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# RECENT DEVELOPMENTS OF HIGH STRENGTH LINEPIPE STEELS ON COIL

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## ABSTRACT

The present paper deals with the recent steel development for linepipe applications at ArcelorMittal. With the recent upgrade of the downcoiler capabilities in three European steel plants it is now possible to supply hot rolled coils in width up to 2150mm for the economical production of X70 large diameter, spiral welded transmission trunk lines with 25.4mm wall thickness.

In view of the increased dimensional feasibility range a couple of new product development projects had been launched. Two of these products with very demanding application properties are already being industrialized. It concerns respectively X70 in 22mm thickness with improved low temperature BDWTT properties (85% shear area at -10°C) and X80 in 16mm, likewise with low temperature BDWTT properties and, additionally, with low Y/T ratio. The first pre-series deliveries have been successfully transformed to pipes in one of our client's spiral welded pipe mill. Another product development project which is still in the conception phase concerns the development of X100 in thickness up to 12.7mm. The actual progress of the mentioned projects will be documented here.

Key for the realization of such demanding products is a precise control of the final microstructure. This is in particular true for high strength steels with improved toughness. Therefore, a lot of research efforts were spent in order to understand the link between microstructures and properties. Our current understanding will be detailed in this paper.

## INTRODUCTION

Large diameter, high-pressure transmission pipelines are the most economical means to transport gas from the wells in remote areas to the consumption areas. The transport efficiency is being determined by the balance between pipe diameter and gas pressure. Modern gas pipelines have outer diameters (OD) of 1200mm (48 inch) or even more and may operate at pressures exceeding 10,000 kPa (1,500 psi). The internal pressure in the pipeline has to be opposed by the circumferential strength of the pipe skelp which is usually made of steel. The most commonly used steel grade today is X70. An increase of the operating pressure or the pipe diameter necessitates either an increase of the wall thickness or the replacement by higher strength steels as, e.g. X80, or both.

Until recently, the main source of high-strength large diameter linepipes with high wall thickness above 18mm have been longitudinally submerged arc welded (LSAW) pipes, also called UOE pipes, according to the production process starting from heavy plate. However, due to the inherent discontinuous processes of respectively plate and pipe production, UOE pipes are generally more expensive than pipes made from coil. The latter are more cost efficient since as well hot strip coil processing as pipe production are continuous and characterized by high productivity. Pipes made from hot strip coil are either longitudinally welded (electrical resistance welding, ERW, or, more particular, high-frequency induction welded, HFI) or spiral submerged arc welded (SSAW). While HFI pipes cover the medium diameter range, with OD generally restricted to 24 inch, there is virtually no limit for the OD in the case of SSAW pipes. However, the poor availability of X70 coil with strip thickness above 18mm impeded the spiral mills in the past to compete with UOE mills in the supply of large diameter linepipe with heavy wall thickness. This was an unfortunate situation since the equivalency in properties of UOE and spiral welded pipes is commonly accepted. In an analysis of world wide performed full scale burst tests, Pistone and Mannucci [1] concluded that the ability of spiral welded pipes to arrest ductile running fracture is at least as good as that of UOE pipes.

The reason for the lack of heavy gauge strip was mainly due to the general limitation of the coiling forces in the hot strip mills. For small orders it was, however, possible to produce X70 in thickness above 20mm (e.g. [2]) but for coiling force reasons it was necessary to limit the strip width. Spiral pipe mills prefer, for productivity reasons, to transform strips of at least 1850mm width.

The situation has changed today. ArcelorMittal, largest steel supplier in the world producing about 1 million ton/year coils for the energy market (including casing and coil tubing), recently installed heavy down coilers in three European hot strip mills. The dimensional feasibility of X70 linepipe steel has now been increased to 25.4mm (1 inch) thickness at 2150mm width. The maximum coil weight is 45t.

