Development and Production of HSLA 80ksi (550MPa) Steels at Gallatin Steel

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Abstract: In this paper, the development and production of 80 ksi (550MPa) V-N-Mo microalloyed steels at Gallatin Steel is discussed, along with the influence of Thermo-Mechanical Controlled Process (TMCP) parameters on the mechanical properties. Recrystallization Controlled Rolling (RCR) is used to hot roll 55 mm and 65 mm thin slabs at elevated temperatures, i.e., above the recrystallization stop temperature and then followed by accelerated controlled cooling (ACC) at cooling rates ranging from 10℃/s～45℃/s. With the use of RCR-ACC technique, the yield strengths have consistently achieved in excess of 80 ksi (550MPa), while maintaining good elongation.

Keywords: thin slab; recrystallization; controlled rolling; accelerated cooling; vanadium; nitrogen; molybdenum.

1 Introduction

Gallatin Steel Company located at Ghent, Kentucky is a $360-million joint venture owned by U.S. based GerdauAmeristeel (Tampa) and Canadian based DOFASCO Inc. (Hamilton). The steel plant operates a state of the art SMS-CSP (Compact Strip Production) process for melting, casting and hot rolling of carbon steel. Major equipment includes a twin-shell, DC arc furnace melt shop; a ladle metallurgy facility (LMF); a single-strand CSP (Compact Strip Production) caster. The caster was originally designed for casting 50mm thick thin slabs at widths ranging from 1066mm to 1575mm. A 213.4m long roller hearth furnace; and a high-speed, six-stand (2.25 Mt/a rated capacity) hot strip mill, capable of producing steel strip at thickness from 1.52mm to 17.15mm. Although the plant began operation in 1995 with a design capacity of 1.1 million short tons, Gallain Steel shipped a record 1.52 million short tons in 2004. One of the reasons for this excellent operating performance is that a bottleneck at the caster was eliminated when Gallatin Steel developed and implemented its own dynamic secondary spray cooling system that allows higher casting speeds up to 6.10 m/min for 65mm slabs.

Gallatin Steel's hot strip mill, equipped with CVC work roll shifting and bending, is fully capable of producing hot steel strip with excellent shape and desired gauge profile. Over the past five years, as part of a strategic program for making Gallatin Steel a viable contender in the U.S. market, much effort has been directed towards the development of higher value added higher strength HSLA steels. In particular, the demand from the market for HSLA Grade 80 (80ksi) has increased dramatically over the last couple of years. This growth was precipitated and driven by the economic advantage of using high strength steels for weight reduction in structural and automotive applications.

In recent years there has been a considerable amount of work directed towards the development of high strength steels. Conventional controlled rolling techniques have been commercially employed by both mini mills and integrated steelmakers to hot roll HSLA steel strip and plate below the Crystallization Stop temperature (Tnr) with finishing temperature typically below Ar_3

However, these techniques have not proven to be attractive because a significant increase in mill loads is anticipated by rolling steel strip and plate at lower temperatures. This concern is particularly true for the CSP hot strip mill, which employs the in-line CSP hot rolling process. Gallatin Steel's CSP process consists of a thin slab caster, a tunnel furnace and a 6 stand tandem mill. The CSP caster is designed to directly link with the hot strip mill through a tunnel furnace. The residence time of a thin slab in the tunnel furnace is typically in the range of 10 to 15 minutes in order to equalized the slab temperature. After discharging from the tunnel furnace, the thin slab is hydraulically descaled and subsequently fed into the finishing mill. Unlike the conventional hot strip tandem mill, the CSP hot strip mill is neither equipped with roughing stands nor a delay table for temperature control. The entry temperature of a slab at F1 finishing stand is expected to be much higher that of a transfer bar processed through a conventional tandem finishing mill. Clearly, these constraints make a CSP hot strip mill impractical for using the conventional controlled rolling techniques.

