Effect of Coiling Temperature on Formability and Mechanical Properties of Mild Low Carbon and HSLA Steels Processed by Thin Slab Casting and Direct Rolling

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Production of hot rolled HSLA steel strip is nowadays a well known practice; however information about the possibility to set their mechanical and formability performances through the control of the coiling temperature is quite rare, although the knowledge of this aspect can really improve the efficiency of the production process avoiding the application of other successive thermal treatment to condition the steel. In the present investigation a Nb-alloyed grade, a Nb–V grade and a V-grade have been rolled and coiled at different temperature and their mechanical, formability properties and attitude to the strain aging has been measured as a function of two different coiling temperatures. The results obtained on a mild low carbon steels which have undergone the same technological route have been used as a term of comparison. In the mild steel and in the Nb-alloyed ones the lowering of the coiling temperature improves the strength properties and the attitude to the strain aging, while decreases the formability of the steels while in the V-grade the coiling temperature performs a lower influence on these properties. This situation is confirmed also by the textural measurements and is probably related to the different removing rate of the interstitial elements, i.e. C and N. Actually, in the vanadium grades the precipitation temperature of the compounds formed by the vanadium and interstitial elements takes place about at the same thermal range of the coiling temperature producing a significant slowing of the kinetics of the nucleation and growth of those phases. This statement concerning the fundamental role played by the concentration of the interstitial elements kept in solution in the metal matrix) seems to be supported by the strain aging measurements, which show a clear strain aging of the V-grade only after the artificial heating up which promotes their precipitation of the compounds formed by the interstitial elements.

KEY WORDS: HSLA; rolled strips; coiling temperature; strain aging; textures; formability.

1. Introduction

The formability of a steel sheet is related to its attitude to undergo the deformation during forming operations without the appearance of necking or fracture, which indicates the development of instability phenomena. In the plastic forming operations, i.e. drawing, the instability is associated to the excessive localized thinning of the sheet, that is the equivalent of necking in uniaxial tension loading. The prevention of the fracture phenomena is the key to assure an optimized productive process and an efficient application of the steel produced following the designed technological route. Especially on the demand of the automotive industry, a wide class of materials featured by enhanced strength has been developed. Among these high performing steels, High Strength Low Alloysed (HSLA) steels are very popular and have encountered an important success. The definition of such a class of steels is arbitrary enough, but they can be identified for the presence of elements intentionally added in low concentrations (<0.04–0.03 %). The mainly exploited alloying elements are represented by Ti, Nb, V and B. These elements interact with C and N giving rise to some nano-precipitates which influence the dynamic of the recrystallization process, the nucleation and growth of the phases after the solid phase transition, the associated development of the crystallographic textures and the strength properties of the steels through the interaction with the crystal dislocations. The precipitation of the microalloying elements is influenced by their concentration and by the thermal pattern followed by the steels. One of the main interesting and cheap possibilities in the integrated design of the rolling route and of the chemical composition of the steel is the modulation of the coiling temperature in order to control crystallographic textures and the related mechanical properties.

The formability of metal sheet is strictly influenced by the strain hardening exponent n, the plastic strain ratio r and the strain rate sensitivity coefficient m; information about the straining behavior during the plastic deformation of the
sheet can be described in a more complete way by the so-called Forming Limit Diagram (FLD), by which it is possible to predict plastic instability phenomena related to complex states of deformation. In this study these experimental parameters measured according to the respective standard test methods\(^9\) have been applied to reach a satisfactory characterization of the steel properties as a function of the adopted coiling temperature. The strain aging properties of the strip have been also considered, since these phenomena can be detrimental but also exploitable along the technological route applied to the steel, particularly for the possibility to obtain the bake hardening during the processing of the strip (i.e. during the painting of the car panels).

