

PRODUCING VALUE-ADDED NIOBIUM STEELS FOR AUTOMOTIVE APPLICATIONS USING THE CSP PROCESS AT NUCOR STEEL BERKELEY

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Abstract

In the 16 years since the first hot band coil was rolled using the Compact Strip Production (CSP) at NUCOR Steel Crawfordsville, the product line produced by the sheet division of NUCOR and other minimills has grown in complexity and sophistication. Today, at Nucor Steel Berkeley (NSB), advanced high strength steels such as HSLA and Dual-Phase steels can be produced from electric furnace melts either as hot band or in cold rolled gauges produced on continuous annealing (CA) or continuous galvanizing (CG) lines. Similarly, with the addition of vacuum degassing, Interstitial-Free steels and AKDQ steels can also be produced on CA or CG lines. Niobium has already achieved its normal, prominent position in the HSLA steels and will soon appear in the DP and IF steels, as well. A recent, important development at NSB is the new intensified hot rolling sequence, where heavy gauge skelp of Nb HSLA steel for the X50-X70 API pipe can be rolled resulting in a uniform ferrite microstructure, impressive improvement in strength and toughness, and the absence of aberrant non-destructive test reflections. The ductility and formability of the CAL or CGL sheet grades is good, while the surface quality is more than adequate. It is now clear that high performance steels can be produced by the EAF plus thin slab casting route. This paper will review both some recent advances and their underlying physical and mechanical metallurgy.

Introduction

A major conference was held in Guangzhou in 2002 dedicated to thin slab casting (TSC) steel production [1]. The two major general results of that conference were: (i) the broad range of production sequences that incorporated thin slab casting, and (ii) the wide range of products that were either being produced or were being contemplated. The variation in production route was mainly in the steelmaking area, where liquid steel was supplied from electric arc furnace (EAF) or basic oxygen furnace (BOF) shops. In a true CSP plant the liquid is supplied from an EAF, passes through a ladle metallurgy furnace and then the caster. However, TSC is often retrofitted into integrated plants, hence the BOF steel supply. These variations are shown in Figure 1.

Obviously, the quality of liquid steel will vary depending on the steelmaking route. This quality will vary from scrap-based EAF, through mixtures of scrap plus direct reduced iron (DRI), through BOF. As will be discussed below, the quality of the liquid steel entering the caster can have a large influence on the optimum alloy design, e.g., Nb or V addition, for a given product.

Although Nb is added to a wide range of grades of steel, only three will be discussed here; HSLA, dual-phase (DP) and interstitial-free (IF) steels. The benefits of Nb in HSLA and IF steels are clearly established and are routinely practiced. Laboratory studies exploring the addition of Nb to DP steels have been encouraging, but this practice is still under development.

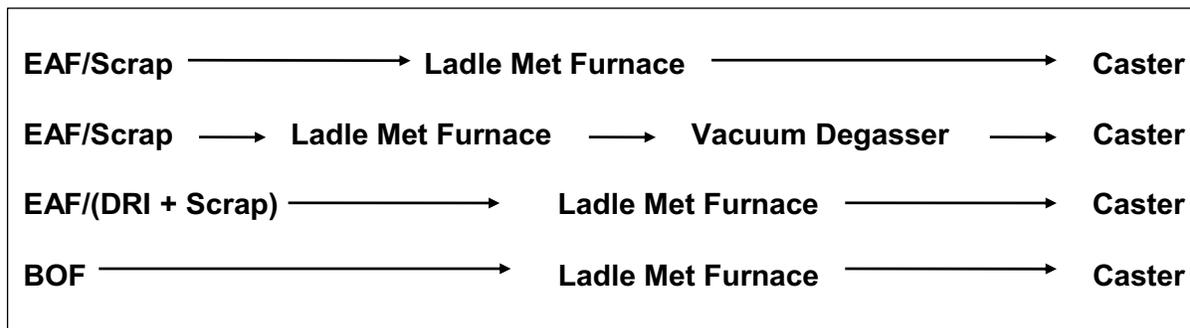


Figure 1. Block diagram showing different steelmaking up to caster.