It is obvious that there is a need to develop an alternative controlled rolling technique that would allow a CSP hot strip mill to roll 80 ksi HSLA steel efficiently and economically. In contrast to the conventional controlled rolling techniques, the approach taken was to use a high temperature recrystallization controlled rolling (RCR) technique followed by accelerated controlled cooling (ACC) [1~3]. The effects of Thermo-Mechanical Controlled Process (TMCP) parameters on mechanical properties were investigated. The alloy design of microalloyed steel used in the present study is a V +N+ Mo based HSLA steel. For the purpose of precipitation strengthening, nitrogen, either present as an inherited residual in steels or enhanced through nitrogen additions is used to promote the formation of nitrogen–rich vanadium carbonitride V(C,N) precipitates. The present study demonstrates that this technique has offered the most promising approach for the production of 80 ksi HSLA steels.

2 Experimental

In order to determine the effects of TMCP parameters on mechanical properties of hot rolled HSLA steel, an extensive and systematic study was carried out at Gallatin Steel's hot strip mill. The technical development path for HSLA Grade 80 basically consisted of the following three steps:

(1)Alloy design.

(2)Hot mill TMCP design..

(3)Full scale trial.

2.1 Alloy design

The steel chemistry of HSLA Grade 80 is designed in accordance with ASTM A1011 G80, A1018 G80, SAE J1392 and SAE080, along with some specific customer requirements.

The typical chemistry of vanadium-nitrogen based HSLA steels with a molybdenum addition in the range of 0.050% to 0.130% is given in table 1. Nitrogen was intentionally added and controlled in the range of 190～220ppm. For such steels, the strengthening mechanism predominantly involves V(C,N), VN and MoC in the fine transformed ferrite grains.

2.2 Hot mill TMCP design

In order to determine the optimal TMCP paths used at Gallatin Steel for HSLA Grade 80, a complete set of roll force and heat flow models was used. The key process variables (KPVs) for TMCP that were monitored and controlled were as follows:

(1) Tunnel furnace discharging temperature.

(2) F1－F6 reduction ratios and deformation strains.

(3) Roll forces and flow stresses.

Table 1 Steel Chemistry

C, wt%	Mn, wt%	Si, wt%	Mo, wt%	V, wt%	N, wt%	Al, wt%
0.050-0.080	1.25-1.45	0.06 - 0.20	0.050-0.130	0.120-0.140	0.0190-0.0220	0.015-0.025

(4) Total processing time.

(5) Mill speeds (F1 entry and F6 exit speeds).

(6) Finishing temperature.

(7) Coiling temperature.

(8) Cooling rate.

2.3 Full scale trial

Full scale trials were carried out at Gallatin Steel's hot strip mill to examine the effect of TMCP KPVs on the mechanical properties of vanadium-nitrogen based HSLA steels. In order to provide clear and complete trends showing the effects of TMCP KPVs on mechanical properties, the analysis was extended to include both the data of HSLA Grade 70 and 80.

The hot strip mill was instrumented to record mill speed, mill drive power, roll separating force, roll gap setting, and the steel strip temperatures at F1 to F6 and down coiler. The full scale trial conditions are given in table 2. The mill exit speeds at F6 were varied from 130 to 460 m/min with the corresponding ACC cooling rates ranging from 10～45 ℃/s.

