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MICROALLOYING ELEMENTS IN THE DIRECT SHEET PLANT

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Abstract

The Direct Sheet Plant (DSP) of Corus Strip Products at IJmuiden is operational since 2000 and presently producing an annual 1.1 million tons of strip. The product range of the DSP comprises HSLA grades of yield strengths from 320 to up to 500 MPa that are microalloyed with niobium and vanadium. Those grades are suited for hot-rolled and cold-rolled applications, e.g. for automotive structural parts or seating and safety systems. This publication describes the IJmuiden DSP process and zooms in on the effects of the microalloying elements Nb and V under the specific DSP thermal conditions in IJmuiden.

Introduction

At its production site in IJmuiden on the North Sea coast Corus operates a fully integrated steel plant with direct access from the sea. Large freight ships supply iron ore, coal and additives, which are then preconditioned in two coke plants and a pellet and a sinter plant for use in the blast furnaces. The two blast furnaces #6 and #7 are among the most efficient in the world, in terms of hot metal output per ton raw material.

Corus IJmuiden produces low carbon steel by the basic oxygen steelmaking (BOS) method, using three converters. The total output of the BOS plant is now 6.6 Mt per annum. The liquid steel is then continuously cast and further processed in a conventional hot strip mill, two cold strip mills, and several annealing and coating lines, before it is eventually delivered to the customers as uncoated, metallic coated or organic coated strip. Alternatively to the conventional continuous casting process, the ladles with liquid steel can be transferred from the steel plant to the adjacent DSP where the melt is continuously cast, homogenised and rolled to thin strip in one single continuous process.

The Direct Sheet Plant

Casting Section

The caster (marked A in Figure 1) at the Corus DSP features a H-tundish that provides cleaner steel at a higher yield than conventional casters. Two ladles can be in place simultaneously (Figures 2 and 3), so ladle change influences are limited to a minimum. Constant tundish levels can be realized and a longer residence time of the steel in the tundish provides temperature homogenization and reduced slag carry-over.

At a slab thickness of 70 mm, the DSP presently operates at a casting speed of 6 m/min and an annual capacity of 1.1 million tons.

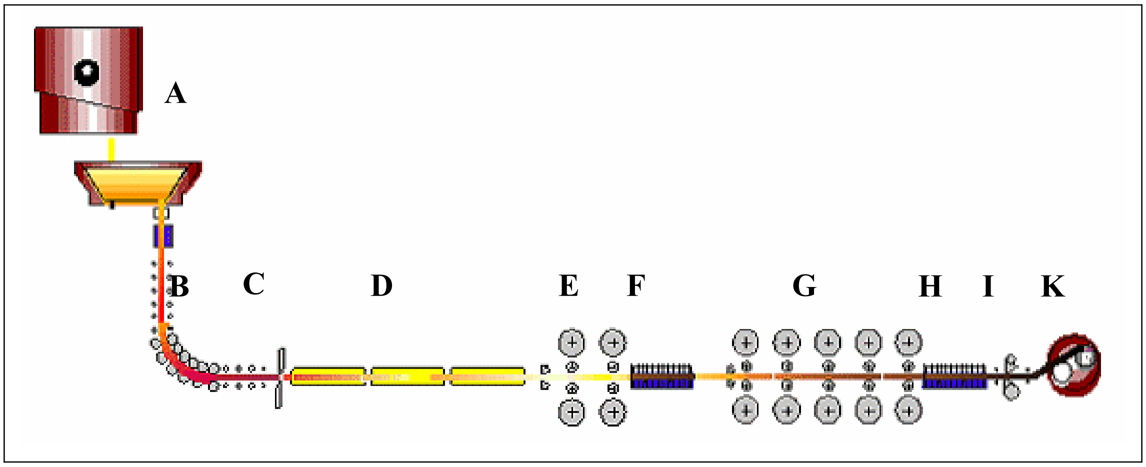

Figure 1. Schematic drawing of the DSP process, starting with the casting section (A), bending to horizontal (B), crop shear (C), tunnel oven (D), roughing stands (E), intermediate cooling (F), finishing stands (G), ultra fast cooling table (H), flying shear (I) and carousel coiler (K).

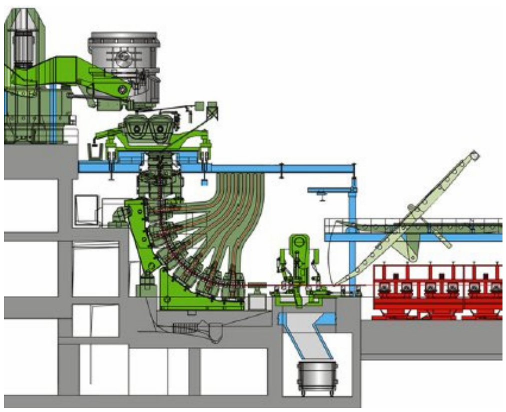

Figure 2. Schematic of the casting section.

Figure 3. The tundish area.

Tunnel Furnace

After bending and unbending (B), the slab is cut to length (15 - 280 m) using a crop shear (C) and homogenized in a tunnel oven of 315 m length (D) at a temperature of 1150 °C. The long furnace provides full temperature homogeneity over the length of the slab, so no speed modulation during rolling is required (Figures 4 and 5).

Figure 4. The entry to the tunnel furnace.

Figure 5. The tunnel furnace.

Rolling Section

In two roughing (E) and five finishing stands (G) the slab is semi-continuously rolled down to a strip thickness of 0.95 to 2.5 mm at widths between 1000 and 1560 mm (Figure 6). For high quality surface finish, there are two controllable descalers and work rolls are lubricated on all stands. To provide full shape control also for long rolling campaigns (up to 6 hours continuously), bending and dynamic pair-crossing (Figure 7) is available on six rolling stands. The rolled strip leaves the finishing section at speeds of up to 20 m/s (70 km/h).

Figure 6. The rolling section.

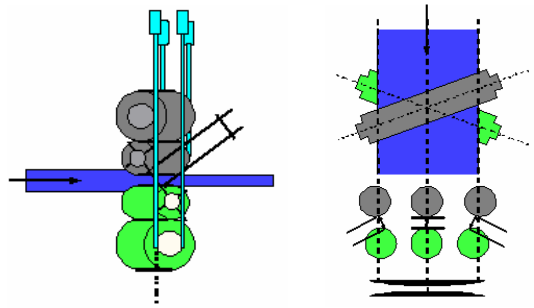

Figure 7. The principle of pair crossing.

Cooling Table and Coiler

The ultra fast cooling (UFC) table (H) of the DSP has a length of only 10 m and the capacity to cool at rates up to 400 K/s. After cooling down to coiling temperature, the flying shear (I) cuts the strip to coil length before it is coiled on the continuous carousel coiler (K, and Figures 8 and 9). Coil weights can vary between 10 and 33 tons.

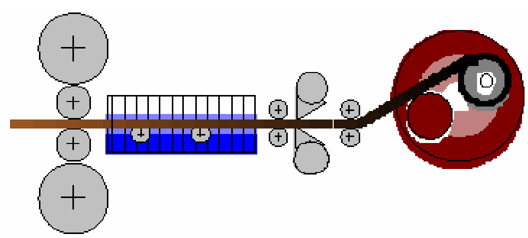

Figure 8. Schematic of ultra fast cooling table, flying shear and carousel coiler.

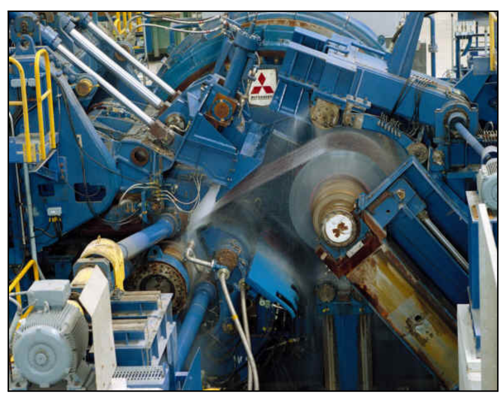

Figure 9. The Carrousel coiler.

The Ymagine® HSLA Product Range

Ymagine is the brand name for a range of high quality pickled and oiled steel products that are manufactured at the Direct Sheet Plant of Corus Strip Products in IJmuiden. Ymagine differs from traditional hot-rolled and cold-rolled material by the quality advantages due to the (semi)endless production process in one heat. Some of these advantages are:

- Narrow geometrical tolerances, regardless of strength levels
- Homogeneous mechanical properties

- Consistent chemical composition per grade
- Low level of residual elements
- Low level of inclusions
- Flexible coil weights free of welds
- Large range of thickness to width ratios
- Shorter lead times
- Weight reduction and cost savings by use of high-strength steels
-

Ymagine is suitable for thin gauge drawing and HSLA applications. Examples of applications in the automotive area are structural components or seating and safety systems. Non-automotive applications can be found in the building and construction area, radiators, drums, racking, lighting columns or furniture. In Table 1 the major mechanical properties of the Ymagine HSLA product range are provided.

Table I. Mechanical properties, parallel to the rolling direction (* under development).