The Compact Strip Production Process

The CSP process has been described in several articles, and will only be briefly described here [1-3]. After steelmaking, the liquid is teemed into the tundish of the caster, after which it is solidified to the desired thickness, 50mm in this case. The slab is then sheared to the proper length and then transported to the tunnel or equilibrating furnace normally set at 1150°C. At this point, the slab exhibits an austenite grain size of 500-1000 μm [4]. After the 20 minute residency time in the furnace, the slab exits the furnace, is crop sheared, and then enters the finishing mill at approximately 1000°C. The grain size entering F1 is not appreciably different from that entering the furnace [1,4]. After the slab passes through the finishing mill of 5, 6 or even 7 stands, it enters the runout table (ROT) where it undergoes cooling to the coiling temperature, after which it is coiled to room temperature. This process is shown schematically in Figures 2 and 3.

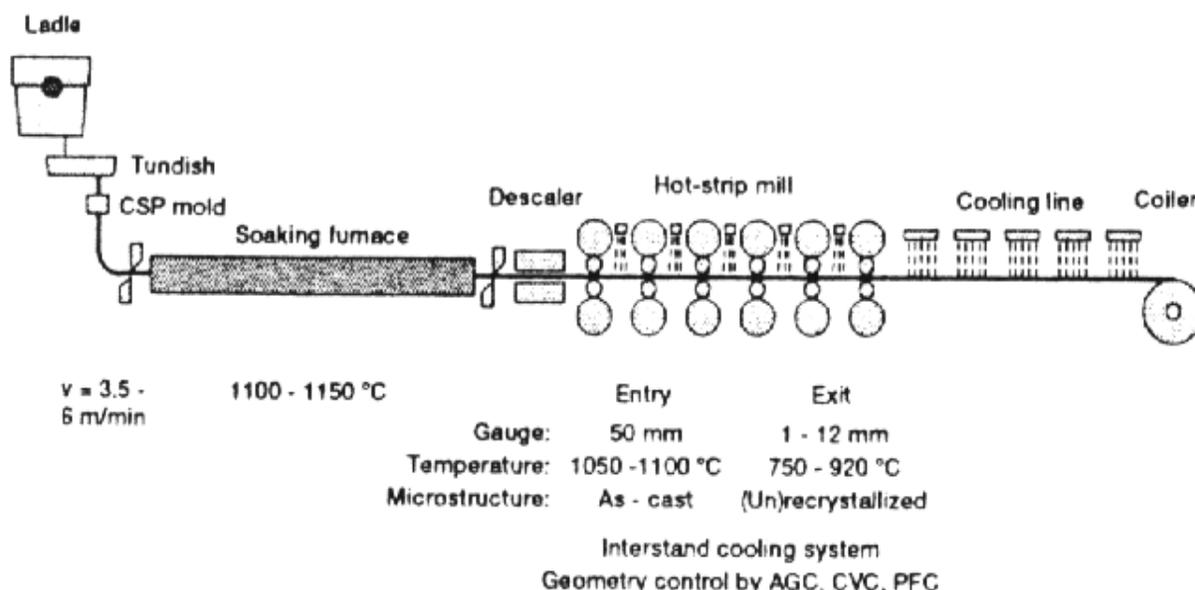


Figure 2. Schematic of the CSP Process.