The enlarged feasibility range at ArcelorMittal has initiated the development of new alloying concepts in order to meet the product targets X70 and X80 even at high thickness. Next to the strength level, the realization of excellent toughness is the major issue for linepipe grades. The most challenging requirement is represented by the Battelle Drop Weight Tear Test (BDWTT), in particular when ductile failure is specified at low temperature. First target for the development was therefore to provide X70 and X80 hot strip in thickness of respectively 22mm and 16mm, both with minimum 85% shear area (SA) at -20°C. According to general experience, this is sufficient to realize 85% SA at -10°C on spiral welded pipes.

The present paper will summarize the progress of both developments. The development of X80 is addressing also the needs of the recently more frequently discussed plastic design, i.e. a low yield ratio Y/T [3]. Furthermore we will document our attempts to develop even higher strength linepipe steel X100 on coil. In contrast to the former steel grades, this development is still in the laboratory phase. In the paper we will also discuss some important aspects concerning the link between microstructure and toughness properties.

## X70 22MM

At the beginning of the project, an alloying concept was existing for the realization of X70 18mm with low temperature BDWTT properties. With the same analysis it was possible to produce also X70 20.6mm [2]. However, some optimization of the process parameters had been necessary to realize low temperature toughness. It was recognized that the feasibility of this alloying concept was exhausted so that a further increase of the thickness was not possible. In order to improve the toughness it was therefore necessary to develop a new alloying concept.

Based on laboratory simulations a new composition was proposed, Table 1. The major difference with respect to the former concept was a decrease of the carbon content and an increase of the total sum of hardening element additions (Mo+Ni+Cr+Cu). The carbon equivalent, expressed as Pcm in accordance with ISO 3183, did not increase with these changes so that good weldability is ensured.

| C | Mn | P | S | Nb+V+Ti | Mo+Ni+Cr+Cu | Pcm |
|---|---|---|---|---|---|---|
| 0.04 | 1.0-1.5 | 0.012 | 0.002 | <0.15 | >0.6 | <0.17 |

**Table 1: X70 steel composition (in weight-%).**

Standard processing conditions with respect to high toughness linepipe steel were applied in the steel shop. The pig iron was de-sulphurisated and then oxygen treated in the convertor. After alloy adjustment in the ladle furnace, the steel was Ca treated for sulfide shape control and finally cast in the continuous casting machine.

The process parameters in the hot strip mill are crucial for the realization of the targeted toughness properties. The reheating temperature was chosen carefully in order to enable complete dissolution of Nb and to prevent excessive austenite grain growth. An adapted roughing strategy under rigorous temperature control was applied in the 5 stand continuous roughing train. By doing so, the limited reduction in the finishing train due to the high final thickness could be compensated. Finishing rolling was performed at a temperature below the no-recrystallization temperature ($T_{nr}$), with a suited distribution of the rolling reduction over the different rolling passes. On the run-out-table an early and heavy cooling was applied in order to promote the formation low-carbon bainitic microstructures. The coiling temperature was chosen high enough to enable homogeneous precipitation of carbide. Figure 1 shows the resulting fine structured microstructure at one quarter thickness of the sheet. It is composed of a mixture of quasi-polygonal ferrite, globular bainite and bainitic ferrite. Cementite is homogeneously distributed in the microstructure and only few amounts of M/A constituents could be identified.