	ReH / Rp (MPa)	Rm (MPa)	A80 (%)
Ymagine H320	320-410	400-510	>22
Ymagine H360	360-460	430-550	>20
Ymagine H420	420-500	480-620	>18
Ymagine H500*	>500	550-700	>12

Microalloying Elements under DSP thermal conditions

Effect of Direct Charging

One major difference of the DSP production process compared to conventional hot rolling is the direct charging of the slab from the continuous caster into the reheating furnace. Direct Charging on the DSP has consequences for the choice of micro-alloying additions for HSLA steels. The effect is particularly noticeable at higher alloy levels and hence alloy design for higher strength levels requires careful consideration.

A main function of micro-alloying elements during hot rolling is to increase the temperature of non-recrystallisation (T_{NR}, see Figure 10), which results in grain refinement. The ranking of typical HSLA elements is well known. Essentially Nb gives the most refinement per unit volume, followed by Ti. V gives the least amount of grain refinement, but provides good precipitation strengthening provided the N level is sufficient.

As a result of direct charging and a tunnel furnace homogenization temperature of 1150°C the loss of micro-alloying elements due to precipitation in the slab is a major issue. The tunnel furnace temperature is relatively low compared to typical hot strip mill reheating temperatures. Hence, it will be difficult to re-dissolve precipitates already formed in the slab. Precipitation in the slab during casting is wasteful, since precipitates formed at higher temperatures are large and do not provide strengthening because they reduce the effective amount of micro-alloy additions available for strengthening during rolling and coiling.

During routine production at the DSP, variations in casting speed can occur during processing. At reduced casting speed, the slab has more time to cool down resulting in a lower slab temperature prior to entering the tunnel furnace (Figure 11). Lower temperatures are more likely to lead to the premature precipitation of micro-alloying elements. In the air-cooled slab, the lowest temperatures will be found at the surface. During routine operation the slab surface temperature should not decrease below approximately 950 °C. This temperature is used as the criterion to assess whether or not premature precipitation is to be expected.

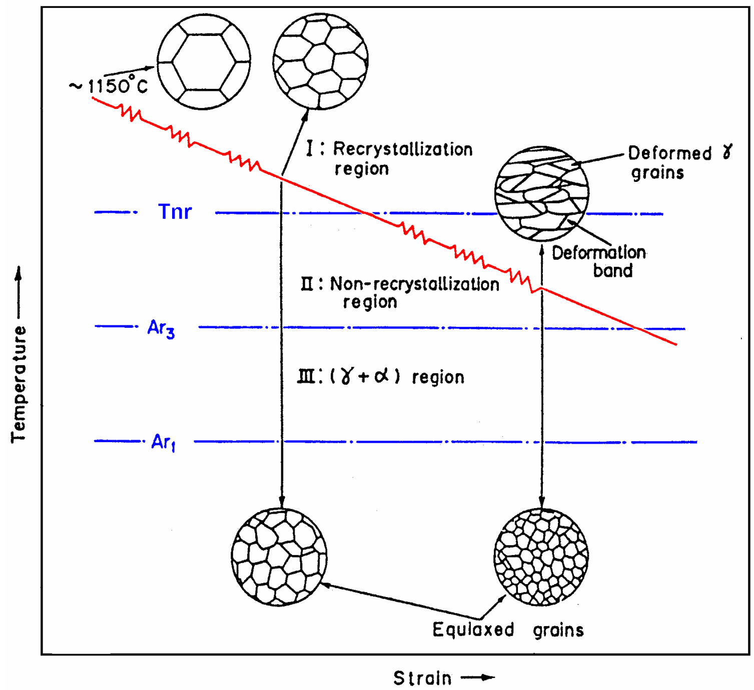

Figure 10. Schematic of the effect of T_{NR} on microstructures during hot rolling.

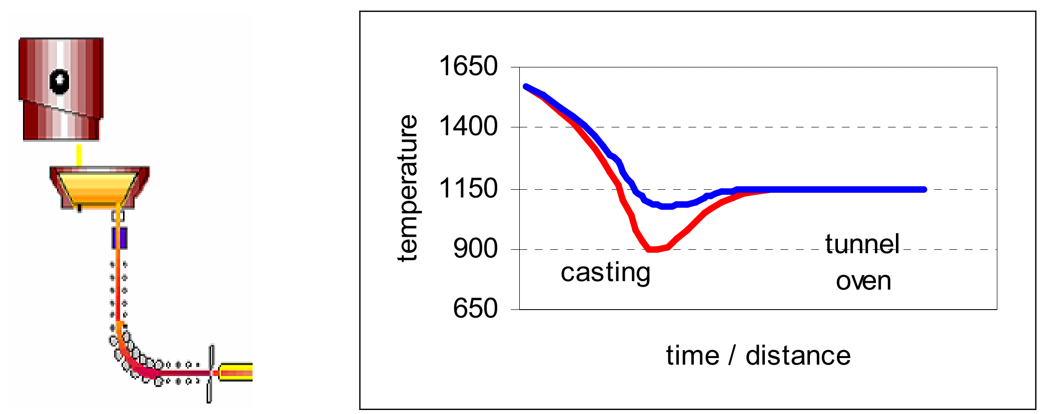

Figure 11. Casting section of the DSP and typical temperature profiles of the continuous slab, in the case of normal operation (blue curve) and in the case of reduced casting speed (red curve).

The TAP model

The model used for the simulations in this work is a precipitation model developed by Corus RD&T. The TAP model is a purely thermodynamic model. It does not take kinetics into consideration. Thermodynamics will determine if a reaction will occur and can predict the final volume fractions. Kinetic data will tell how fast a reaction occurs. The TAP model determines the temperature at which precipitation occurs, under equilibrium conditions. In an industrial process like the DSP, however, the duration of the various process stages will generally be insufficient to allow equilibrium to be reached. In the present case, the TAP model is used to determine trends and allow a comparison between different alloy types. A graphical explanation is shown in Figure 12.

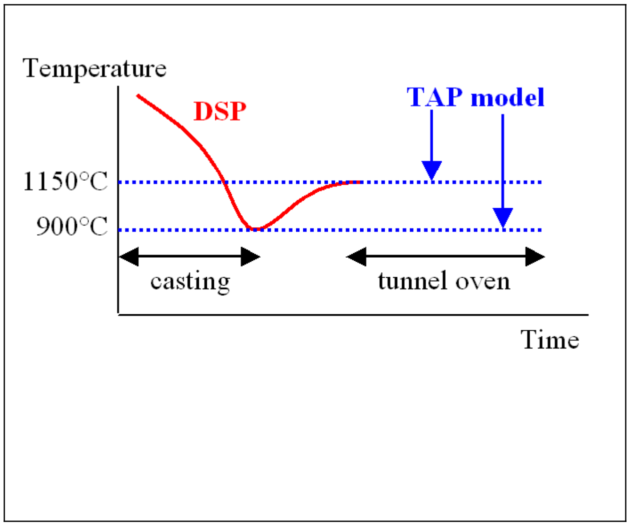

Figure 12. Schematic Representation of Time and Temperature for the TAP model. The red line indicates a typical time-temperature profile for DSP slabs cast at reduced speed.

By assessing the loss of solute over a temperature range (blue lines) a comparison can be made between different alloys to determine which are most sensitive. The TAP model may indicate that precipitation does not begin below 900 °C, which is then regarded uncritical.

Effect of Ultra Fast Cooling

The other major difference of the IJmuiden DSP compared to conventional hot rolling mills is its ultra fast cooling (UFC) unit. Due to the very high cooling rates, a cooling table of only 10 m in length is sufficient to reach similar coiling temperatures as in a HSM. The very high cooling rate has a strong influence on the final microstructure of the materials produced. In general, grain sizes are found to be significantly smaller than in HSM produced materials. With the major effect of microalloying elements being the increase of strength by reduction of grain size, the UFC will have an influence on the efficiency of microalloying elements.

Experimental Procedure

Several experimental Nb-based alloys were produced and laboratory-processed simulating the rolling, cooling and coiling operations at the DSP. The experiments were focused on the cooling trajectory and not on the thermal effects of direct charging. Therefore, the reheating prior to hot rolling was done for 1 hour at 1250°C in order to get all precipitates dissolved. The finish rolling temperature was kept at 880°C for all simulations. Two coiling temperatures were used (650°C and 550°C). For each coiling temperature, both UFC and laminar cooling were applied. After the coiling temperature was reached, the material was subjected to slow furnace cooling. After simulating the rolling and cooling procedure in the DSP, the material was examined for its mechanical properties by tensile testing and microstructural features using optical microscopy.

Nb-only Compositions for Medium Strength

Effect of Direct Charging

For Nb based alloys, higher N levels will be the most likely cause of precipitation in the slab. Hence, in terms of compositions, the process will be most sensitive to fluctuations in N levels. Therefore, three different N levels were assessed for each composition. These were 0.003, 0.004 and 0.005wt%.

The alloy compositions and the results of the TAP thermodynamic modelling are summarised in Table 2 below, showing the predicted temperatures at which Nb will begin to precipitate for the highest N content of 0.005wt%.

