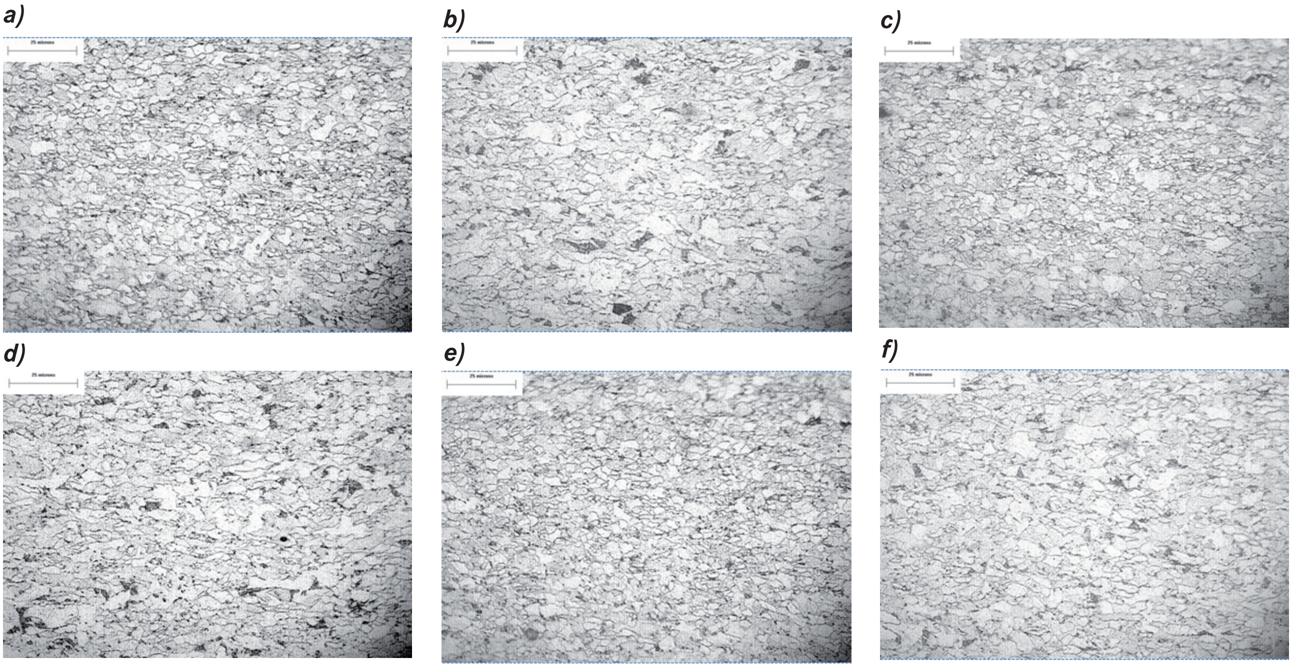

Fig. 2 – Metallographic analysis on S460MC: (a) head proximal to the surface, (b) head on the thickness, (c) center proximal to the surface, (d) center on the thickness, (e) end proximal to the surface, (f) end on the thickness.

Fig. 2 – Analisi metallografica dell'acciaio S460MC: (a) head in prossimità della superficie, (b) head lungo lo spessore, (c) center in prossimità della superficie, (d) center lungo lo spessore, (e) end in prossimità della superficie, (f) end lungo lo spessore.