Table 2 Full scale trial conditions

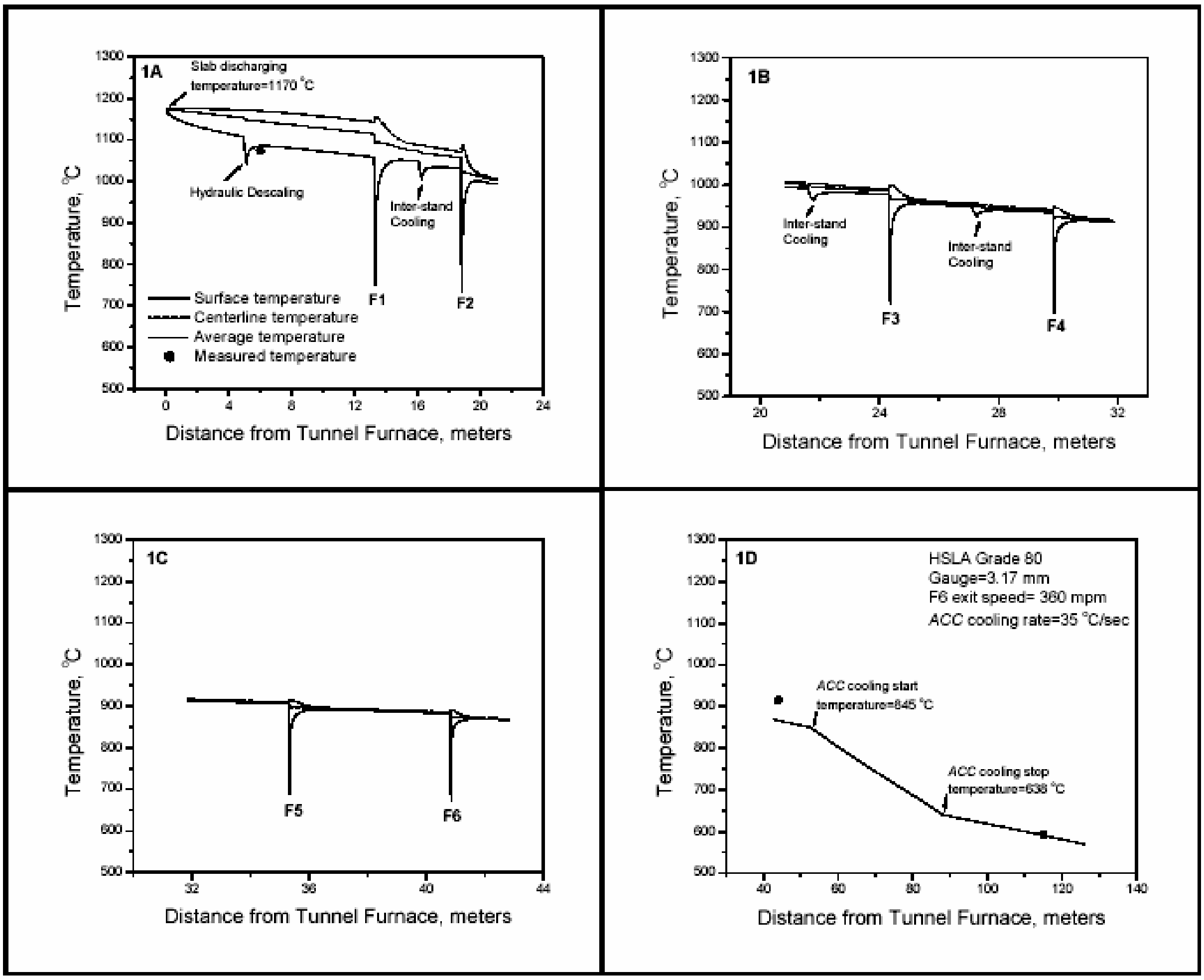
Thickness, mm	F6 Exit Speed, mpm	F1 Temp, °C	F6 Temp, °C	Coiling Temp, °C	Cooling Rate, °C/Sec
2.46-9.32	130-460	1040-1080	860-950	540-650	10-45

F1 Strain	F2 Strain	F3 Strain	F4 Strain	F5 Strain	F6 Strain
0.24-0.42	0.15-0.40	0.10-0.28	0.09-0.17	0.05-0.15	0.04-0.09

3 Results and Discussion

The mechanism of RCR for grain refinement is based on the repeated recrystallization phenomena of austenite structure during the hot rolling process. Upon passing the last finishing stand, the steel strip is subsequently transformed to a finer and more uniform ferrite grain structure via ACC. Concurrent with this transformation process, a rapid precipitation of V(CN), VN and Mo_2C is finely dispersed into a ferrite grain structure.