However, in austenite there is a competition between Al and Nb to combine with the free N. NbN precipitation will depend on whether AlN precipitates first or not. Therefore, the precipitation start temperatures have been calculated for both cases, i.e. assuming AlN forms first and assuming AlN forms later or vice versa. The evaluation was done on the basis of an average of both temperatures.

Table II. Chemical Composition of Nb Alloys (in wt%) and calculated precipitation start temperatures (in °C)

	C	**Mn**	**N**	**Nb**	**pptn start**
Alloy A	0.045	0.280	0.005	0.011	887
Alloy B	0.045	0.500	0.005	0.013	910
Alloy C	0.045	0.750	0.005	0.020	968
Alloy D	0.045	0.900	0.005	0.024	978
Alloy E	0.045	0.900	0.005	0.016	936

The results of the calculations show that if in the case of compositions A and B precipitation should not be an issue, provided the slab temperature can be kept above 887 °C and 910 °C, respectively. Under normal conditions it should be possible to keep a slab temperature above those temperatures. For compositions C and D, however, precipitation could become an issue. This is a temperature that the slab surface can reach prior to entry into the tunnel furnace. Hence, precipitation potentially is a problem with those compositions. Composition E is probably on the borderline. Precipitation could begin at 936 °C.

Effect of Ultra Fast Cooling

The basic compositions of the five experimental Nb-microalloyed steels that were laboratory-processed under different cooling conditions are given in Table 3 below.

Table III. Compositions of experimental alloys for lab simulations

	C	Mn	N	Nb
Alloy F	0.054	1.620	0.006	0.013
Alloy G	0.051	1.611	0.006	0.027
Alloy H	0.053	1.606	0.005	0.043

Plots of the yield stress (R_p) and tensile strength (R_m) values measured on material processed at the laminar cooling and UFC conditions are shown in Figures 13, 14, 15 and 16 for varying Nb contents and a coiling temperature of 650°C.

The amount of additional strength attainable from UFC is dependent upon the Nb level. At higher Nb levels the yield stress R_p increase resulting from UFC diminished. This is shown for the 650°C coiling temperature in Figure 13. The data in Figure 13 has been re-arranged to show more clearly the effect of Nb on additional R_p increase as a result of UFC. At Nb levels greater than 0.04wt%, any additional R_p increase from UFC is negligible. This can be seen in Figure 15. The effect of Nb levels on R_m level is examined in Figure 14. This shows a similar trend to R_p but is not as extreme. The data in Figure 14 has been rearranged to show more clearly the effect of Nb on additional R_m increase as a result of UFC. As Nb levels increase, there is a linear reduction in the additional R_m increase resulting from UFC. This can be seen in Figure 16.

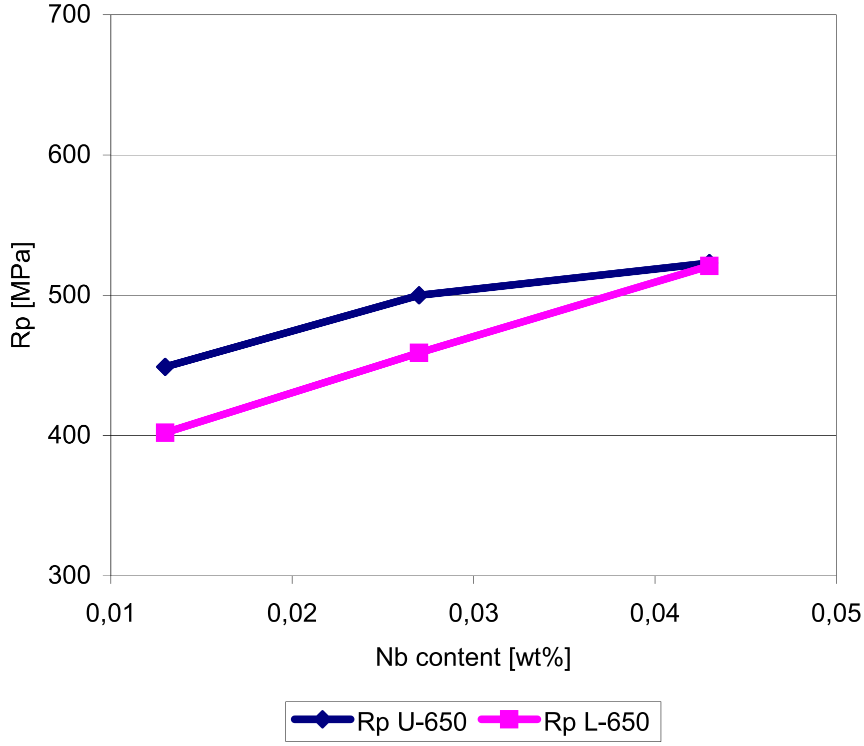

Figure 13. Yield stress R_p vs. Nb content, for UFC and laminar cooling down to 650 °C coiling temperature.

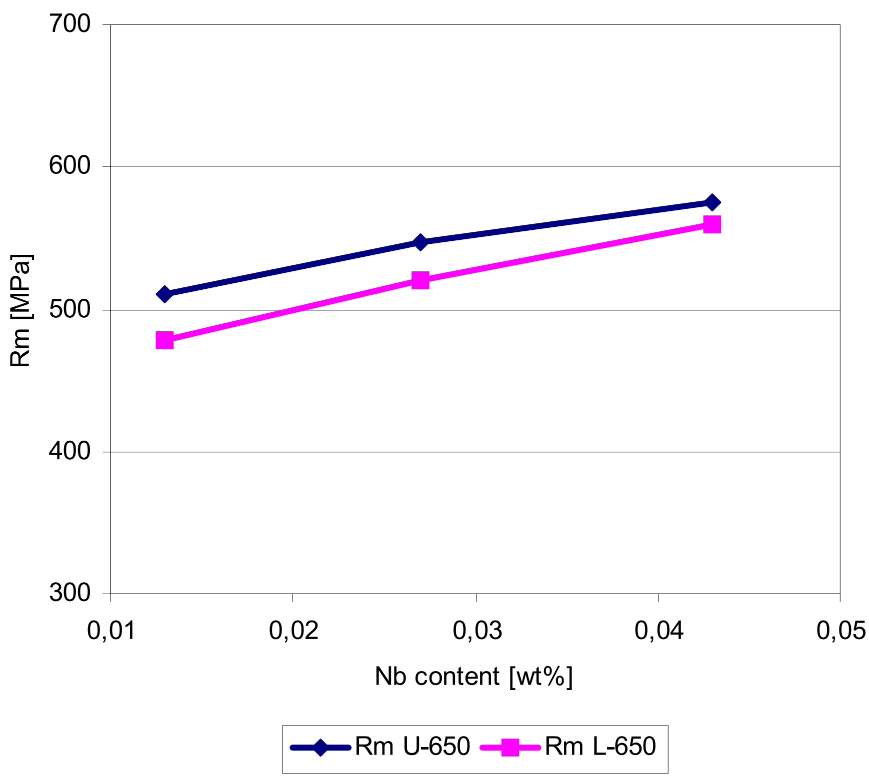

Figure 14. Tensile strength R_m vs. Nb content, for UFC and laminar cooling down to 650 °C coiling temperature.

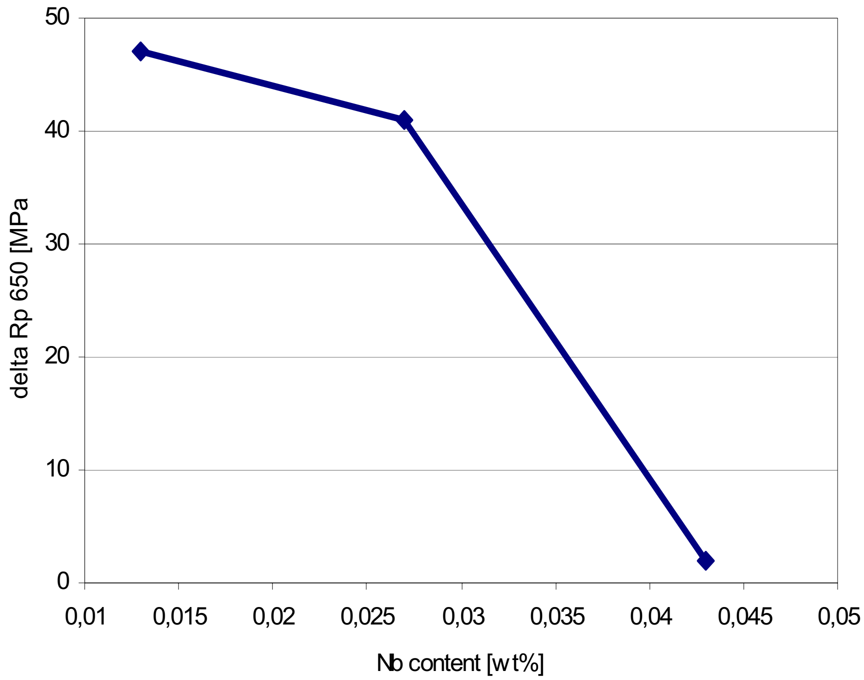

Figure 15: Yield stress gain ΔR_p of UFC vs. Nb content at 650°C coiling temperature.