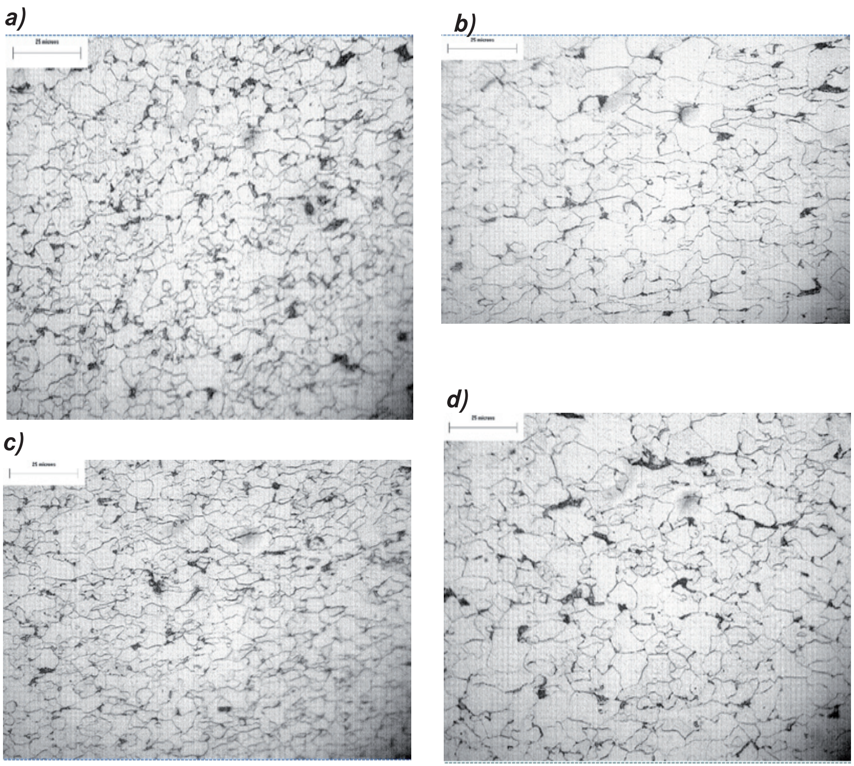

Fig. 3 – Metallographic analysis on S420MC: (a) head proximal to the surface, (b) head on the thickness, (c) end proximal to the surface, (d) end on the thickness.

Fig. 3 – Analisi metallografica dell'acciaio S420MC: (a) head in prossimità della superficie, (b) head lungo lo spessore, (c) end in prossimità della superficie, (d) end lungo lo spessore.

The mechanical tests are conducted on samples taken from different strip zone: head, center and end. The samples are representative of the direction at 0°, 45° and 90° in relation to the rolling direction (fig.5).
The mechanical tests point out a good homogeneity of properties along the stip. According to microstructural analysis, the values measured on the head, centre and end of the strips are very similar with variations of only about 20 MPa. As usual for hot rolled material, the yield strength and the tensile strength are greater along the transverse direction than along the rolling one, but the difference is very low with a good anisotropy of the sheet and there are no change in elongation.
Total elongation is an interesting feature for the ste-

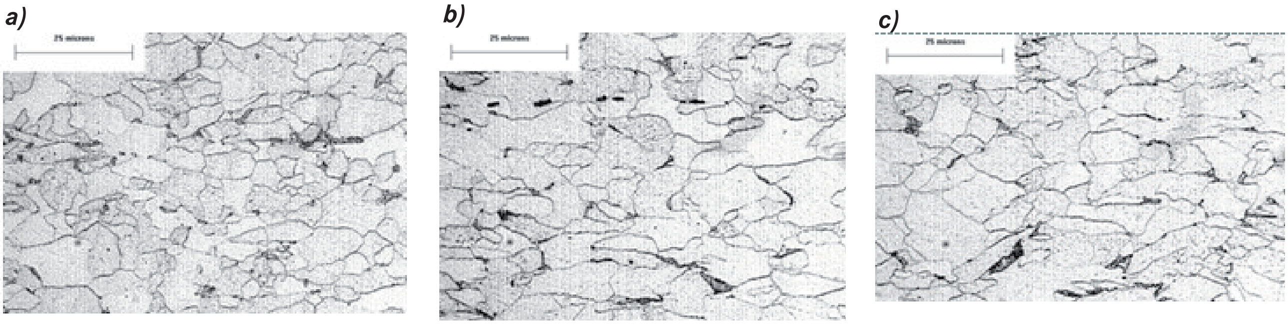

Fig. 4 – Metallographic analysis on S355MC: (a) head on the thickness, (b) center on the thickness, (c) end on the thickness.