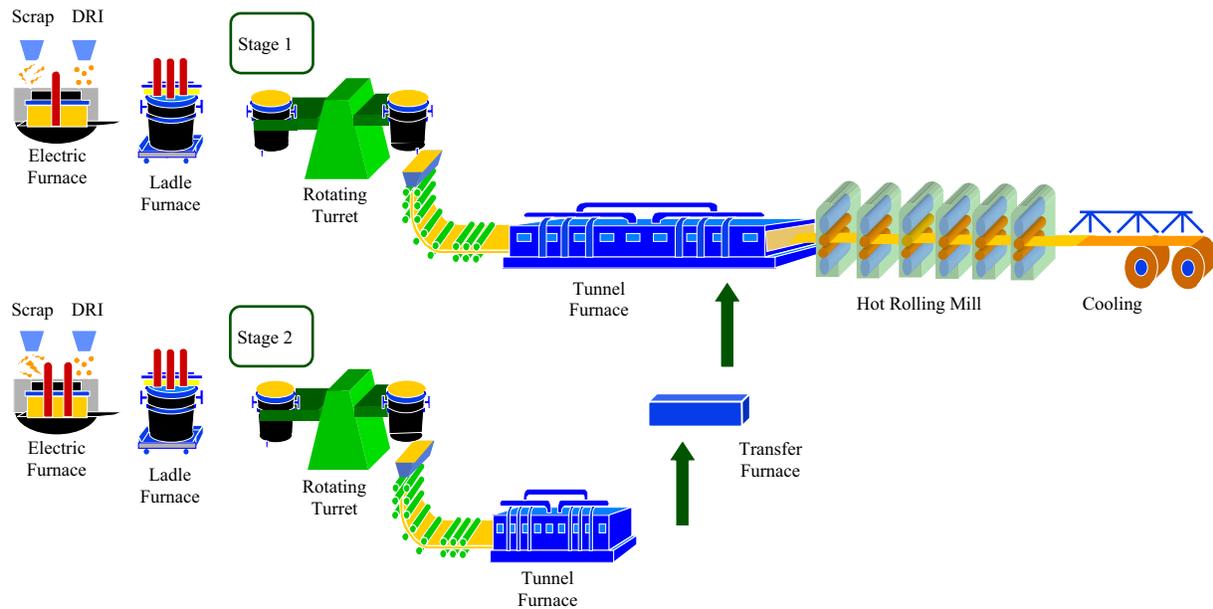


Figure 3. Schematic of the CSP Process.

Steelmaking Challenges in Improving Niobium Effectiveness

As was clearly shown in the literature [5], NbC does not fit well in either the austenite or ferrite lattice. The precipitation of NbC must occur by heterogeneous nucleation, i.e., on pre-existing high surface energy crystalline defects or substrates. One very common such surface is provided by TiN that can precipitate either in the liquid, interdendritic liquid regions between the delta ferrite dendrites, or in the austenite. Because of the segregation tendencies of Ti and N, conditions favorable for TiN precipitation exist in all but the cleanest liquid [6,7], and are often observed in both thick and thin slabs. This TiN and associated NbCN in the cruciform particles are not an issue in cold charged, thick slabs as found in the typical integrated plant, since reheating temperatures in excess of 1200°C are high enough to dissolve all of the Nb and some of the TiN in these small particles. In CSP production, however, the TiN + NbC will not normally dissolve in the tunnel furnace before entering the finish rolling train, and these particles can have a strong effect on the subsequent behavior of the steel.

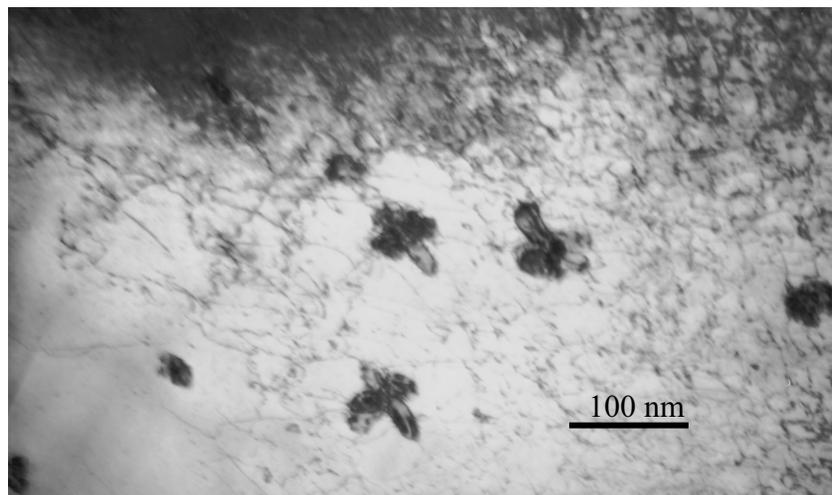


Figure 4. TEM micrograph of star-like particles.