Since the RCR-ACC technique was used for developing HSLA Grade 80 steels, optimization of the rolling pass schedules for RCR－ACC was important. A one dimensional heat flow model, coupled with a roll force model, was used for the design of the rolling pass schedule. Figures 1A to 1D show the calculated temperature profiles for the hot rolling of HSLA Grade 80 using the simulation conditions given in table 3. The simulations were performed using a 55mm thin slab at an aim final steel strip gauge of 3.17mm. The simulations started from the exit of the tunnel furnace, throughout 6 finishing stands, to the run out table accelerated cooling, and ended at the down coiler. For the purpose of validating the model, the calculated steel strip surface temperatures were compared with measured steel strip surface temperatures at F1 strip surface temperatures at F1, F6 and the down coiler. Superimposing the measured steel strip temperatures on figures 1A, 1C and 1D, it can be seen that there is consistently good agreement between the predicted and measured temperatures. Note that the average temperatures through the steel strip thickness and the centerline temperatures are also plotted in these figures. In all cases, as steel strip passed through the roll gap, radical surface temperature variations adjacent to the roll gap were observed due to excessive work roll cooling. Although heat generated both by plastic work in the roll gap during deformation and by frictional heat due to slippage between the work roll and the steel strip surface compensates for part of heat loss, roll gap cooling significantly decreases the steel strip temperature. figures 1A to 1C also illustrate the variations of temperature around the hydraulic descaling and inter-stand cooling areas. The ACC cooling rate was controlled at 35°C/s with an aim ACC cooling stop temperature and coiling temperature at 640 and 590°C, respectively.



Figures 1A to 1D: Computer simulation of steel strip temperature profiles from the exit of tunnel furnace throughout 6 finishing stands to down coiler.

Table 3 Computer simulation conditions

Thickness, mm	F1 Temp °C	F6 Temp, °C	Coiling Temp, °C	F6 Exit Speed, mpm	Cooling Rate, °C/Sec
3.17	1072	876	592	360	35

F1 Strain, -	F2 Strain, -	F3 Strain, -	F4 Strain, -	F5 Strain, -	F6 Strain, -
0.398	0.387	0.208	0.107	0.075	0.066

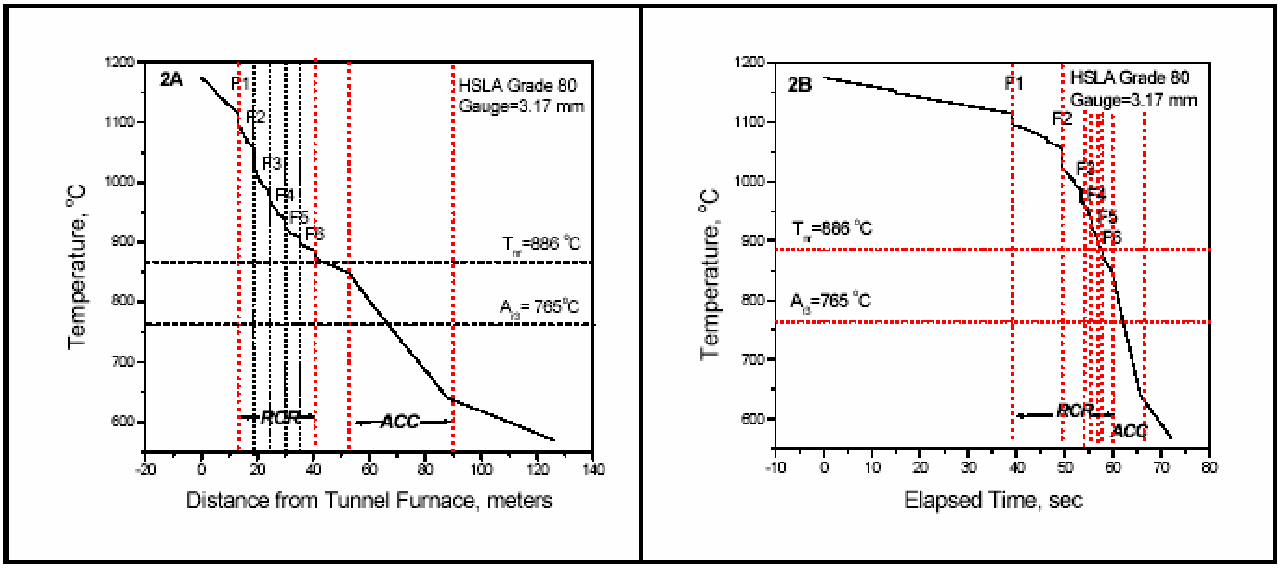


Figure 2A: Computed average steel strip temperature profile for TMCP path plotted against distance from tunnel furnace.