Fig. 4 – Analisi metallografica dell'acciaio: (a) head lungo lo spessore, (b) center lungo lo spessore, (c) end lungo lo spessore.

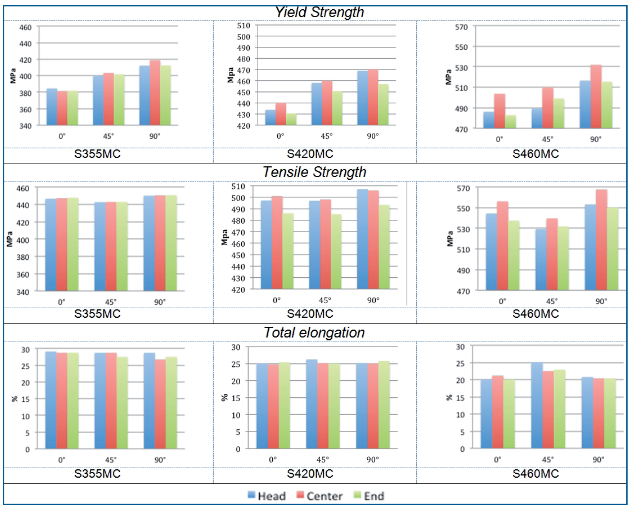

Fig. 5 – Mechanical properties of the different steel grades, in different strip sections and along 0°, 45°, 90° to the rolling direction.

Fig. 5 – Proprietà meccaniche dei diversi acciai, in diverse sezioni del laminato e orientate a 0°, 45°, 90° rispettato alla direzione di laminazione

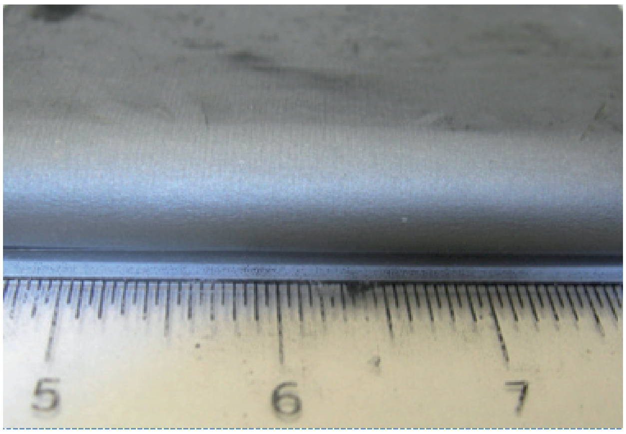

Fig. 6 – Bend test on S460MC Diameter/thickeness = 0,8 – 180°

Fig. 6 – Test di piegatura su S460MC Diametro/spessore = 0,8 – 180°

Steel id.	S355	S420	S500
n	0,17	0,15	0,14

Tab. 3 – Strain hardening coefficient.

Tab. 3 – Coefficente di incrudimento.

el drawing; actually this well represents the formability limit of the materials [3, 4]. The measured values are constant for all samples and direction and show the typical [4] decrease increasing the steel yield strength (S355MC>S420MC>S460MC). Considering the steel grades, HSLA, and the innovative process route (EAF+ESP), it is interesting to underline that these values are significantly higher that the lower limit of European standards and also automotive standards. The very good formability of the Arvedi steel grade was confirm by simple bend test, as reported in Fig. 6. No cracks are detectable on the outside bens surface.

The strain hardening exponent has been calculated for all the considered directions and for any strip section. In Table 3 the values of this parameter are reported.

The highest values of the strain hardening exponent are pointed out by steel S355MC. This implies that this steel shows a greater increase of the yield stress than the highly resistant steels after the strain hardening. This strain hardening will be induced by the plastic deformation mechanism that can be applied by cold forming operations. The higher the hardening coefficient the more homogeneous is the distribution of the strain along the different directions during the plastic deformation and this provides a better formability [5].