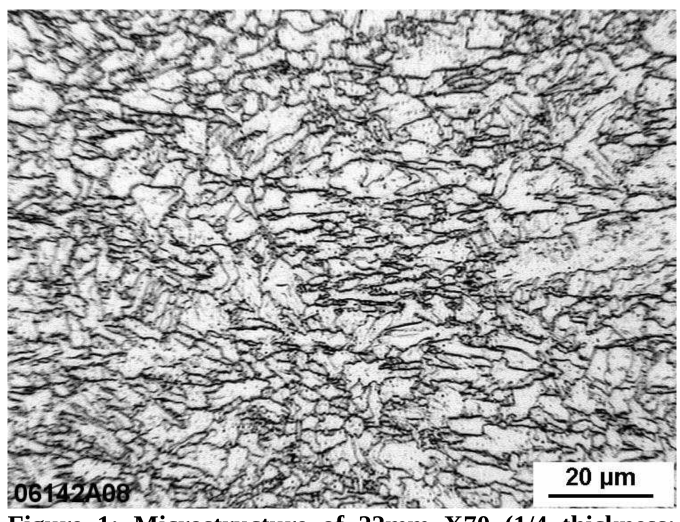

**Figure 1: Microstructure of 22mm X70 (1/4 thickness; etching $HNO_3$)**

Coils of two different thicknesses, 18mm and 22mm (Figure 3), were produced in a first rolling campaign and supplied to a client who transformed the steel to 42” diameter spiral welded pipes. The mechanical properties measured on coil in the steel plant and measured on pipe at the customer's are listed in Table 2. As an overall conclusion it can be stated that all targeted properties on pipe were met, in particular including the low temperature BDWTT objective at -10°C.

| | | 18mm | | 22mm | |
|---|---|---|---|---|---|
| | Target pipe (T) | Coil (T) | Pipe (T) | Coil (T) | Pipe (T) |
| $R_{t0.5}$ (MPa) | >483 | 565 | 520 | 534 | 505 |
| $R_m$ (MPa) | >565 | 633 | 619 | 602 | 593 |
| A (%) | >18 | 34.7 | | 34.9 | |
| KCV (J) at -10°C | >68J | | 380 | | 448 |
| BDWTT SA at -10°C | >85% | | 99% | | 99% |

**Table 2: X70 properties on 18mm and 22mm coil and pipe.**

The detected yield strength drop of 30 to 40MPa from coil to pipe measurement was actually not unexpected. The reason for this difference is without doubt partly due to the reversed cold bending during pipe forming and flattening which generally causes a virtual loss of yield strength (the so-called Bauschinger effect). For another part the yield stress drop is due to the difference in the measuring direction at the two production sites. The measurement of the as-delivered material was made in transverse direction of the coil (angle between rolling direction (RD) and specimen long direction 90°) while the measurement on pipe was performed transverse to the pipe axis in hoop direction (angle between RD and specimen long axis about 30°). However, yield strength drops of this magnitude are already anticipated during alloy design and hot strip processing so that the X70 strength requirements according to API 5L were perfectly met.

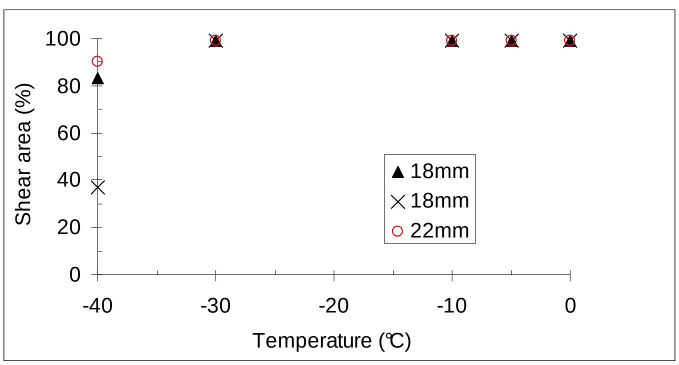


**Figure 2: BDWTT transition curves of 18mm and 22mm X70 spiral welded pipes.**

The BDWTT performance of the pipes was additionally characterized in terms of transition curves. The results, Figure 2, exceeded all expectations. An almost 100% ductile shear fracture was observed for both WT down to a temperature of -30°C. A deterioration of the ductile fracture behavior was not visible until a temperature as low as -40°C.

In the meantime, several heats have been produced in order to further optimize the processing parameters and to investigate the properties in the whole thickness range between 18 and 25mm. The first results on 25mm coil were promising but were still insufficient for low temperature BDWTT requirements. It is possible that the alloying concept still needs some adjustment.