Figure 2B: Computed average steel strip temperature profile for TMCP path plotted against elapsed times.

Figures 2A and 2B show the typical RCR-ACC TMCP paths used at Gallatin Steel for processing HSLA Grade 80 steels. The computed average temperature profiles obtained from figures 1A to 1D are plotted as a function of distance from the exit of the tunnel furnace to the down coiler as shown in figure 2A. In order to examine the time effect, figure 2B shows the same computed average temperature profile, plotted against elapsed times of steel strip after discharging from the tunnel furnace. The calculated Tnr (recrystallization stop temperature), Ar_3 (γ to α transformation temperature), are superimposed on figures 2A and 2B. Clearly, one can see that the steel strips were rolled at the high temperature regime, i.e., above recrystallization temperature from entering the first and subsequent reduction passes. As expected, the microstructure of the steel strip is constantly changed under various deformation strains during the hot rolling process and hence influences the flow stress of the steel strip and the roll forces required. Therefore, the flow stresses, which were calculated from the roll force model using the measured roll separating forces, could provide additional information about the austenite deformation and evolution phenomena during hot rolling. Guidance for the design of hot rolling pass schedules for producing a fine and uniform austenite structure prior to the phase transformation could also be provided. Figure 3 shows the calculated flow stress plotted against the Zener-Holloman parameter (temperature compensated strain rate) for the finishing mill stands from F1 to F6. As can be seen from figure 3, the flow stresses are constant from F1 to F3. F4 to F6 exhibit a strong positive linear relationship with the Zener-Holloman parameter. The difference in flow stress behavior between F1－F3 and F4-F6 can easily be accounted for by the difference in austenite grain structure of the steel strip. Therefore, the microstructure of the steel strip from F1 to F3, which is subjected to the repeated complete recrystallization for grain refinement due to the repeated breaking down of as cast structure, is believed to be coarser than those from F4 to F6. The flow stress curves exhibit a zero slope (constant value) as the Zener-Holloman parameter increased at the beginning of rolling (F1 to F3).

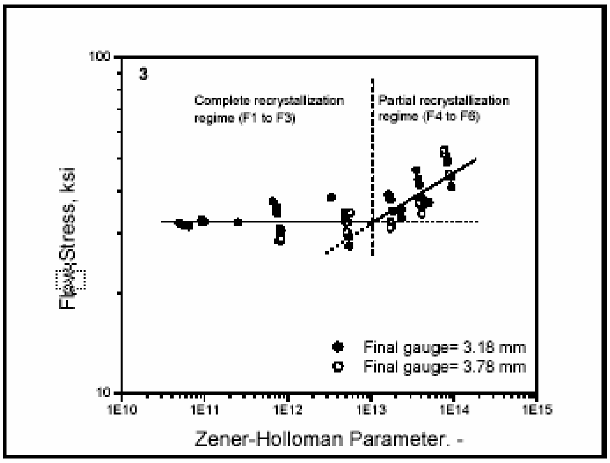


Figure 3: Flow stress plotted vs. Zener-Holloman Parameter.

On the other hand, the flow stresses are seen to increase linearly with the increase of the Zener-Holloman parameter (F4 to F6). This phenomenon reflects the transition from complete recrystallization to partial recrystallization, but the data may not be accurate enough to define the transition temperatures. However, based on the results from the simulations using a one dimensional heat flow model, it is likely that the transition temperatures from complete recrystallization to partial recrystallization are around 1030～1050℃. The increase of flow stress during hot rolling in the partial recrystallization regime is likely due to the effect of the increased Zener-Holloman parameter as mill speeds increase. Another contributing factor is that, after the F3 rolling pass, the steel strip is believed to be completely recrystallized, and the grain size is further refined throughout the remainder of the rolling pass schedule.