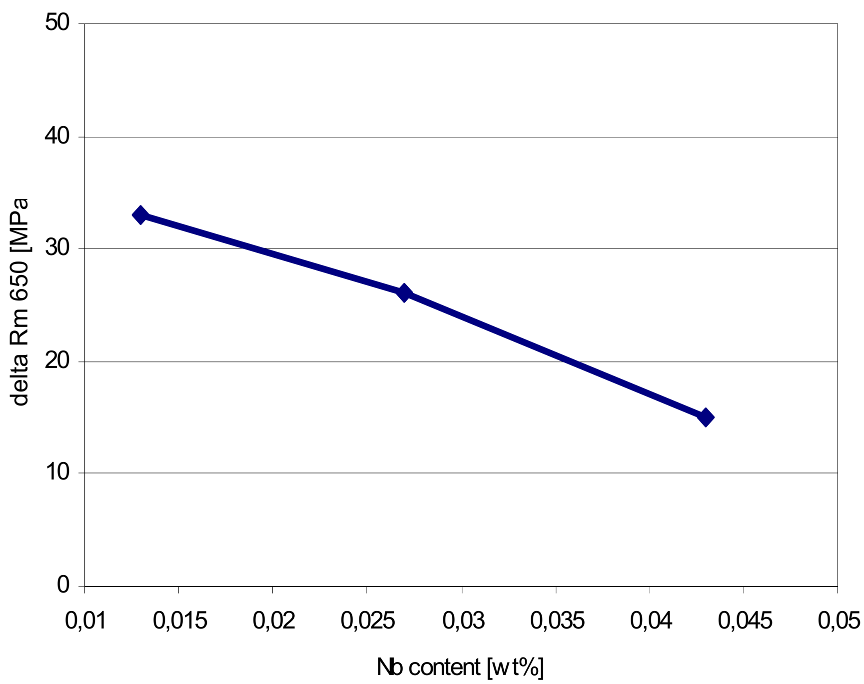

Figure 16. Tensile strength gain ΔR_m of UFC vs. Nb content at 650°C coiling temperature.

Plots of the yield stress (R_p) and tensile strength (R_m) values measured on material processed at the laminar cooling and UFC conditions are shown in Figures 17, 18, 19 and 20 for varying Nb contents and a coiling temperature of 550°C.

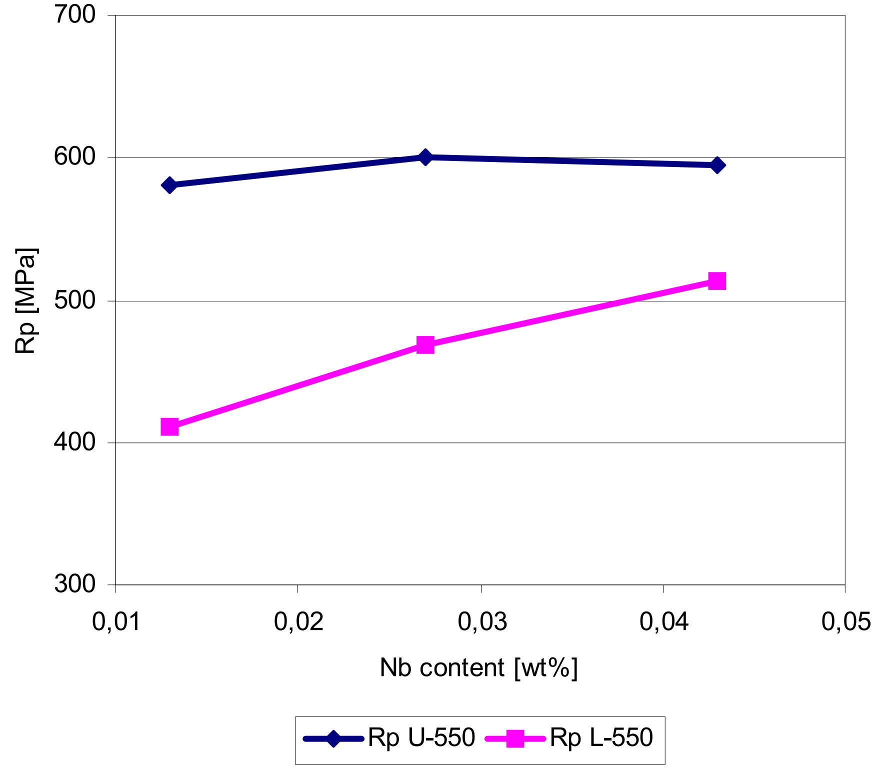

Figure 17. Yield stress R_p vs. Nb content, for UFC and laminar cooling down to 550 °C coiling temperature.

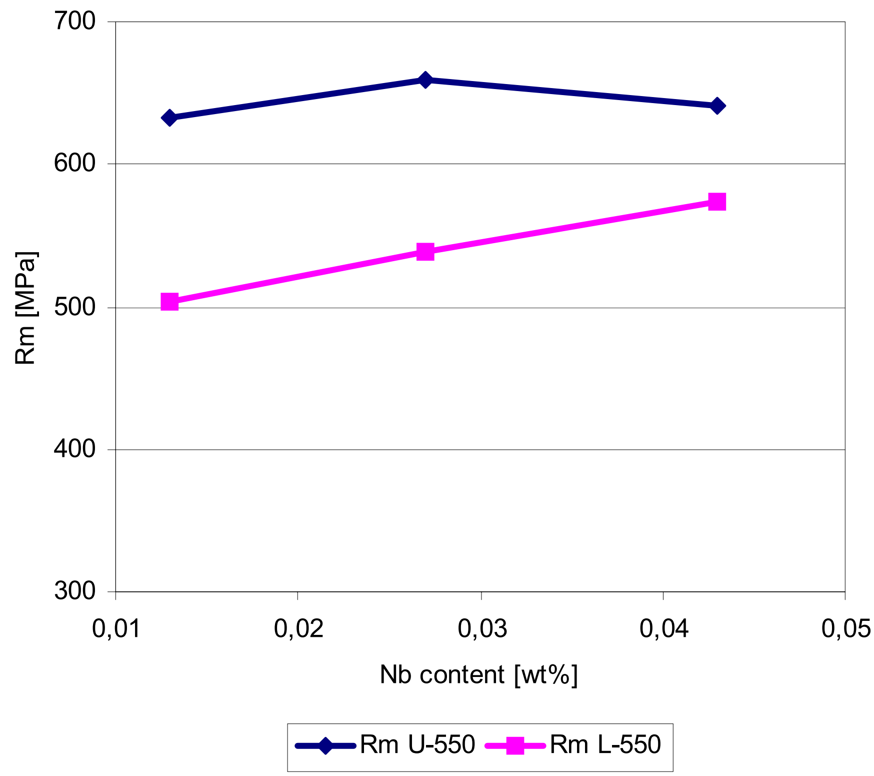

Figure 18. Tensile strength R_m vs. Nb content, for UFC and laminar cooling down to 550°C coiling temperature.

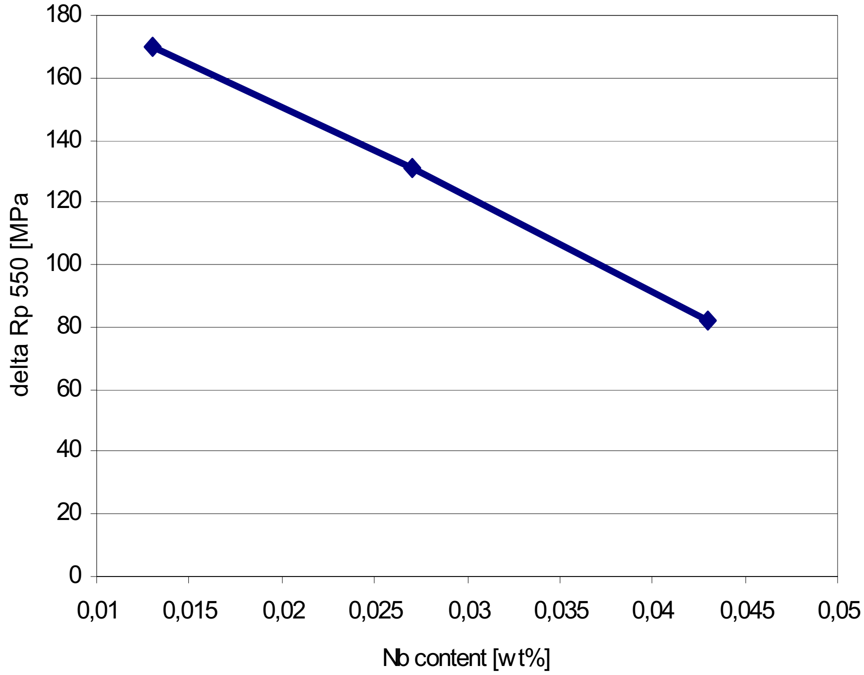

Figure 19. Yield stress gain ΔR_p of UFC vs. Nb content at 550°C coiling temperature.