**Figure 3: X70 22mm coil on the cutting line.**

## X80 16MM

The development of X80 with low temperature BDWTT in thickness up to 16mm addressed two objectives. In the first case, it was the aim to realize a steel with low yield ratio ($R_{t0.5}/R_m$ or Y/T) as it is required for plastic design of pipelines. The idea behind the low Y/T ratio is that plastic deformation of the installed pipeline, e.g. due to ground movement, leads to pronounced strain hardening so that local strain accumulation and collapse is prevented. The low Y/T requirement is generally referring to the tensile properties in longitudinal pipe direction; however, in the present study we will look mainly at the tensile properties transverse to the rolling direction (transverse RD = TD), instead. This approximation seems reasonable considering the fact that the angle between longitudinal pipe direction and TD is about 30°, and that yield and tensile strength are almost constant at these angles (compare e.g. [2]).

In the second case, the development target was to provide a steel with rather ordinary tensile test behavior, characterized by a yield ratio of about 0.9 which is typical for a microalloyed steels of this high strength level.

Two alloy concepts were designed corresponding to the two different targets, in the following called X80 low Y/T and

X80 ordinary Y/T, respectively. The alloy compositions are given in Table 3. The main difference in chemical composition is a higher content of carbon and hardening elements (Mo+Ni+Cr+Cu) in the alloy dedicated to the low Y/T properties.

| | C | Mn | P | S | Nb+V+Ti | Mo+Ni+ Cr+Cu | Pcm |
|---|---|---|---|---|---|---|---|
| X80 low Y/T | 0.07 | 1.2-1.8 | 0.012 | 0.002 | <0.15 | >0.6 | <0.2 |
| X80 ordinary Y/T | 0.05 | 1.2-1.8 | 0.013 | 0.003 | <0.15 | <0.6 | <0.17 |

**Table 3: Alloying concepts X80 16mm for the two different development targets.**

Several heats of both alloys were industrially cast and hot rolled in a way similar to that described above in the context of X70 development. The final strip thickness was 12.7mm and 15.9mm in case of the concept X80 low Y/T and 15.5mm in case of the other concept. Since the final reduction at temperature below $T_{nr}$ in the finishing train was much higher as compared to the heavy gauge X70 productions, roughing and finishing rolling were considered as less critical for the toughness properties. On the other hand, lab simulations had turned out that the product properties were very sensitive to the cooling conditions after hot rolling. Therefore, adapted cooling patterns and appropriate coiling temperatures were chosen for the rolling campaigns.

Figure 4 shows the tensile curves of both alloying concepts, both determined on as-rolled material in transversal direction. As expected, the lower alloyed X80 concept displayed a rather classical flow curve with a pronounced yield point elongation and limited strain hardening. Average $R_{t0.5}$ and $R_m$ were determined to 606MPa and 679MPa, respectively, resulting in an average yield ratio of 0.89. The microstructure of the material is shown in Figure 5. It is mainly composed of quasi-polygonal ferrite, globular bainite and bainitic ferrite with limited amounts of M/A constituents and some lower bainite.

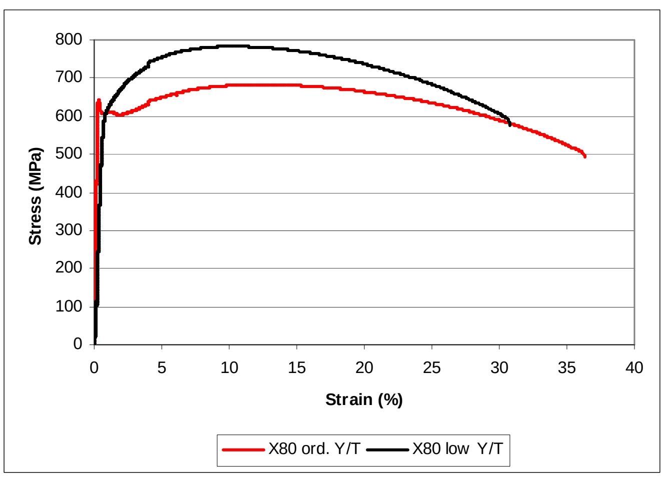


**Figure 4: Tensile curves of both X80 16mm concepts. Thickness is close to 16mm.**

In contrast, the tensile curve of the material dedicated to low Y/T shows continuous yielding, pronounced strain hardening and a very high tensile strength. It is striking that the yield strengths of both alloying concepts are very similar while the tensile strengths differ by about 100MPa.