As was shown in [7], scrap-based EAF steel containing 40PPM Ti and 100PPM N in a Nb containing HSLA steel can precipitate TiN during casting, slab shearing and transfer to the tunnel furnace in a conventional CSP plant. This TiN was very fine and delineated the interdendritic pools of liquid just prior to final solidification. Detailed metallography showed that NbC or NbCN had precipitated on these TiN particles during the same time/temperature interval. The resulting complex particle had cores of TiN and arms of NbC. An example of the cruciform or star-like particles is shown in Figure 4, while their distribution is exhibited in Figure 5.

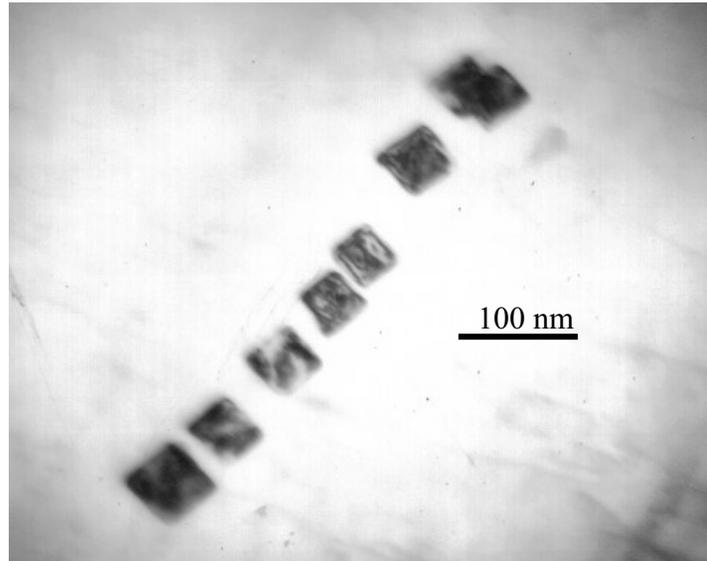


Figure 5. Lines of small TiN or star-like particles.

Obviously, the Nb lost to the arms of the star-like particles will not be available for either conditioning the austenite in the finishing train or strengthening the ferrite. The Nb particles would not form in this temperature range in the absence of the TiN.

Hence, the presence of the TiN + NbCN star-like particles mean that higher bulk levels of Nb are required to reach the normal solute levels expected in these steels and that are required to achieve the desired final mechanical properties.

It is clear that the formation of TiN will depend on the composition of the liquid as it enters the caster. Steels with a high (Ti)(N) product will obviously be susceptible to their formation, while those steels with a low product will not. A summary of the precipitation potential of TiN, as influenced by steelmaking route, is shown in Table I.

As noted earlier, a major concern is how to avoid the loss of Nb as NbC associated with the star-like or cruciform-shaped particles. The TiN will probably not be a major problem in the last three processing routes shown in Table I. The absence of the TiN in these steels will preclude the formation of the star-like particles and the loss of otherwise usable Nb. These steels will exhibit the required microstructure and properties with the normal bulk Nb levels. However, TiN will be a problem in standard CSP production using the scrap based EAF + LF practice, leading to the formation of the star-like particles and the loss of solute Nb. Higher levels of Nb will be required in these steels to achieve the required final microstructure and properties. It should be noted that similar complex precipitates have been observed in V-bearing HSLA steels [8].

Table I. Precipitation potential of TiN for different steelmaking practices.

| Steelmaking Route | Residual Ti Content | N Content | TiN Precipitation Potential at 1050°C |
|----------------------|---------------------|-----------|---------------------------------------|
| EAF(no DRI) + LF | M | H | VH |
| EAF(high DRI) + LF | L | L | L |
| EAF + LF + Vac Degas | L | VL | VL |
| BOF + LF | VL | VL | L |