The measurements of r-coefficient were carried out at defined strain (12%). The experimental data show the greatest values of the r-value along the direction at 45° from the rolling one. The average r-coefficients (normal anisotropy ratio) were calculated, applying the Eq. (2). If the normal anisotropy is greater than unity (deep-drawing steel cold rolled and annealed), it may be associated with a greater

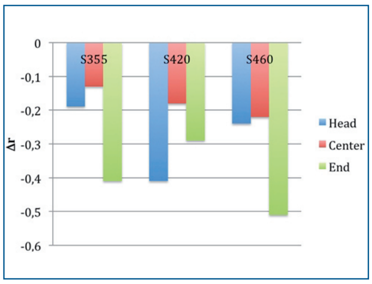

Fig. 7 – Average r-coefficient for the different steel grades and strip section.

Fig. 7 – Media del coefficente-r per differenti acciai e diverse sezioni del laminato.

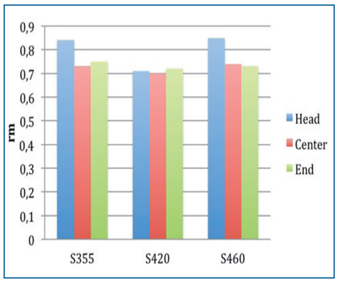

Fig. 8 - Planar anisotropy coefficients for different steel grades and strip section

Fig. 8 – Coefficienti di anisotropia planare per differenti acciai e diverse sezioni del laminato.

strength in the trough-thickness direction and, generally, to thinning [5]. These value, less than unit, indicate the slightly tendency of the sheet to undergone thinning. For hot-rolled HSLA steels rm value is always less than 1. The three steel grades show similar behavior with rm values in the range 0,7-0,9 (Figure 7).
The planar anisotropy was calculated applying the Eq. (3), for the three steels. This coefficient is a measure of the magnitude of the r45° value compared with the ones featuring the other direction coefficients [5,6]. The values show the tendency of any steel to point out slightly earing phenomenon. If the magnitude of the planar anisotropy is large, either positive or negative, the orientation of the sheet with respect to the die of the part to be formed will be important. Earing could verify at the end of the strip but it will be less pronounced at the strip center. At the strip center the values are close to zero and this indicate the formation of flat edge during deep drawing. These steels are usually used in automotive and this Δr values are good for sheet forming.
The EBSD investigation is needed to better understand the metals anisotropy [7,8,9,10]. The EBSD results are reported in figure 9. The inverse polar figures are reported for each studied steel.
For all the steel grades the inverse polar figures show that [101] direction are preferentially aligned along the rolling directions. The texture is weak and this situation is probably associated to a recrystallization phenomenon, as previously pointed out in the metallographic results. These results are also validated by Ray and al. actually, after a finish rolling procedure performed at 1020°C, the main texture components in both steels are the {001}〈110〉 and the {110}〈110〉. These textures components represent the main recrystallization component derived from the texture component featuring the γ-phase (austenite): namely the cube texture and its twins. The sharpness of the rotated cube component {001}〈110〉 component increases as the finish rolling temperature is decreased (Table 4) {110}〈110〉, whereas {110}〈110〉 component is very intense after the rolling of the ferrite phase has taken place[11].
The orientation along the [101] is originated by a transformation phenomenon and the rm values obtained by mechanical tests are consistent with the values pointed out by [11] (table 5).