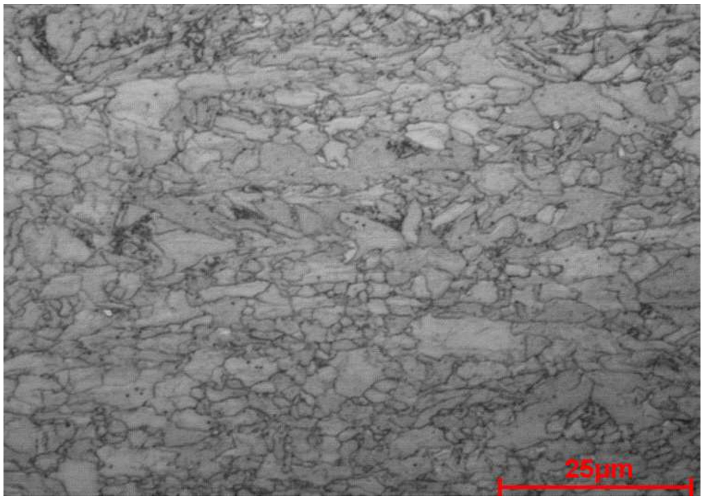


**Figure 5: Microstructure X80 ordinary Y/T, 15.5mm (1/4 thickness, etching Le Pera).**

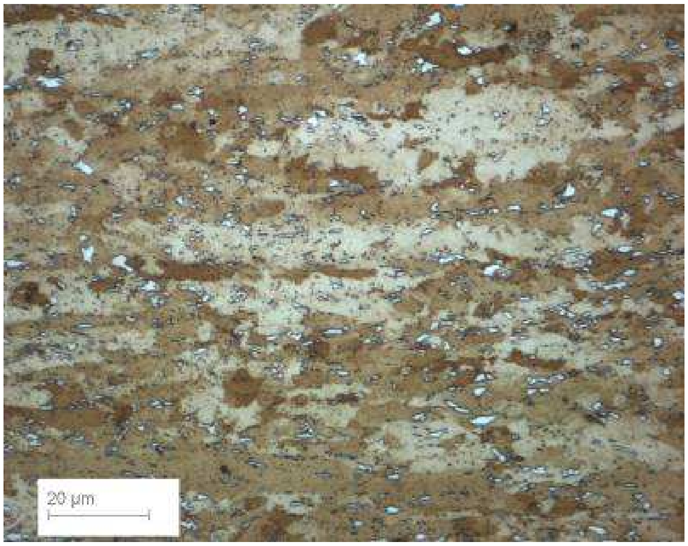


**Figure 6: Microstructure X80 low Y/T, 15.9mm (1/4 thickness, etching Klemm).**

The flow curve of the low Y/T concept shows all characteristics of the so called dual phase behavior. Indeed, a high volume content of M/A constituents could be identified in the microstructure (white phase in Figure 6). The reason for the pronounced strain hardening is related to dislocation multiplication in the soft matrix surrounding the islands of hard phases. The dislocations are emitted as soon as the hard phase suffers a volume change which is typically caused by the transformation of austenite to martensite. The tensile strength can be described on the basis of a suited mixture rule taking into account the stability of the austenite. It is therefore directly related to the volume content of the hard phases. On the other hand, the large number of free dislocations does not allow for the presence of a yield point effect. This fact makes it particularly difficult to realize a low scatter of yield strength properties since small variations in yielding behavior can shift $R_{t0.5}$ easily by several dozens of MPa in any direction. It is questionable if it will be possible to control the amount and distribution of hard phases in the microstructure in a suitable manner. More research is required in this respect.