Note: VH = Very High, H = High, M = Moderate, L = Low and VL = Very Low

Recent research [7,9] has shown that there are two ways of lowering the volume fraction of the star-like particles that forms prior to entering the tunnel furnace in scrap-based EAF + LF steels. The first is to raise the tunnel furnace temperature to 1200°C, at which point most of the particles will dissolve. Even this approach is less than fully satisfactory since the dissolved particles can reform during the early stages of finish hot rolling. The second approach is based on the temperature of formation of the TiN in HSLA steel typified by API X 50-80. The bulk of the TiN particles were observed to form between 1150 and 1050°C as the strand super cools between exiting the caster and entering the tunnel furnace operating at 1150°C. For example, it is not uncommon for the outer portions of the strand to fall to 1000-1050°C just before it enters the furnace. Studies have shown that this is the temperature range where much of the TiN and star-like particles form [9]. This TiN can be minimized if a cooling practice were used where the strand surface never falls below 1100 or 1150°C. Figure 6 illustrates this approach. It is estimated that perhaps 20-35% of the total Nb or V might be saved by implementing these practices.

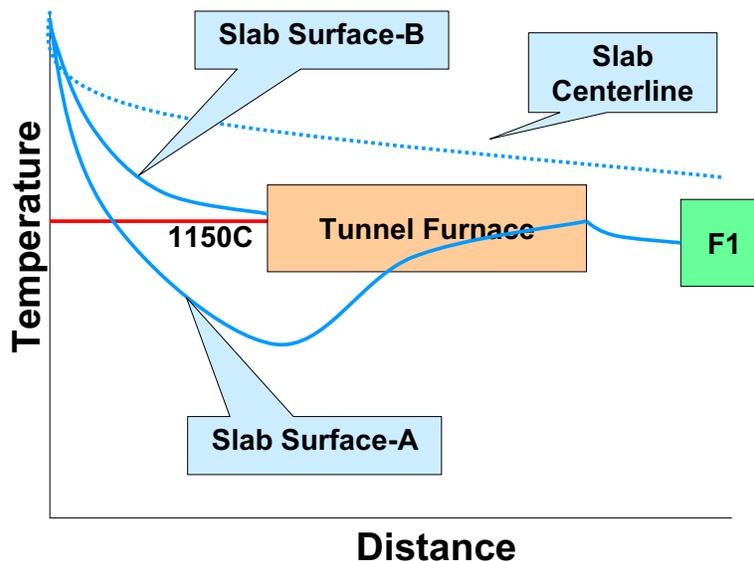


Figure 6. Cooling paths from caster to tunnel furnace.

Hot Rolling Challenges in Product Improvement

There are two major challenges facing optimum rolling of hot band. The first is attempting to achieve the minimum gauge possible for either thin gauge hot rolled applications or for feed stock to the cold mill. The second is to attain a uniform microstructure in heavy gauge hot band intended for linepipe applications such as the API grades. Only the second issue will be discussed here.

As pointed out earlier, one problem with Nb bearing steels produced by CSP, or similar processes, is the mixed grain structure often observed [6], especially in the heavier gauges, over approximately 6mm. An example of this phenomenon is shown in Figure 7. Notice that there are lines of coarse, high temperature polygonal ferrite mixed in with the lower temperature non-polygonal/acicular ferrite expected at this coiling temperature of 565°C. This mixed grain structure is the inevitable consequence of rolling a 50 mm slab to 9.5mm in six passes while starting with an initial average austenite grain size of about 800 μm . These mixed structures cause a deterioration of strength and toughness and spurious readings during UT-NDT of pipes and welds.