1020°C	870°C	730°C	630°C
{001}〈110〉	{001}〈110〉	{001}〈110〉	{001}〈110〉
{110}〈110〉	{110}〈110〉	{110}〈110〉	
		{223}〈110〉	{223}〈110〉
		{554}〈225〉	{554}〈225〉

Tab. 4 - Texture observed after finishing rolling in plain carbon steel

Tab. 4 - Tessiture osservate dopo la passata di finitura in acciai al carbonio

Texture component	Source	r_m	Δr
{001}〈110〉	Transformation	0,4	-0,8
{113}〈110〉	Transformation	1,0	-1,7

Tab. 5 – Major transformation texture components and their related orientations

Tab. 5 – Principali componenti di trasformazione delle tessiture e relative orientazioni

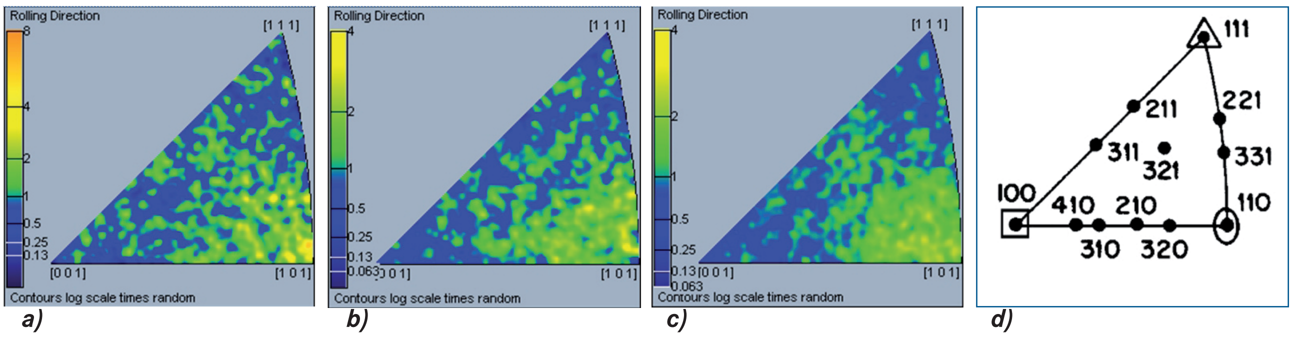

Fig. 9 – Inverse polar figure of (a) S355, (b) S420; (c) S460 and (d) key-map.

Fig. 9 – Polari inverse di (a) S355, (b) S420; (c) S460 e (d) key-map.

CONCLUSIONS

The ESP process appear very efficient for the in-line rolling of the high quality steel (i.e. for automotive application). The first results of the characterization of three different HSLA steel grades (S355MC, S420MC, S460MC) point out a very good formability attitude that is associated to the strength properties imposed by steel specification. Such a behavior can be explained by the satisfactory microstructural features induced at the surface and at the core of the in-line hot rolled plates. The endless production route guarantees the stability of the properties along all the strip (head, center, end).
Future definition of Formability Limit Diagram and crystallographic investigation can cast new light on the relations between the microstructural features and the mechanical behavior of the investigated steel.

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PROPRIETÀ DI ACCIAI LAMINATI A CALDO PRODOTTI MEDIANTE ENDLESS CASTING-ROLLING

Parole chiave: ESP - Anisotropia - Imbutitura - Tessitura cristallografica - HSLA

In questo lavoro è stata studiata la formabilità e le caratteristiche microstrutturali (in termini di omogeneità, dimensione del grano e tessitura cristallografica) di acciai al carbonio e micro-legati prodotti in un moderno impianto ESP (endless strip production) a seguito di specifiche prove realizzate presso l’acciaieria Arvedi Steel Technology. L’analisi ha mostrato le interessanti ed eccezionali proprietà meccaniche raggiunte dai laminati associate a differenti processi termo-meccanici. La caratterizzazione ha evidenziato che il processo ESP è più efficiente dal punto di vista produttivo di un impianto tradizionale e permette un ottimo controllo dei parametri operativi in modo da indurre opportune caratteristiche microstrutturali in grado di ottimizzare la combinazione di resistenza meccanica e di formabilità, specialmente per acciai micro-legati. In effetti, questa tipologia di acciai è sensibile alla nucleazione e successivo accrescimento di nano-precipitati indotti dalle oscillazioni termiche più pronunciate e meno controllate in una linea di laminazione tradizionale rispetto alle medesime riscontrate in un impianto ESP.