Coils of both thicknesses were delivered to a pipe mill and transformed to 48”OD spiral welded pipes. The average properties obtained on coil and pipe are summarized in Table 4. It is obvious that the yield strength drop is very limited while the tensile strength remains rather unaffected. In consequence, the low yield ratio observed on the coil could be preserved on the pipe. In spite of the fact that no data is available concerning the tensile properties in longitudinal pipe direction, the results suggest that the yield ratio also in this direction will be lower than 0.85.

| | | 12.7mm | | 15.9mm | |
|---|---|---|---|---|---|
| | Target pipe (T) | Coil (T) | Pipe (T) | Coil (T) | Pipe (T) |
| $R_{t0.5}$ (MPa) | >552 | 601 | 576 | 591 | 593 |
| $R_m$ (MPa) | >621 | 749 | 749 | 749 | 761 |
| Y/T | <0.85 | 0.8 | 0.77 | 0.79 | 0.78 |
| A (%) | >18 | 28.2 | | 30.1 | |
| KCV (J) at -5°C | | | 203 | | 190 |
| BDWTT SA at -5°C | >85% | | 100% | | 99% |

**Table 4: X80 low Y/T properties on coil and on pipe, 12.7mm and 15.9mm.**

The BDWTT transition curves determined on pipe are given in Figure 7. The results were extraordinary. The 12.7mm material displayed 100% ductile fracture over the whole investigated temperature range down to -60°C. Even the thicker material showed fully ductile failure down to -30°C.

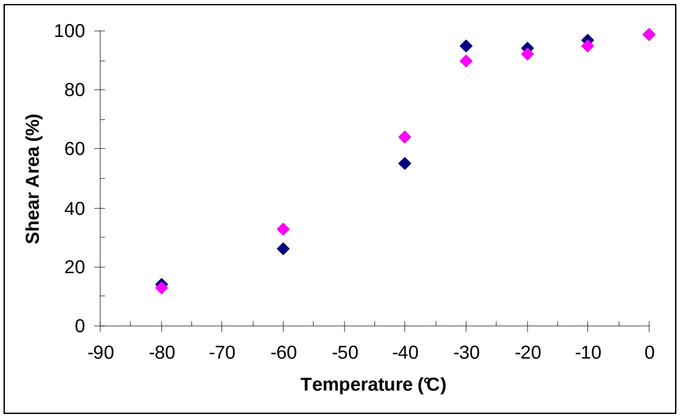


**Figure 8: BDWTT transition on 2 coils of X80 ordinary Y/T, 15.5mm.**

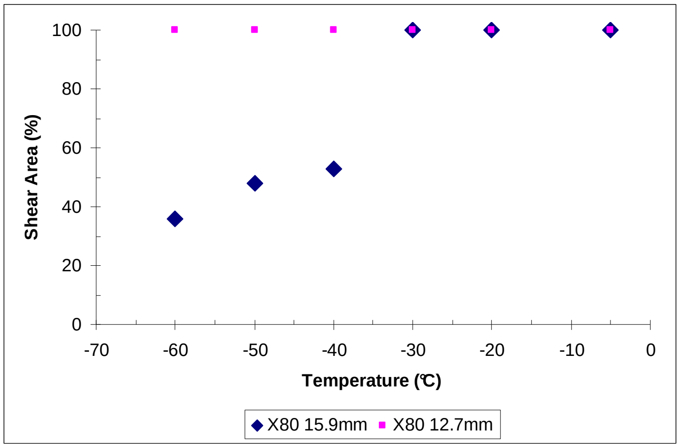


**Figure 7: BDWTT results on pipe of X80 low Y/T concept, thickness 15.9mm and 12.7mm.**

With these results it can be stated that a low temperature BDWTT X80 with low Y/T has successfully been realized. However, as already mentioned earlier, the feasibility of a yield strength guarantee with low scatter is suspected.

Another issue seems related with the presence of a low yield ratio, i.e. with the presence of hard M/A phase in the microstructure. It concerns the Charpy impact toughness. When comparing the Charpy transition curves of the two concepts, Figure 9, it can be noticed that the ductile to brittle transition temperature (DBTT) of the X80 ordinary Y/T concept is much lower compared to that of the low Y/T ratio concept. Furthermore, it appears that the upper shelf energy is lower in presence of large amounts of M/A. On the other hand, the transition from ductile to brittle fracture behavior seems to take place over a larger temperature interval. Analogous observations will be reported below in the context of the X100 development.