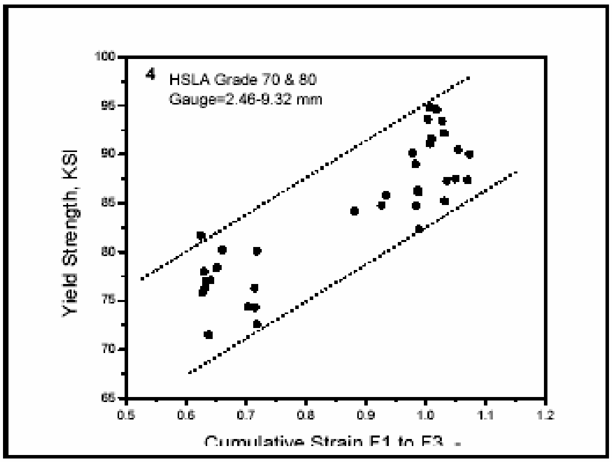


Figure 4: Yield strength vs. cumulative Strain F1 to F3.

Figure 4 shows the yield strength plotted against cumulative strains from F1 to F3. The cumulative strains are defined as the summation of deformation strains at F1, F2, and F3. As can be seen from figure 4, the yield strengths are very sensitive and are in a linear relationship with cumulative strains. It appears certain that the steel strip, with a considerable amount of deformation in the complete recrystallization regime, obviously has some positive contribution to the increased yield strengths. To refine as cast structure via repeated complete recrystallization, heavy pass reductions of 50% or more at F1 to F3 are required. The present hot rolling pass schedule for HSLA Grade 80 employs heavy pass reductions at F1 to F3 to breakdown as cast structure at the higher temperature regime, i.e., above complete recrystallization temperature. The austenite grain refinement occurs by repeated cycles of deformation and recrystallization from the start of hot rolling. The steel strip is believed to be refined appreciably before the minimum temperature for complete recrystallization is reached. On the other hand, with the use of heavy pass reduction and deformation in the partial recrystallization regime, it is possible that a mixed structure of fine and coarse austenite grains can develop. This can eventually transform to a pronounced banding and a mixed ferrite grain size, which could result in deterioration of strength and toughness.

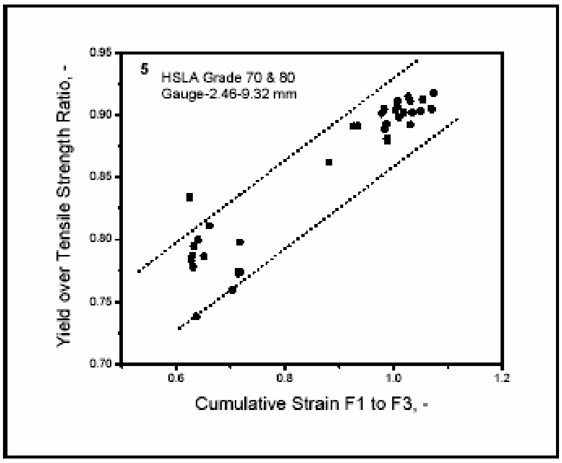


Figure 5: The effect of cumulative strain of F1 to F3 on yield strength.

Figure 5 shows the effect of cumulative strains of F1 to F3 on a yield over tensile strength ratio. The detrimental effects of yield strength on elongation are shown in Figure 6. At higher levels of yield strength the additional strength is likely provided by the increased precipitation strengthening, which also results in lowering elongation and toughness.

The effect of total processing time and cooling rate are shown in Figures 7 and 8, respectively. The increase in yield strength is inversely proportionally to the reduced total process times. In other words, higher rolling speeds have a beneficial effect on improving yield strength. This is attributed to the suppression of recrystallized grain growth because of the shorter time interval between passes.

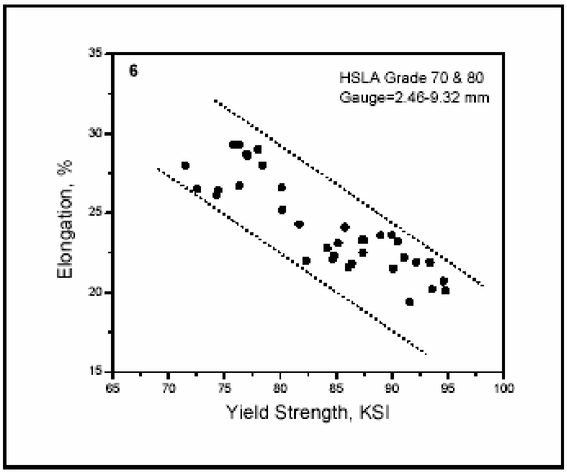


Figure 6: The effect of yield strength on Elongation.