All these features are shown and analyzed as a function of two main parameters, the chemical composition and the coiling temperature: four chemical compositions (mild C steel, Nb, V and Nb–V steels) and two coiling temperatures (580°C and 680°C respectively) have been considered in order to develop this study.\(^6,7,9\)

2. Experimental Procedure

The chemical compositions of the tested materials are reported in Table 1. Four classes of materials are considered: mild low carbon steel and some HSLA steel grades, containing as alloying elements Nb, V, and Nb–V. The hot rolled studied strips are 1.5 mm thick and are produced by the thin slab casting and direct rolling (TSDR) technology at I.S.P (In-line Strip Production) plant of Acciaieria Arvedi SpA in Cremona (Italy) have been investigated\(^10\) using a typical mild steel as the reference condition for the discussion of the results (Fig. 1). The Arvedi plant has been chosen to perform the industrial experimental trials for its high flexibility and the good control assured on the final coiling temperature; moreover, the obtained results can be regarded as easily transferable to the industrial practice.

The temperature at the coiling station is the only varied operative parameter; during the processing schedule in the rolling stands all the investigated steels follow to the same thermal profile, exiting from the last finishing stand at nearly 870°C. From this point two different cooling rates are set, thus resulting in two different values at the coiling station, namely 680°C and 580°C. The eight different experimental conditions are listed and denominated in Table 1. The characterization of the fundamental mechanical properties, of the hardening exponent \(n\) (ASTM E 646), of the plastic strain ratio \(r\) (ASTM E 517) and of the strain rate sensitivity associated to each experimental condition have been carried out by tensile tests. As usual for the evaluation of properties of a rolled sheet, sampling of specimens has been carried out along three directions respect to the rolling direction (RD) of the strip, i.e. tensile specimen axis is oriented at 0°, 45° and 90° to RD. The metallographic examination has permitted to measure also ferritic grain size according to ASTM standard A112.

The determination of the Forming Limit Diagram (FLD) has been carried out with some drawing tests in the Nakazima configuration. The test has been performed according to ASTM E2218. The size of the apparatus, particularly the diameter of the loading punch, is compelled by the maximum axial force expressed by the testing machine, a 150 kN MTS© electro-mechanic universal testing machine.

Table 1. Resume of the considered experimental conditions, i.e. chemical composition and coiling temperature.

<table>
<thead>
<tr>
<th>Steel</th>
<th>Chemical Composition (% wt)</th>
<th>°C coiling (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mild Steel</td>
<td>580</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>680</td>
</tr>
<tr>
<td>3</td>
<td>Nb</td>
<td>580</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>680</td>
</tr>
<tr>
<td>5</td>
<td>V</td>
<td>580</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>680</td>
</tr>
<tr>
<td>7</td>
<td>V-Nb</td>
<td>580</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>680</td>
</tr>
</tbody>
</table>

Fig. 1. Layout of the casting and rolling line in the AST (Arvedi Steel Technology) plant.
and it has been estimated by Eq. (1) in order to evaluate the maximum punch load:

\[ F = 0.7tD \pi \cdot UTS \]  

(1)

where \( t \) is the sheet thickness (in this case 1.5 mm), \( D \) the punch diameter (50 mm) and \( UTS \) ultimate tensile strength (in the studied cases this reaches a maximum value of 500 MPa). An equipment with a 75 mm punch (the lower punch diameter required from the standard) would reach the maximum load of the testing machine before the test is finished. In a recent study, the effect of the punch diameter on FLD has been investigated: comparison among the tests characterized by different diameters demonstrates that this variable is not influencing on the final result; on the basis of this outcome, the results of the formability tests performed with a 50 mm punch diameter could be considered reliable and significant. The sampling of the coupons has been planned to collect a wide range of data, since different sizes of samples involves a different strain path for the sheet (for this reason seven different shapes were obtained, \( \text{i.e.} \) from the 130×130 mm (to obtain the performance of the material near to biaxial stretching condition, to the rectangular 95×130 mm, 80×130 mm, 65×130 mm, 50×130 mm and the 30×130 mm sample). The orientation of the samples is parallel to the major side of the sample. A typical configuration for the Forming Limit Diagram (FLD) is presented in Fig. 2: this diagram reports on the axis the values of the strains measured evaluating the deformation of the dot markers during the test. The deformation of markers is reported in terms of the measure of their two principal axis, that is to say along the rolling and the transverse direction of the sheet.