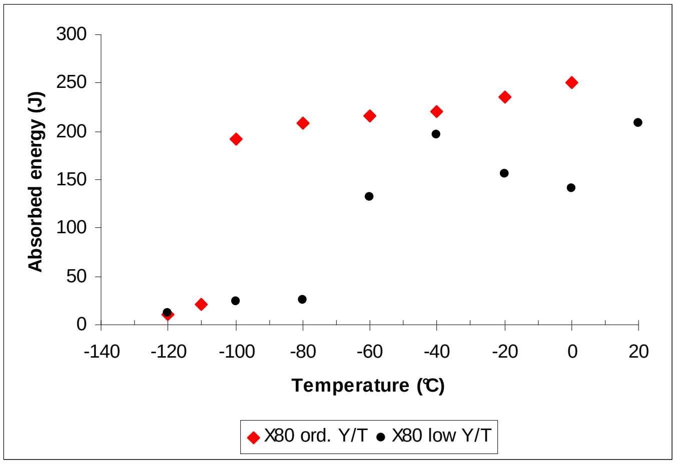


**Figure 9: Charpy toughness on coil of both X80 concepts.**

Pipes have not yet been produced from the coils dedicated to the X80 ordinary Y/T concept. However, the potential for low temperature BDWTT can be shown by means of BDWTT transition curves of coil material, Figure 8. The as-rolled steel reveals a shear area of more than 90% SA down to -30°C.

### X100 12.7MM

For the development of X100 on coil with excellent toughness, several chemical compositions have been cast and processed on a laboratory scale, Table 5.

| C | Mn | Nb+V+Ti | Mo+Ni+Cr+Cu | Pcm |
|---|---|---|---|---|
| 0.06 | 1.5-2.5 | <0.15 | 1.0-2.5 | <0.27 |

**Table 5: Composition range of laboratory processed X100 steels (weight %).**

The laboratory trials simulated typical conditions of the hot strip mill with a final targeted thickness of 12 mm. For a number of heats and suitable processing conditions, X100 strength properties could be identified, i.e. YS>690MPa. Figure 10 shows how the coiling temperature rules the strength properties of a selected composition. For lower coiling temperatures, higher yield strengths together with lower tensile strengths were obtained. A high yield ratio is therefore favorable to achieve X100 properties. Moreover, toughness properties are deeply related to processing parameters. This is demonstrated in Figure 11 with a plot of the Charpy transition curves corresponding to the three coiling temperatures shown in Figure 10 (same steel composition). It appears that lower coiling temperatures are causing a shift of the DBTT to lower temperatures and, in addition, increase the upper shelf energy.

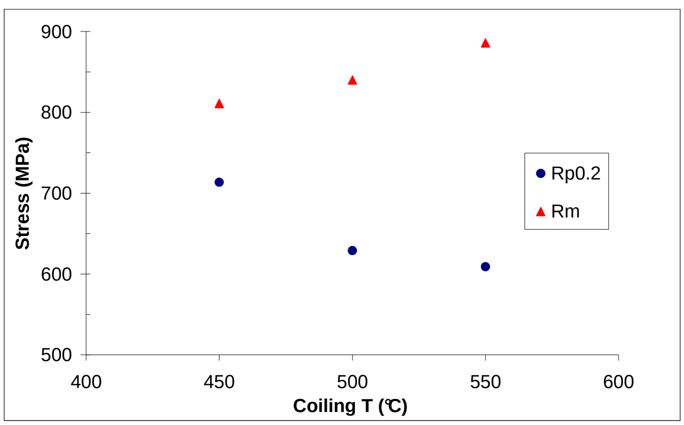


**Figure 10: $R_{p0.2}$ and $R_m$ of an X100 composition as function of the coiling temperature.**

Microstructure analysis can explain the results displayed by Figure 10 and Figure 11. Figure 12 shows the microstructure of the given steel composition after processing with the high coiling temperature. A large amount of M/A component can be detected (white phase), which is very probably the cause for the limited Charpy toughness performance of this steel. In analogy to the above described X80 results, the hard microstructure component is supposed to be at the basis of the high $R_m$ values and the low $R_{t0.5}$ values, respectively.