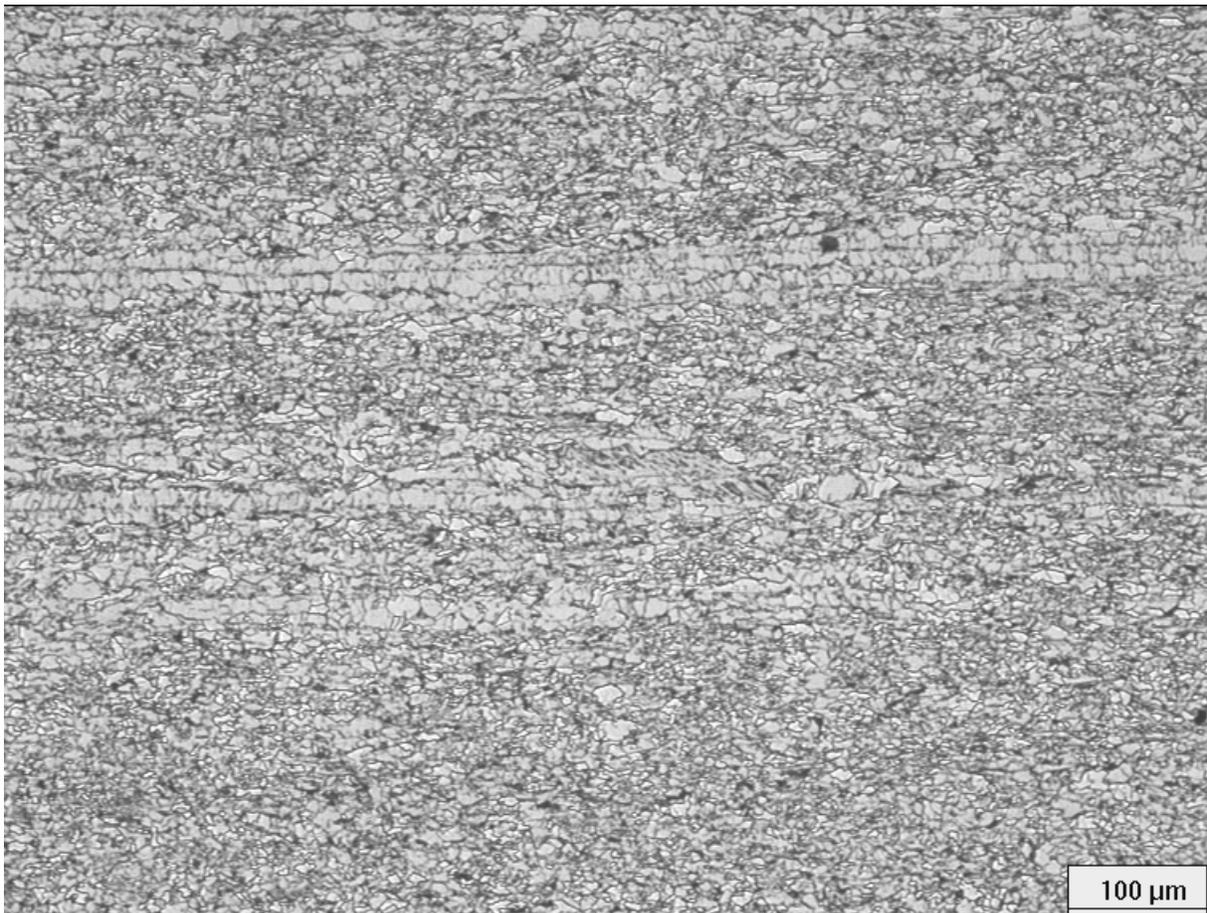


Figure 7. Optical micrograph of mixed grains.

When austenite undergoes hot deformation, it follows the sequence shown in Figure 8. Essentially full recrystallization occurs above temperature T_{95} , while approximately complete suppression of recrystallization occurs below temperature T_5 . This diagram will change with starting grain size, composition and interpass time. Also shown on Figure 8 is the normal six stand pass sequence used at NUCOR Steel Berkeley.

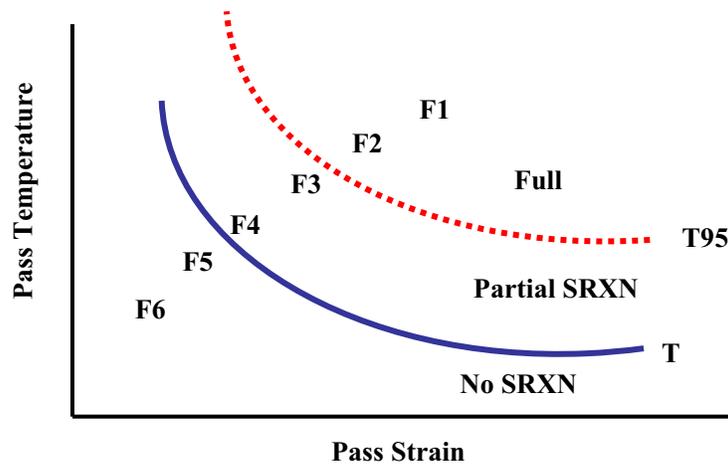


Figure 8. Hot deformation behavior of austenite.