On the basis of the strains measured on the markers of each tested specimens and on the basis of corresponding situation of the materials—integrity, presence of necking or other instability phenomena—it is possible to define the regions of safe or unsafe behaviour of the material; the border between these behaviours represents the forming limit curve (FLC). Particular importance is given to the value of the FLC corresponding to plain strain condition (minor true strain \( \varepsilon_2 = 0 \)), that is the most critical deformation state faced by the sheet during drawing, usually corresponding to the minimum value of the curve, defined as FLD0.

The entity of the strain ageing of the tested materials has been evaluated measuring the variation in mechanical properties due to trapping of dislocations played by interstitial atoms in solution, namely C and N. The adopted experimental procedure is structured to estimate the ageing effect and aims at determining the strain ageing through the index \( \Delta P/P \) defined in Eq. (2) (Fig. 3), which is the variation of the yield stress of the steel after a pre-straining and a period of storage at room temperature or at particular temperature.

Finally, crystallographic textures of the rolled strip have been considered, since the strong relation between the orientation of crystalline grains induced by the thermo-mechanical processing and the properties shown by the material during the successive sheet forming operations is widely known. Representation of textures has been obtained in terms of orientation distribution functions (ODF), where orientation of single crystals is represented by three angular coordinates (\( \varphi_1, \Phi, \varphi_2 \)) in a tridimensional Euler space. ODFs are the results of Electron-Back-Scattering-Diffraction (EBSD) experiments over a 750×300 mm area, with a 6 \( \mu \text{m}^2 \) resolution and a working tension of 20 kV for the SEM electron beam, as reported in some previous papers.

The TEM observations have been performed on the different steel grades after the electrolytic thickening and applying a working voltage of 200 kV for the TEM electron beam. The average investigated area for each sample is of 0.9 \( \mu \text{m}^2 \). Because of the little size of the examined area these observations are featured by a low statistical significance, but they can offer a qualitative indication of the distribution of the nano-precipitates which appears useful for the interpretation of the experimental results.
### 3. Results and Discussion

Dealing with hot rolled low carbon steels, usually the right choice for a given application is to find a good compromise between strength and formability properties. In Table 2 the measurement of the ferritic grain size is recorded, as revealed by the optical micrographs after chemical etching (Nital 2% applied for 10 s) (Fig. 4).

Grain size is almost constant all over the thickness of the strip: it is clear that the microalloying elements play a fundamental role in controlling this feature, mainly for the case of Nb–V steels, where ASTM G index reaches the maximum of 12 indicating the finest grain size. The coiling temperature effect is clear and also its relation with the grain size: the higher the coiling temperature the lower the G index, which indicates a more coarsened grain.

The results of the tensile tests are recorded in Table 2 with the yield strength LYS, ultimate tensile strength UTS, yield point elongation YPE, elongation at fracture EL and strain hardening index $n$. All these values have been estimated through the averaging procedure (3):

\[
X = \frac{(X_0 + 2X_{45} + X_{90})}{4}
\]

where $X$ represents a generic tensile property (i.e. LYS, UTS, EL, n) in correspondence of the direction rotated by an angle of 0°, 45° and 90° from the rolling direction.\(^\text{14}\)

To summarize qualitatively the trend followed by the properties as a function of the specimen axis with respect to the rolling direction, an increase of the yield strength passing from 0° to the 45° and to the 90° condition has been observed; this is shown in Fig. 5.