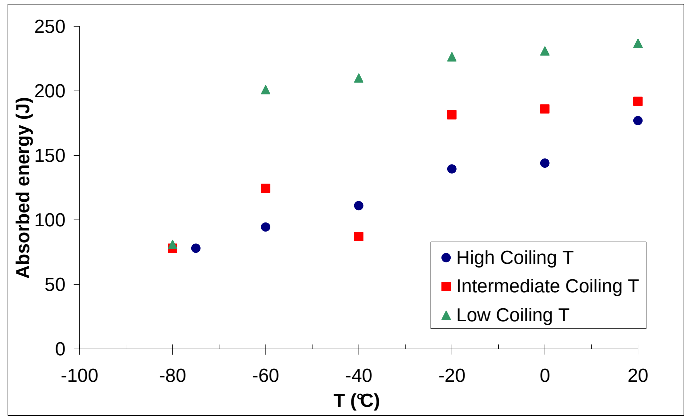


**Figure 11: Charpy transition curves of X100 grade for different coiling temperatures.**

In view of the impact on yield ratio and Charpy toughness it is preferable to avoid the formation of these hard M/A phase upon processing. However, a compromise must be identified since the low coiling temperatures are at, or even beyond, the feasibility of the hot strip mills.

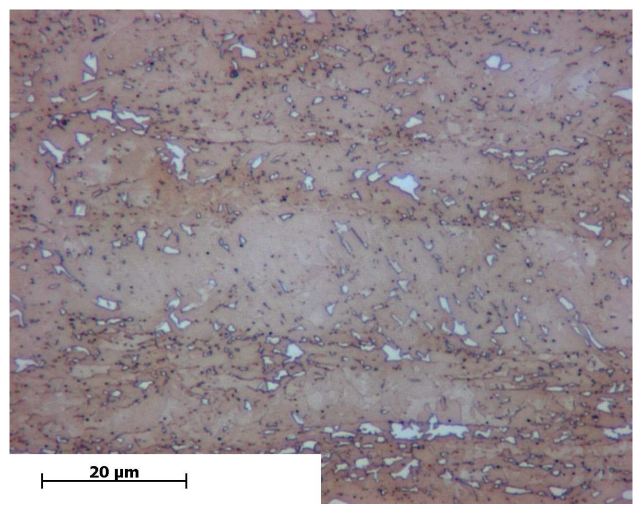


**Figure 12: Microstructure of X100 composition processed with high coiling temperature (etching Le Pera).**

### CONCLUSIONS

- ArcelorMittal has recently equipped three hot strip mills with heavy downcoilers. The coiling feasibility of X70 in thickness up to 25.4mm and width up to 2150mm offers a new opportunity for spiral mills to close up to UOE mills in the competition in the field of large diameter pipe with high wall thickness. Next to that, it is possible to deliver coils for the production of 26" OD HFI linepipe, e.g. in thickness 20mm.
- Coils for X70 low temperature BDWTT spiral pipe in thickness up to 22mm have successfully been produced.
- The X80 low temperature BDWTT development is in progress; the first pre-series deliveries in thickness up to

16mm have been successfully transformed to spiral welded pipes with low temperature BDWTT. The hot strip mills are ready to ramp up the production gradually.

- The X80 trials comprised respectively low and ordinary Y/T behavior. The production of low Y/T material in large tonnages is suspected due to anticipated difficulties in realizing a low yield strength scatter.
- The development of X100 in thickness up to 12.7mm is on schedule.
- High volume contents of M/A constituents were found to promote low Y/T ratios and to increase the Charpy transition temperature.

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