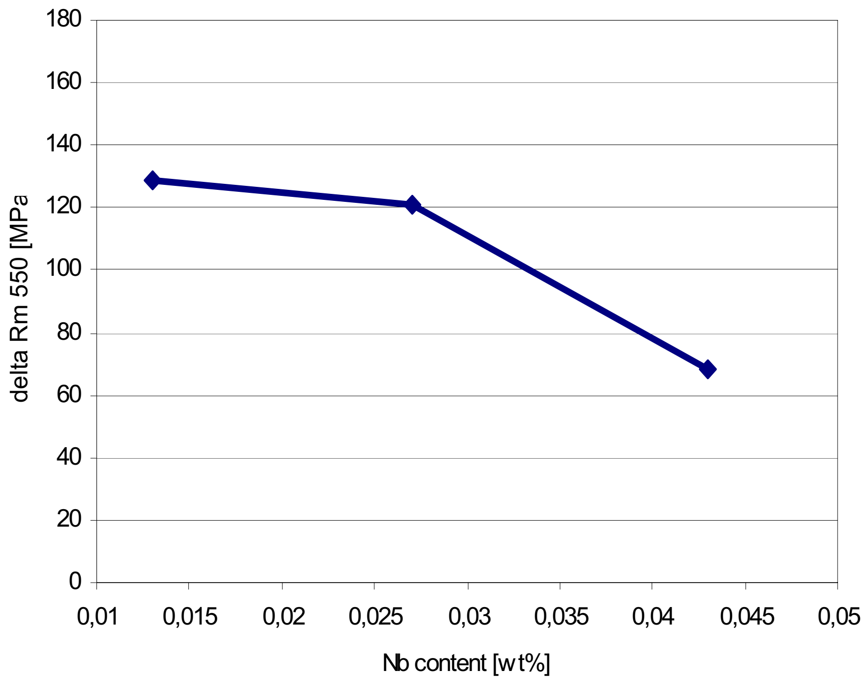

Figure 20. Tensile strength gain ΔR_m of UFC vs. Nb content at 550°C coiling temperature.

Similar to the situation for 650°C coiling temperature, also for 550°C coiling temperature, the amount of additional strength attainable from UFC is dependant upon the Nb level. At higher Nb levels the yield stress R_p increase resulting from UFC diminished, as shown in Figure 17. As expected, the level of yield stress for UFC is clearly higher than for laminar cooling. However, it is also evident that the increase in yield stress with increasing Nb content is significantly lower in the UFC case. The data in Figure 17 has been re-arranged to show more clearly the effect of Nb on additional R_p increase as a result of UFC. At Nb levels greater than 0.04wt%, any additional R_p increase from UFC is negligible, as can be seen in Figure 19.

The effect of Nb levels on R_m level is examined in Figure 18. This shows a similar trend to R_p, we also see a less strong Nb effect than at 650 °C coiling temperature. The data in Figure 18 has been re-arranged to show more clearly the effect of Nb on additional R_m increase as a result of UFC. As Nb levels increase, there is a reduction in the additional R_m increase resulting from UFC. This can be seen in Figure 20.

<u>Microstructures</u>

Examples of the relevant longitudinal microstructures for the Nb HSLA steels are shown in Figures 21-32. A very fine grain structure was evident on all samples hence a magnification of 500 × has been used. There was a variation in grain size through the sample thickness and this was most evident on the laminar-cooled samples. Therefore, for consistency, all photographs are taken from the mid thickness position.

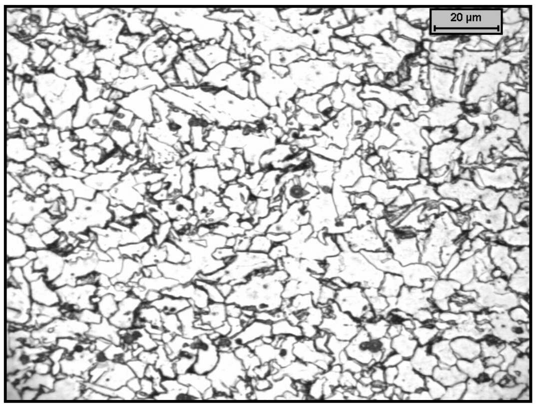

Figure 21. Microstructure of Alloy F after laminar cooling down to a coiling temperature of 550°C.

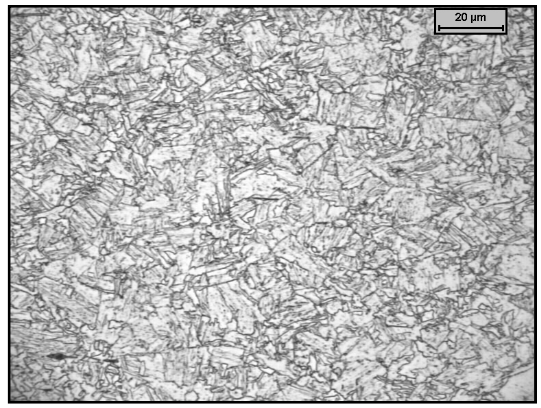

Figure 22. Microstructure of Alloy F after ultra fast cooling down to a coiling temperature of 550°C.

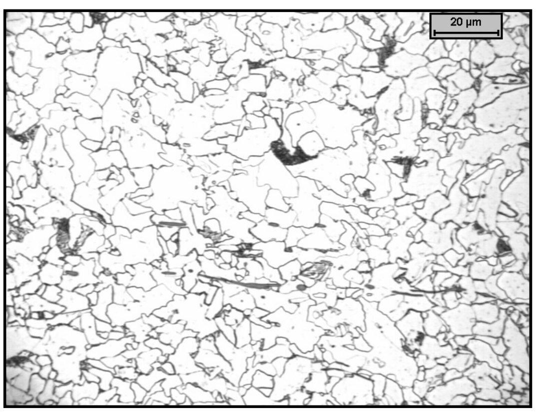

Figure 23. Microstructure of Alloy F after laminar cooling down to a coiling temperature of 650°C.

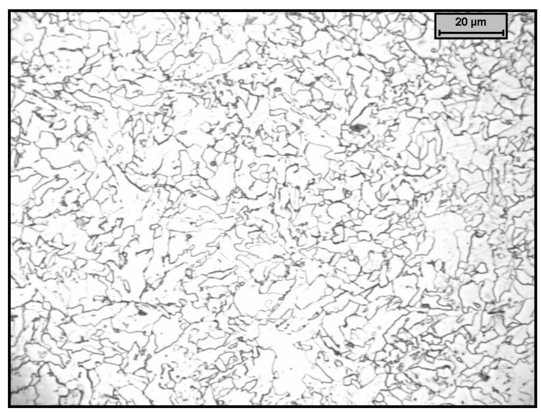

Figure 24 Microstructure of Alloy F after ultra fast cooling down to a coiling temperature of 650°C.

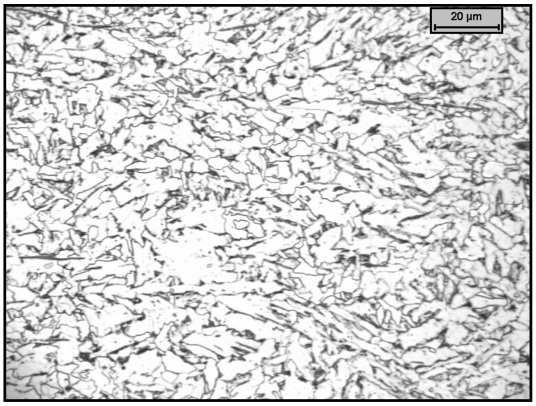

Figure 25. Microstructure of Alloy G after laminar cooling down to a coiling temperature of 550°C.

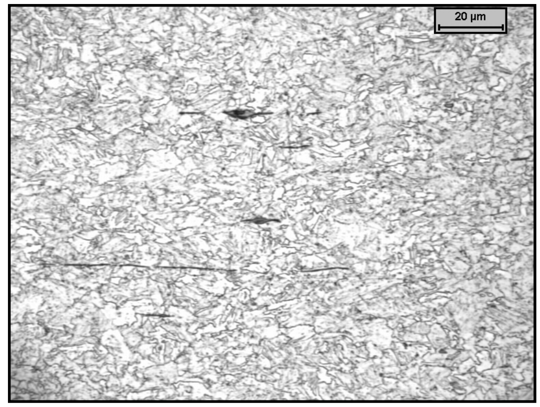

Figure 26. Microstructure of Alloy G after ultra fast cooling down to a coiling temperature of 550°C.

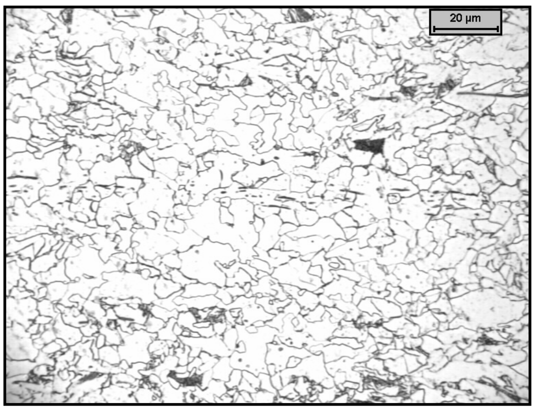

Figure 27. Microstructure of Alloy G after laminar cooling down to a coiling temperature of 650°C.