Moreover, the tensile strength shows a minimum value for the samples at 45° and this is common to all the investigated steel grades. A clear influence of the coiling temperature on the averaged tensile properties has been pointed out, although the V-alloyed grade seems to be less sensitive to the applied variation of the coiling temperature; although this exception the coiling temperature appears to be a parameter which becomes of primary importance for the optimization of the productive process, in order to take the maximum advantage from the specific addition of microalloying elements. The decreasing of the coiling temperature seems to cause the increasing of yield and ultimate tensile strength only for the mild steel and for the Nb-alloyed ones, while the effect of the coiling temperature seems to be not significant on these properties of the V-alloyed grade. Although in all the steel grades the increasing of the coiling temperature implies an improving of the ductility as indicated by the increase of the elongation at fracture (EL), the increase of the micro-alloying concentration seems to lessen this tendency; actually the maximum increase is related to the mild steels and the minimum is observed in the steel alloyed by V. This statement is probably due to the presence of the strengthening particles produced by the micro-alloying elements and by the interstitial ones which have a detrimental effect on the ductility. From the combination of the information provided by the tensile mechanical properties and by the ductility ones is evident that the interstitial elements, i.e. carbon and nitrogen played a strengthening role related to the precipitation of the carbide in the mild steel and of carbide and complex carbo-nitride in the micro-alloyed grades.\(^\text{13}\) This effect is particularly pronounced in the mild steels and in the grades containing Nb, while the grade alloyed only by V seems to be not particularly sensible to the variation of the coiling temperature.

In the present study, $n$, $r_m$ and $\Delta r$ values of the investigated steel grades are contained within the typical ranges for these types of alloys.\(^\text{13}\) Among the microalloyed steels, higher normal plastic anisotropy (expressed by the $r_m$ values) are obtained in the V-steel sheets and a general trend to increase $r_m$ values as the coiling temperature increases is evident. The planar anisotropy values, which are correlated

#### Table 2. Resume of results from mechanical characterization with tensile tests.

<table>
<thead>
<tr>
<th>Steel</th>
<th>G</th>
<th>LYS [MPa]</th>
<th>UTS [MPa]</th>
<th>YPE [%]</th>
<th>EL [%]</th>
<th>$n$</th>
<th>$r_m$</th>
<th>$\Delta r$</th>
<th>$m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Mild Steel</td>
<td>10</td>
<td>349</td>
<td>409</td>
<td>3.66</td>
<td>30</td>
<td>0.17</td>
<td>0.91</td>
<td>-0.11</td>
<td>0.008</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>280</td>
<td>354</td>
<td>0.49</td>
<td>38</td>
<td>0.16</td>
<td>0.95</td>
<td>-0.05</td>
<td>0.014</td>
</tr>
<tr>
<td>3 Nb</td>
<td>11</td>
<td>385</td>
<td>432</td>
<td>3.56</td>
<td>27</td>
<td>0.16</td>
<td>0.91</td>
<td>-0.24</td>
<td>0.010</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>386</td>
<td>440</td>
<td>2.07</td>
<td>33</td>
<td>0.14</td>
<td>0.93</td>
<td>-0.18</td>
<td>0.007</td>
</tr>
<tr>
<td>5 V</td>
<td>11</td>
<td>402</td>
<td>467</td>
<td>2.02</td>
<td>29</td>
<td>0.13</td>
<td>0.95</td>
<td>-10</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>398</td>
<td>466</td>
<td>1.01</td>
<td>31</td>
<td>0.12</td>
<td>0.99</td>
<td>-0.06</td>
<td>-</td>
</tr>
<tr>
<td>7 V-Nb</td>
<td>12</td>
<td>444</td>
<td>496</td>
<td>2.58</td>
<td>27</td>
<td>0.13</td>
<td>0.91</td>
<td>-0.22</td>
<td>0.010</td>
</tr>
<tr>
<td>8</td>
<td>11</td>
<td>429</td>
<td>486</td>
<td>1.96</td>
<td>30</td>
<td>0.13</td>
<td>0.93</td>
<td>-0.23</td>
<td>0.006</td>
</tr>
</tbody>
</table>

![Fig. 4. Revealed microstructure of (a) Steel 1, (b) Steel 5 revealed by Nital 2% etching.](image-url)
closely with the amount of earing that occurs in deep drawing, are all negative and this indicates the tendency to form earing at 45° respect to the rolling direction, but it is worth noting that this value is near zero for the steel with higher r values realizing a good and advantageous combination of the formability properties.