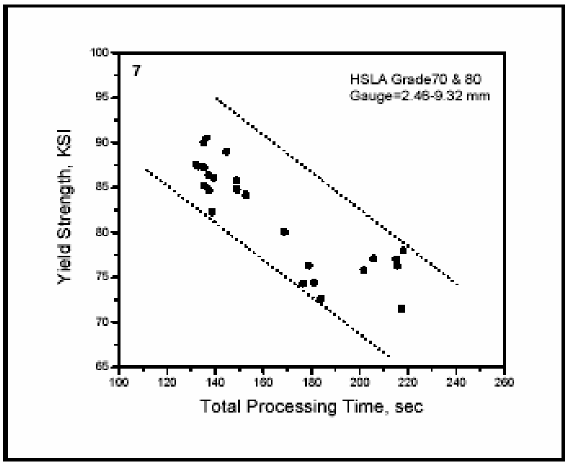


Figure 7: The effect of processing time on yield strength.

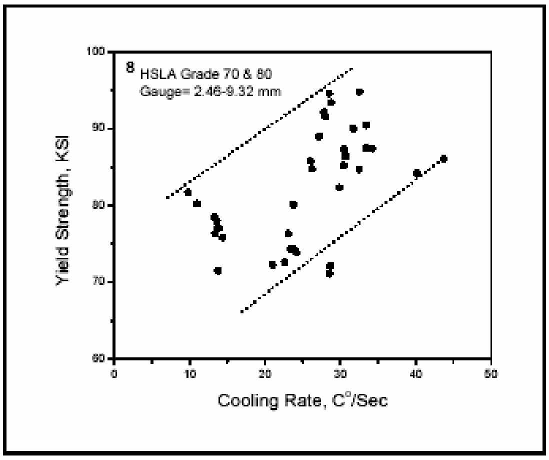


Figure 8: The effect of cooling time on yield strength.

Another compounding effect is that shorter processing times can effectively reduce the premature precipitation of V(C,N) and Mo2C due to strain induced precipitation. Therefore, more Mo, V and N are available for the subsequent rapid precipitation on the run out cooling table. For all trialled rolling conditions, Figure 8 shows an increase in the strength of the steel with increasing cooling rate. The reasons for the positive effect of cooling rate on yield strength are well understood in the literature. First of all, an increased cooling rate will lower the austenite to ferrite-pearlite transformation temperature, resulting in both strength and toughness improvements due to the decrease of pearlite lamella spacing and finer transformed ferrite grain structure. Secondly, intensive cooling rates will promote a rapid precipitation of finely dispersed V(C,N) and Mo2C particles into a polygonal ferrite structure, which significantly enhance the effectiveness of precipitation strengthening. In order to avoid the formation of bainite or martensite, the cooling stop temperature was carefully controlled and ensured to be above 500 ℃. Figure 1D shows that an intensive cooling rate of 35 ℃/s was applied to promote the precipitation of V(C,N) and Mo2C at the start of the accelerated cooling. Subsequently, the cooling rate was reduced when the temperature of the steel strip approached 640℃. It should be pointed out that the scatter of the data in these figures is thought to be an intrinsic aspect of gauge effect on yield strength.

4 Summary

Gallatin Steel has developed the steel chemistry and the hot strip mill processing practices to successfully produce HSLA Grade 80 high strength steels. The effects of TMCP KPVs on mechanical properties have been examined at Gallatin Steel's CSP hot strip mill.

The RCR - ACC technique is an effective and practical method for the controlled rolling of V-N-Mo based HSLA Grade 80 steels with enhanced steel strength and toughness. The use of RCR-ACC technique makes a fine, uniform, transformed ferrite Structure with the corresponding ASTM grain size in the range of 13-14. Heavy reduction passes at a higher temperature regime are critical, i.e., above the complete recrystallization temperature during the hot rolling process. Having shorter processing times, in particular shorter interval times between passes, and using ACC with intensive cooling rates are also important to promote a rapid precipitation of V(C,N) and Mo2C.