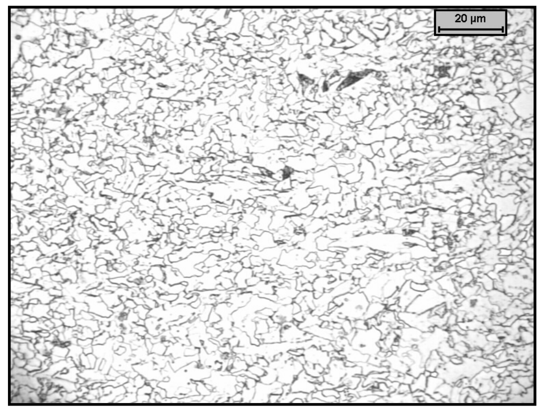

Figure 28. Microstructure of Alloy G after ultra fast cooling down to a coiling temperature of 650°C.

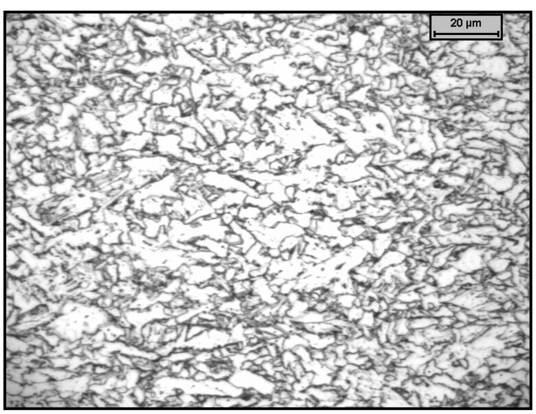

Figure 29. Microstructure of Alloy H after laminar cooling down to a coiling temperature of 550°C.

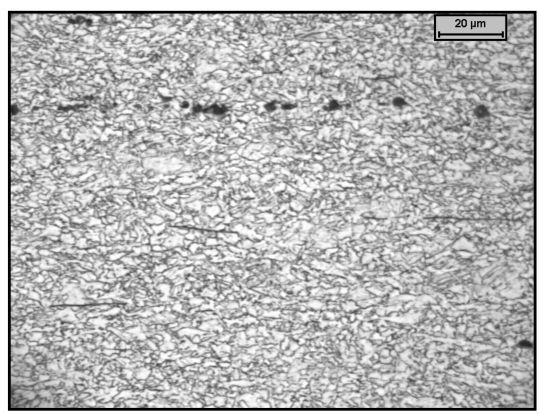

Figure 30. Microstructure of Alloy H after ultra fast cooling down to a coiling temperature of 550°C.

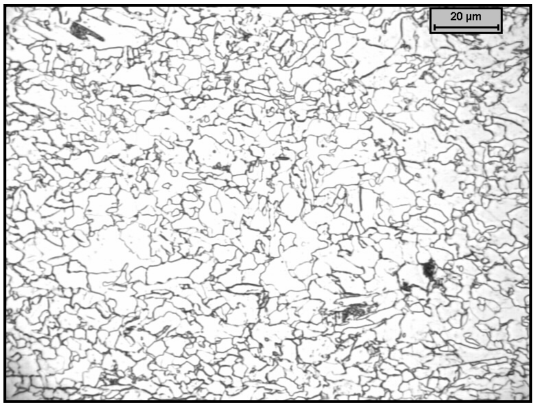

Figure 31. Microstructure of Alloy H after laminar cooling down to a coiling temperature of 650°C.

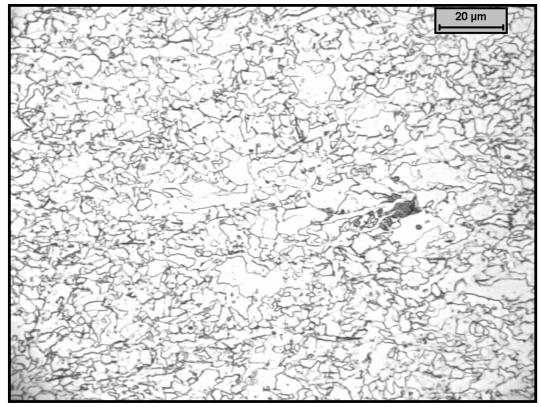

Figure 32. Microstructure of Alloy H after ultra fast cooling down to a coiling temperature of 650°C.

In Table 4, an overview is given on the dominant microstructural features of the samples produced.

Table IV. Summary of microstructures for Nb steels.

	650°C coiling temperature		550°C coiling temperature	
	Laminar	UFC	Laminar	UFC
Alloy F	Largest grain size of all casts for these conditions.	Largest grain size of all casts for these conditions	Heavy carbides	Bainite, laths coarser than other compositions
Alloy G	Fine grains, mixed sizes	Grain size finer than laminar	Acicular ferrite, heavy carbides	Bainite
Alloy H	Fine grains, mixed sizes	Grain size finer than laminar	Acicular ferrite, heavy carbides	Bainite

Nb-V Compositions for High Strength

Effect of Direct Charging

This alloying concept provides a combination of grain refinement and precipitation strengthening. The Nb level can be kept relatively low, whilst V can be added to increase strength through fine precipitates that are formed after rolling has taken place. V precipitates are the most soluble in austenite. Thus, the risk of precipitation occurring before rolling is expected to be small. There is, however, one disadvantage in that higher N levels are required and this increases the likelihood of Nb precipitation during casting and in the tunnel furnace.

Table V. Chemical Compositions of Nb-V Alloys (in wt%).

	C	**Mn**	**N**	**Nb**	**V**	**pptn start**
Alloy I	0.045	0.800	0.009	0.010	0.055	< 850
Alloy J	0.045	0.750	0.009	0.010	0.160	< 850

An assessment was made of the influence of slab temperature and chemical composition on precipitation, for the compositions presented in Table 5. The fact that these alloys have a higher

N addition could result in the precipitation of NbN at a higher temperature. However, the experimental data shows that there will not be a problem in the typical slab temperature range of the DSP with N levels up to 0.009wt%. This composition should be reasonably robust with respect to slab temperature variations.

Effect of Ultra Fast Cooling

The basic compositions of the experimental Nb-V-microalloyed steels are given in Table 6 below. The simulation of the rolling and cooling procedure in the DSP was only carried out for a coiling temperature of 650°C. After processing, the material was examined for its mechanical properties and microstructural features.

Plots of the yield stress (Rp), tensile strength (Rm) and fracture elongation (A80) values measured on material processed using laminar cooling and UFC conditions, are shown in Figures 33-35, for Alloys K through O, and a coiling temperature of 650°C.

Table VI. Nb-V experimental compositions.

	C	**Mn**	**N**	**Nb**	**V**
Alloy K	0.042	0.250	0.009	0.016	trace
Alloy L	0.041	0.850	0.008	0.039	trace
Alloy M	0.094	1.370	0.011	0.042	trace
Alloy N	0.044	1.450	0.014	trace	0.19
Alloy O	0.075	1.330	0.010	0.048	0.084

A summary of the yield stress values for each of the five compositions is shown in Figure 33. UFC gives an increase in strength over laminar cooling. However, the increase of yield stress with UFC is relatively small. V-containing compositions (N, O) are much stronger than the Nb-only compositions (K,L,M). The yield stress of the Nb-only compositions increases with increasing Nb content.

Tensile strength levels (Figure 34) follow a similar pattern to yield stress. However, there is no significant difference between UFC and laminar cooling for the V-containing steels.

A summary of the elongation values for each of the casts at the two cooling conditions is shown in Figure 35. UFC produces a reduction in elongation when compared to laminar cooling. The elongation decreases with increasing Nb content, for both UFC and laminar cooling.

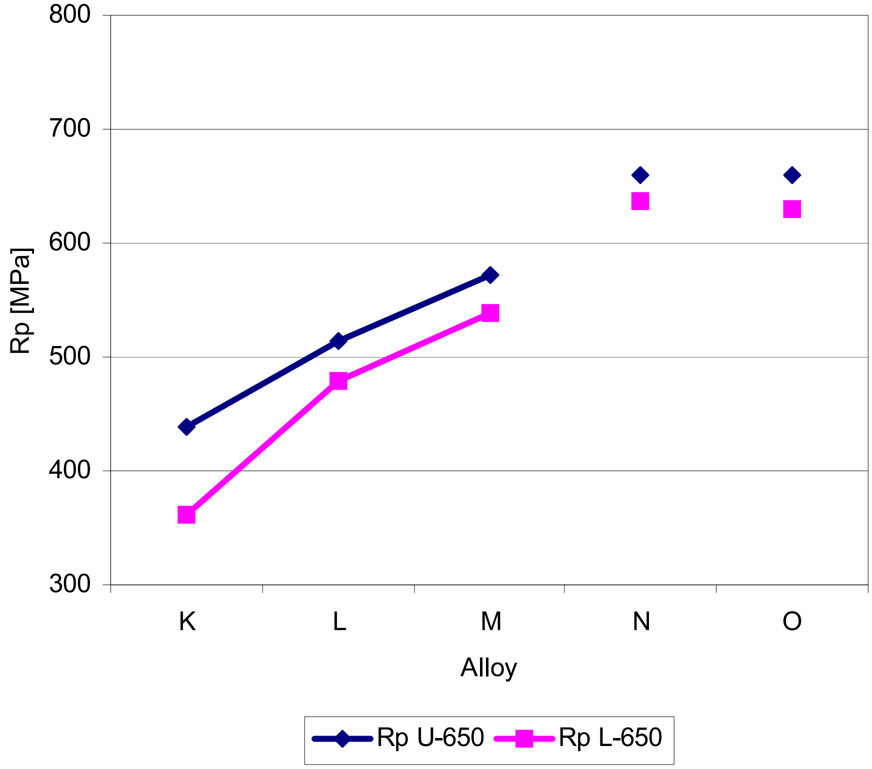

Figure 33. Variation of yield strength R_p for Alloys K – O.