The definition of the Forming Limit Diagrams (FLD) (Fig. 6) has allowed to separate the field of safe behaviour from that characterized by instability (necking or fracture). As indicated by ASTM E2218 standard for the drawing of the curve, this curve must lie below all the instability points (necking and/or fractures) verified on the tested samples.

The FLD0 values (Fig. 7) (Table 3) corresponding to the most dangerous condition featured by plane strain and representing the minimum point of the FLD diagram have been experimentally determined, collected and compared with the values estimated on the basis of the empirical relation extrapolated by Keeler12) specifically for the microalloyed steels:

\[ \text{FLD}_0 = (67.304 \cdot t + 110.95) \cdot n \]..............(4)

where \( t \) is the thickness of the strip, \( n \) the strain hardening index.

Comparison of the computed values with those experimentally obtained shows a clear discordance, i.e. FLD0 from mechanical tests seems to be shifted to the lower values respect to the computed ones, by a factor that could be estimated in 7%. On the other hand, this variation could be due to the experimental conditions, especially to the size of the adopted dot marker (4 mm diameter in these tests, vs. 2.54 mm in the standards and in Ref. 11). Looking at FLD0 values, these results do not differ in a significant way from those found in literature for hot rolled microalloyed steels. The coiling temperature seems to be not significant, whereas the different chemical composition and the different microalloying elements clearly affect the trend of the forming limit curve. The best values are provided by the mild steels, while the presence of V seems to be detrimental for the value assumed by FLD0 and tends to lower the whole forming limit profile. The steel classes containing Nb as an alloying element show higher FLD0 values and a better behavior in the plane tensile stress zone. The analogous trend shown by the strain hardening index and by FLD0 is consistent with the information contained in literature.11)

Yield point elongation (YPE) is a very significant parameter for steel sheet for drawing operations, since it describes the extension of the period of non uniform deformation after yielding, also because it affects the quality of forming operations for contained plastic strains. This value is essentially influenced by the concentration of the interstitial elements in solution, i.e. carbon and nitrogen, and it is consequently related to the strain aging behavior. For this parameter the coiling temperature has a marked influence: the trend to reduce the extension of the plateau of instability after the yielding is related to the decrease of the coiling temperature and this relation is respected for all the studied steel grades.

The results about the strain aging (Table 4) have been elaborated taking into account the typical anisotropy affecting this kind of products, so a mean strain aging parameter

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Fig. 6. Resulting FLDs for the steels studied.

Fig. 7. Comparison of the FLD₀ and index \( n \) values trends as function of the chemical composition and of the coiling temperature.

Table 3. Comparison of estimated and measured FLD₀ values.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLD₀ estimated</td>
<td>36</td>
<td>34</td>
<td>32</td>
<td>30</td>
<td>28</td>
<td>25</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>FLD₀ measured</td>
<td>46</td>
<td>45</td>
<td>36</td>
<td>38</td>
<td>34</td>
<td>32</td>
<td>36</td>
<td>34</td>
</tr>
</tbody>
</table>
has been calculated on the basis of the averaging procedure described in Eq. (3) obtained from specimens with the tensile axis rotated 0°–45°–90° from the rolling direction of the strip.

\[
(\Delta P / P)_{\text{mean}} = \frac{\Delta P / P_0 + \Delta P / P_{45} + \Delta P / P_{90}}{3} \ldots (3)
\]

A general classification of behavior of steels regarding to the aging tendency could be based on this classification:
- \(\Delta P / P < 10\%\) steels with no tendency the aging;
- \(10\% < \Delta P / P < 14\%\) steels with mean tendency to aging;
- \(\Delta P / P > 14\%\) steels with strong tendency to aging.

The results provided by the two adopted aging procedures (Fig. 8) indicate the sharp effect produced by the coiling temperature on the aging intensity: the steels coiled at higher temperatures could be considered as not affected by aging effects, whereas the lower coiling temperature implies the production of steels strongly affected by this phenomenon. In this case the mild low carbon steel and the Nb-alloyed grades show the greatest tendency to aging in natural aging condition, but what is more impressive is the different behavior shown by the V-alloyed grade which after the artificial aging has pointed out a significant increase of the aging parameters.

These statements, obtained about the YPE and the strain aging behaviour, casts a light which can permit to provide a reliable interpretation of the dependence of the measured mechanical characteristics on the chemical composition and on applied coiling temperature. In the V-alloyed grade the formation of the vanadium-based precipitates remove a lower quantity of the interstitial free elements, i.e. carbon and nitrogen, than the amount removed by Nb and this due to the different thermal range interesting the precipitation. Actually, in the analyzed range of chemical composition the vanadium carbo-nitrides begin to precipitate at a lower temperature than the niobium ones and this delayed precipitation associated to the lower temperature range limit the growth of the precipitates promoted by the diffusion process which is temperature controlled as seems to be confirmed also by the TEM observations (Fig. 9).

As a consequence of this situation the described phenomenon is accentuated by the lowering of coiling temperature which further slows the removing of the interstitial elements from the metal matrix as suggested by the experimental evidences. In order to corroborate this hypothesis, it is worth noting that in all the examined steel grades the lower the coiling temperature is, the higher is the strain aging attitude due to the larger amount of the interstitial elements kept in solution. The importance of the kinetic aspect is pointed out by the fact that also in the vanadium-grade coiled at the lowest temperature the super-saturation interesting the steel is so high that, after the artificial strain aging, the yield strength increase is the largest revealed by the measurement, because the induced heating activate the strengthening process due to the precipitation of the interstitial elements (Fig. 10).

In the mild low carbon steels and in the Nb-alloyed
grades the modulation of the coiling temperature is always effective and it is possible to state that the highest coiling temperature implies a decrease of the tensile strength properties, an increase of the ductility, a reduction of the entity of the strain aging and an increase of yield elongation point. All these phenomena are consistent with the hypothesis that the lowest coiling temperature imposed after the finishing rolling maintain in solution a larger amount of the interstitial elements which cannot precipitate under the form of carbide, nitride or complex carbo-nitride but can develop their strengthening effects after a thermal cycle composed by a heating up for a certain period (Fig. 11).

The representation of the orientation distribution function (ODF) reported in this paper has been limited to the section of the Euler space, since it is widely known that the major textures components involved in the deformation and in the transformation related to the rolling of the bcc cell alloy lie in this section of the Euler space (Figs. 12, 13).

Ignoring the effects due to friction between strip and rolls, the shown textures are related to the core of the strip. Comparing images obtained from EBSD (Fig. 13) with the theoretical reference reported in Fig. 12 some information about the mechanism that produced a particular texture component could be obtained (i.e., plastic deformation, recrystallization, phase transformation, etc.); in this way it is possible to formulate plausible hypothesis about the crystallographic evolution of the microstructure, associating this aspect with the thermal cycle and with the mechanical properties exhibited by the strip.

Results for crystallographic textures analysis after EBSD experiments are discussed in detail in some previous studies and in literature are also summarized some fundamental aspects, mainly related to the macroscopic behavior of the material.

For all the investigated steels the texture components derived from the recrystallization of austenite stand out, also in the case of the microalloyed steels, where elements like vanadium and mostly niobium are effective in retarding the kinetics of the phase transformation. The effect of Nb in the delaying of the recrystallization is due to the fact that (as already mentioned) for the concentration object of this investigation the precipitation of niobium-based compounds precipitate at a thermal range significantly higher than the...
\(\gamma-\alpha\) phase transition. The textures inherited by microalloyed steels seem to be slightly influenced by the coiling temperature: for the highest coiling temperature the steel texture are organized in some fiber and this is especially evident for the vanadium alloyed steels. For the studied materials undergoing the designed processing, the texture components from phase transformation of deformed and non-recrystallized austenite seem to reach a relative predominance over the ones derived from recrystallized austenite: for example, in Steel 4 the Cube components are not present and in Steel 6 and Steel 8 \(\beta\) and \(\gamma\) fibers are well distinct. A possible interpretation of this outcome could be related to the grain growth of ferritic grains after phase transformation: since the strained and non-recrystallized austenitic grains are favored to activate first the phase transformation due to the higher stored energy, the ferrite nucleated grains are advantaged to realize the subsequent coarsening. Moreover, the fastest nucleated ferrite grains are in the best condition to grow at the expense of the adjacent grains lately nucleated, because the size of a grain larger than the average size of the other surrounding grains is one of the main condition supporting the selective growth of the greatest grains at the expense of the most little within the transformed micro-structure.\(^5\) It is interesting that the chemical composition seems to affect the texture pattern in a way analogous to the variation observed in the mechanical properties: the V-alloyed grades seems to show less differences between the different coiling temperatures than the mild low carbon steels and the Nb-alloyed ones. The most probable reason is still related to the thermal range interesting the formation of the vanadium-based precipitates which makes the difference of the coiling temperature nearly non-effective. On the other hand, the role played by the vanadium seems clearly to induce favorable values of high normal anisotropy coefficient and planar anisotropy coefficient nearly null related to the formation of clear texture components distributed along the \(\gamma\)-fiber and around the very intensive Goss component \(\{110\}\langle 100\rangle\).