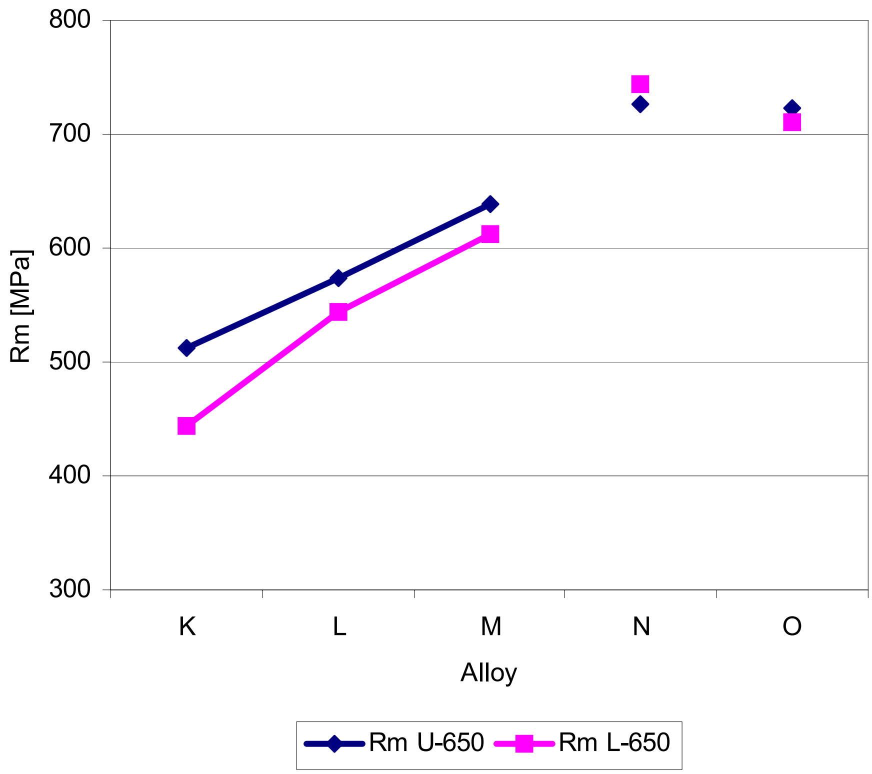

Figure 34. Variation of tensile strength R_m for Alloys K – O.

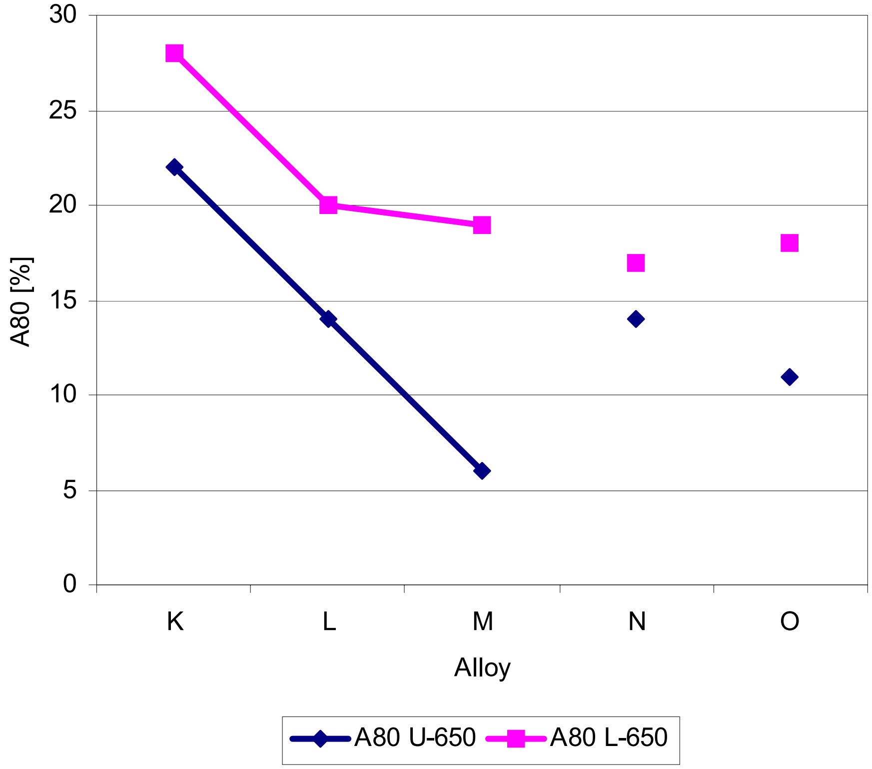

Figure 35. Variation of elongation A_{80} for Alloys K – O.

Microstructures

Examples of the relevant longitudinal microstructures for the Nb+V steels are shown in Figures 36-45**.** A very fine grain structure is evident. Hence a magnification of 500 × has been used. There was a variation in grain size through the sample thickness and this was most evident on the laminar-cooled samples. For consistency, all photographs are taken from the mid thickness position.

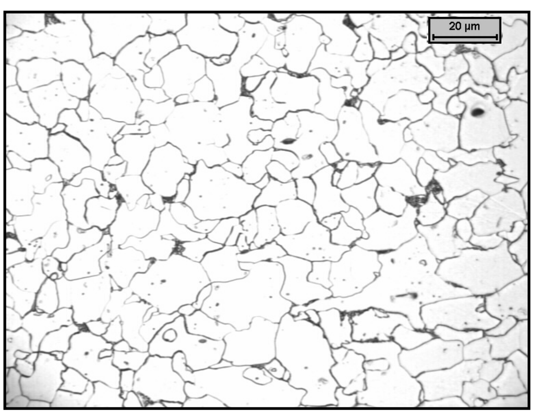

Figure 36. Microstructure of Alloy K after laminar cooling down to a coiling temperature of 650°C.

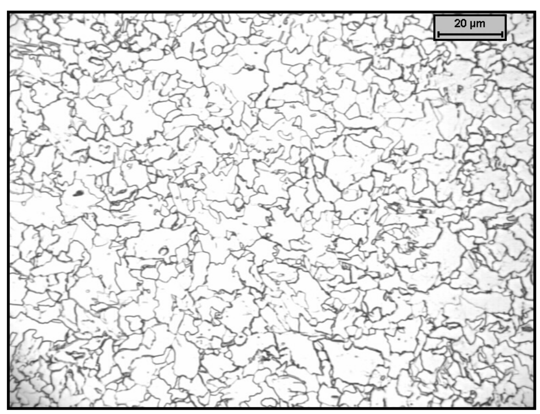

Figure 37. Microstructure of Alloy K after ultra fast cooling down to a coiling temperature of 650°C.

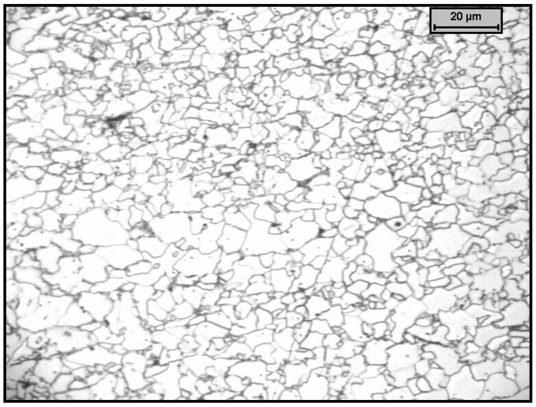

Figure 38. Microstructure of Alloy L after laminar cooling down to a coiling temperature of 650°C.

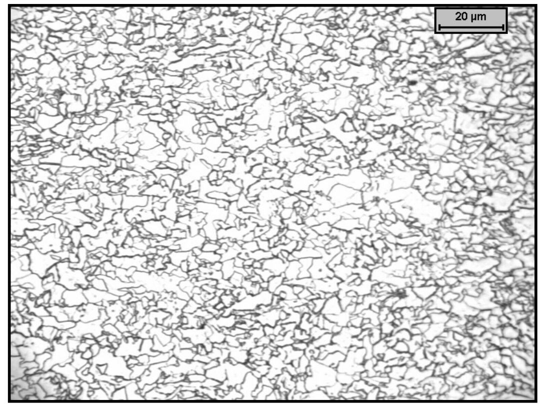

Figure 39. Microstructure of Alloy L after ultra fast cooling down to a coiling temperature of 650°C.