4. Conclusions

In this study, formability properties of mild low carbon steels and of some steels microalloyed by vanadium and niobium produced by the in-line Thin Slab Direct Rolling plant (TSDR) have been investigated in order to evaluate the possibility to modulate the steel properties through the control of the temperature at the coiling station which can be cheaply and strictly controlled.

(1) The correct modulation of the coiling temperature as a function of the chemical composition of the steel can permit to modulate the mechanical, formability properties and the attitude to undergo the strain aging phenomenon.

(2) The applied coiling temperature has proven to be a crucial factor to control the strength and formability properties of the mild low carbon steel and of the Nb-alloyed ones. In these cases the higher coiling temperature allows a more extensive precipitation of the interstitial elements from the metal matrix. This phenomenon enhances the formability properties and the attitude to the strain aging proved by the highest values assumed by the yield strength also after the performed natural aging procedure.

(3) The lowest coiling temperature increases the keeping in solution of the microalloying and interstitial elements and this increases the YPE and the tendency to strain aging.

(4) The V-alloyed grade shows a significantly different behavior if compared with the mild steel and the Nb-alloyed ones because it seems insensitive to the variation of the coiling temperature and this is confirmed also by the developed texture pattern which shows only little variation between the two coiling regimes. The most reliable hypothesis is that this phenomenon is due to the significant slowing imposed to the precipitation and growth of the vanadium compounds in the both the applied thermal coiling regimes.

(5) This last statement, implying a strong super-saturation of the micro-alloying elements in the metal matrix after the coiling, is corroborated by the fact that after the artificial aging of the steel coiled at the lowest temperature this one undergoes the largest observed strain aging probably due to the activation of a huge precipitation of the interstitial elements.

(6) The V-alloyed steel grade stands out the best formability properties due to the good combination of high normal anisotropy coefficient and the nearly null planar one. This is due to the formation of the favourable texture components distributed on the \(\gamma\)-fiber and the Goss one \(\{110\}\langle 100\rangle\).

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Nomenclature

- \(r\) : Normal anisotropy coefficient of a tensile specimen
- \(r_m\) : Average anisotropy coefficient of a tensile specimen
- \(r_s\) : Anisotropy coefficient measured on a specimen taken along a direction rotated by \(X\) from the axis of the rolling direction
- \(\Delta R\) : Planar anisotropy coefficient
- \(EL\) : Elongation at fracture
- \(FLD\) : Forming limit diagram
- \(FLD_0\) : Minimum point on the forming limit diagram corresponding to the plane strain state
- \(YPE\) : Yield point elongation [MPa]
- \(UTS\) : Ultimate tensile stress [MPa]
- \(LYS\) : Lowest yield stress [MPa]
- \(P\) : Stress applied during the tensile test [MPa]
- \(P_x\) : Stress applied during the tensile test on a specimen taken along a direction rotated by \(X\) from the axis of the rolling direction [MPa]
- \(n\) : Strain hardening coefficient
- \(m\) : Strain rate sensitivity coefficient
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