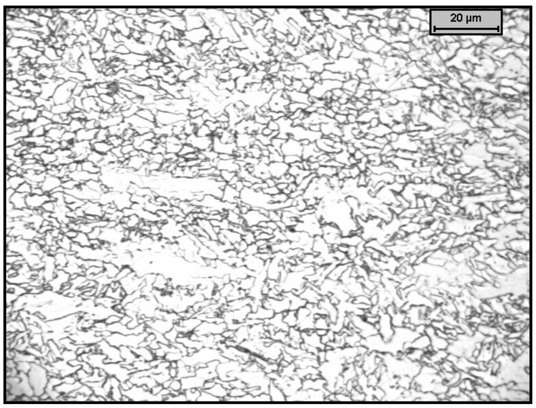

Figure 40. Microstructure of Alloy M after laminar cooling down to a coiling temperature of 650°C.

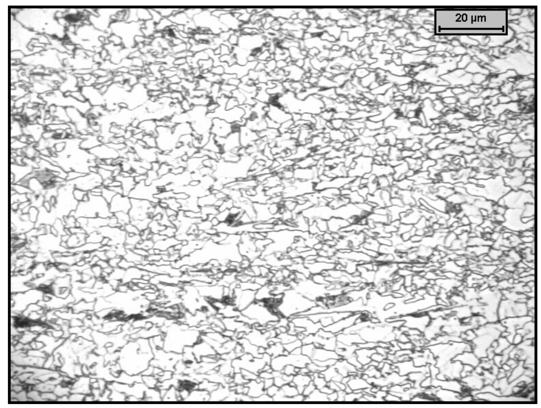

Figure 41. Microstructure of Alloy M after ultra fast cooling down to a coiling temperature of 650°C.

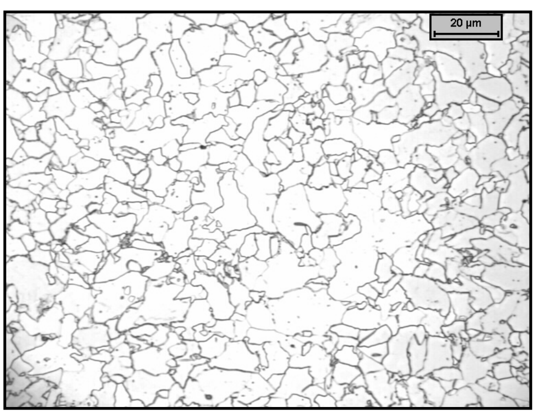

Figure 42. Microstructure of Alloy N after laminar cooling down to a coiling temperature of 650°C.

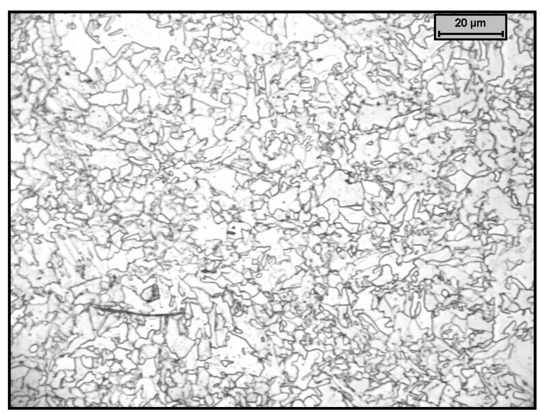

Figure 43. Microstructure of Alloy N after ultra fast cooling down to a coiling temperature of 650°C.

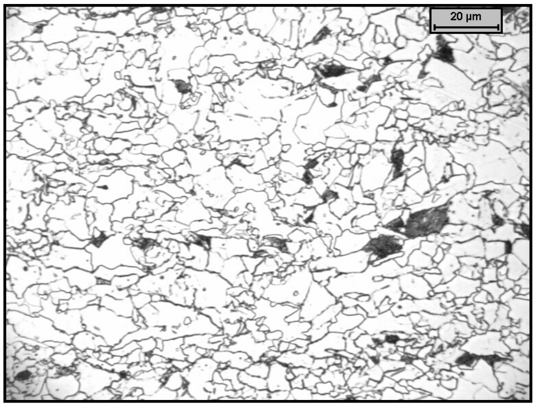

Figure 44. Microstructure of Alloy O after laminar cooling down to a coiling temperature of 650°C.

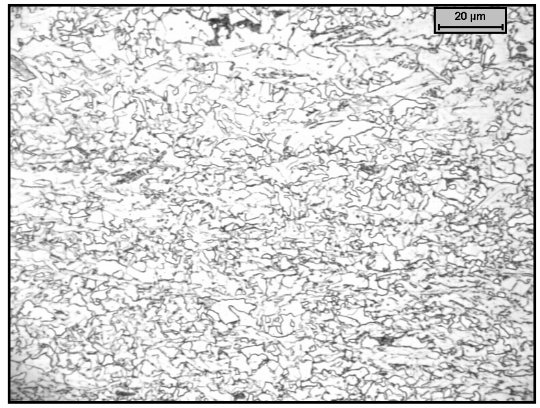

Figure 45. Microstructure of Alloy O after ultra fast cooling down to a coiling temperature of 650°C.

In Table 7, an overview is given on the microstructural features of the samples produced.

Table VII. Summary of microstructures for Nb-V steels.

	650 °C coiling Temperature	
	Laminar	**UFC**
Alloy K	Largest grain size of all casts for these conditions. Largest difference in grain size between laminar and UFC.	Largest grain size of all casts for these conditions.
Alloy L	Fine grains, mixed sizes.	Fine grains, mixed sizes. Finer than laminar.
Alloy M	Fine grains, mixed sizes.	Fine grains, no difference to laminar
Alloy N	Fine grains, mixed sizes.	Fine grains, mixed sizes. Finer than laminar.
Alloy O	Fine grains, mixed sizes.	Fine grains, mixed sizes. Finer than laminar.

Discussion

Effect of Direct Charging

Nb-only alloys are considered the ideal option for the lower strength range of DSP products. There is little benefit in considering other options.

Nb-V compositions appear to be a suitable option for the DSP, in particular for higher strength alloys. This alloying concept will be robust with respect to typical variations in processing conditions. Higher N levels will be required. However, it is recommended that the maximum N level be 0.010 wt.% as this will ensure that the steel remains insensitive to variations of process conditions. V-only alloys will not be sensitive to typical process variations. V alloys will not require the same N restrictions as Nb-V alloys. However, unlike Nb, the strengthening effect of V is not enhanced by Ultra Fast Cooling (UFC).

Effect of Ultra Fast Cooling

Nb-only Compositions. There is a noticeable increase in R_p and R_m when UFC is used. A significant reduction in elongation is also evident. This effect is most significant at a coiling temperature of 550°C. An increase in R_p and R_m of approximately 100 N/mm^2 can be achieved when using UFC compared with laminar cooling for this coiling temperature. However, the majority of the microstructures from material cooled to 550°C were bainitic. This is confirmed by the very low elongation values. It is therefore evident that the main strengthening mechanism occurring when UFC is used in conjunction with a 550°C coiling temperature for these compositions is transformation strengthening. However, the formation of bainite is detrimental to ductility and must be avoided.

When using a coiling temperature of 650°C, the increase in R_m and R_p is approximately 30 N/mm^2. This value is much smaller than seen for the 550°C coiling temperature. There is also a small reduction in elongation for the UFC route, but this is much less significant when compared with the results for 550°C.

The increase in strength as a result of UFC is dependant on the Nb level. For Nb levels above 0.03 wt.%, the benefit from UFC becomes negligible. Both UFC and Nb provide higher strength via grain refinement. Thus at higher Nb levels there is no additional strength increase from UFC. Nb works by increasing the temperature of non-recrystallisation, thus a heavily deformed substructure is formed at the end of hot rolling. This provides substantial nucleation sites for ferrite grains, and hence results in a fine grain structure after cooling. Hence, in terms of chronological order the effect of Nb comes before UFC. At high Nb levels the heavily deformed substructure will provide so many nucleation sites for grain growth that any addition benefit from UFC will be very small.

Nb-V Compositions. Only one coiling temperature was assessed for these steels. This was 650 °C. In general, UFC provides a small increase in R_p over laminar cooling. No significant difference in R_m could be detected between UFC and laminar cooling. As seen previously with the Nb steels a reduction in elongation was apparent for UFC. The strength levels of these two compositions are sufficiently high to allow a reduction in alloying additions and still safely meet the required strength levels.

Conclusions

UFC provides an increase in R_p and R_m for Nb HSLA steels. However, the extent of the strength increase is related to the Nb content. A higher increase is evident for lower Nb levels.

When using V an increase in R_p was observed, however no significant difference in R_m was evident between UFC and laminar cooling.

UFC results in a decrease in elongation for both Nb and V HSLA steels.

It is theoretically possible to meet a S550MC specification with a Nb-only steel. This requires UFC with a coiling temperature of 550°C. However, this is not a practical solution for a production process. The process window is minimal. Small fluctuations in chemistry or coiling temperature could result in bainite formation and thus rejections due to lack of ductility. The best solution to achieve the S550MC specification via the DSP is with a Nb-V or V-only composition.