This pass sequence has caused mixed grains in heavy gauge skelp intended for API linepipe applications. A typical rolling pass sequence is shown in Table II for a thinner product, while the resulting mill loads, flow strength of the austenite, and other rolling parameters are shown in Figure 9.

Table II. Rolling conditions versus pass number for standard NSB six pass schedule.

| Pass No. | T, °C | e, % | t1, ms | t2, sec |
|----------|-------|------|--------|---------|
| F1 | 1029 | 40 | 130 | |
| F2 | 1005 | 27 | 60 | 5.5 |
| F3 | 978 | 25 | 40 | 4.3 |
| F4 | 957 | 23 | 30 | 2.8 |
| F5 | 936 | 18 | 20 | 2.8 |
| F6 | 915 | 13 | 10 | 2.4 |

e = Reduction, t1 = Contact Time, t2 = Interpass Time

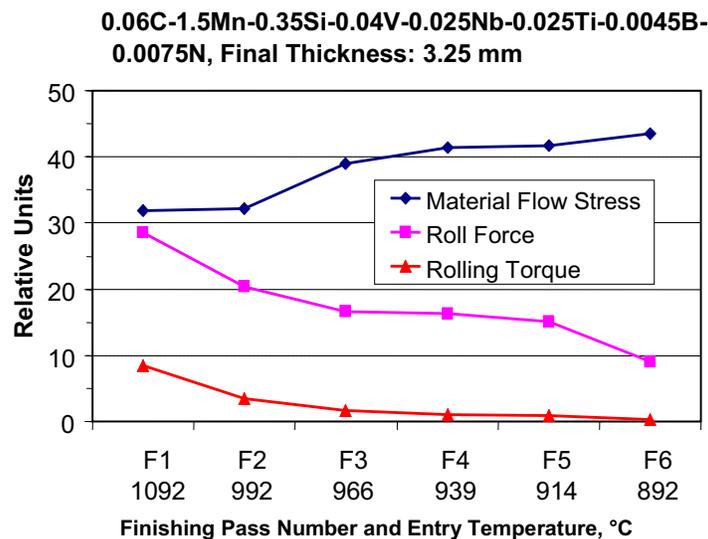


Figure 9. Rolling data versus pass number for standard NSB six pass schedule.

A new pass sequence has been developed to eliminate this mixed grain problem in heavy gauge skelp used, for example, in API linepipe grades [6]. This innovation has resulted in U. S. Patent No. US-2005-0115649-A1 issued on June 2, 2005. It is based on achieving both grain refinement and pancaking of the austenite grains, all within the six pass finishing train. It is known from the literature and basic principles that achieving 100% static recrystallization of low carbon HSLA austenite in a finite time (interpass time) depends on four factors: initial grain size, composition, strain, and temperature. As the slab approaches F1, the grain size, composition and temperature are fixed, so only strain is available to aid the recrystallization kinetics. It has been found that eliminating passes F3 and F4 is the key to achieving the desired metallurgical objective. The much heavier passes in F1 and F2, together with the longer interpass time from the exit of F2 to the entry of F5, are sufficient to result in complete recrystallization of the austenite in Nb-bearing HSLA steels between stands F2 and F5. These heavier early passes, together with the heavier pancaking passes, result in a very well conditioned austenite that eliminates the mixed grain final structure, even in heavy gauge steels. This new pass sequence is shown in Figure 10 using actual mill data. Note that there are three pass sequences shown in Figure 10. The standard six-pass practice is shown for coils 38-1 and 85-2. The second practice is with F3 dummied, shown as coil 68-5, while the third is with F3 and F4 dummied, shown as coils 36-1 and 38-3.

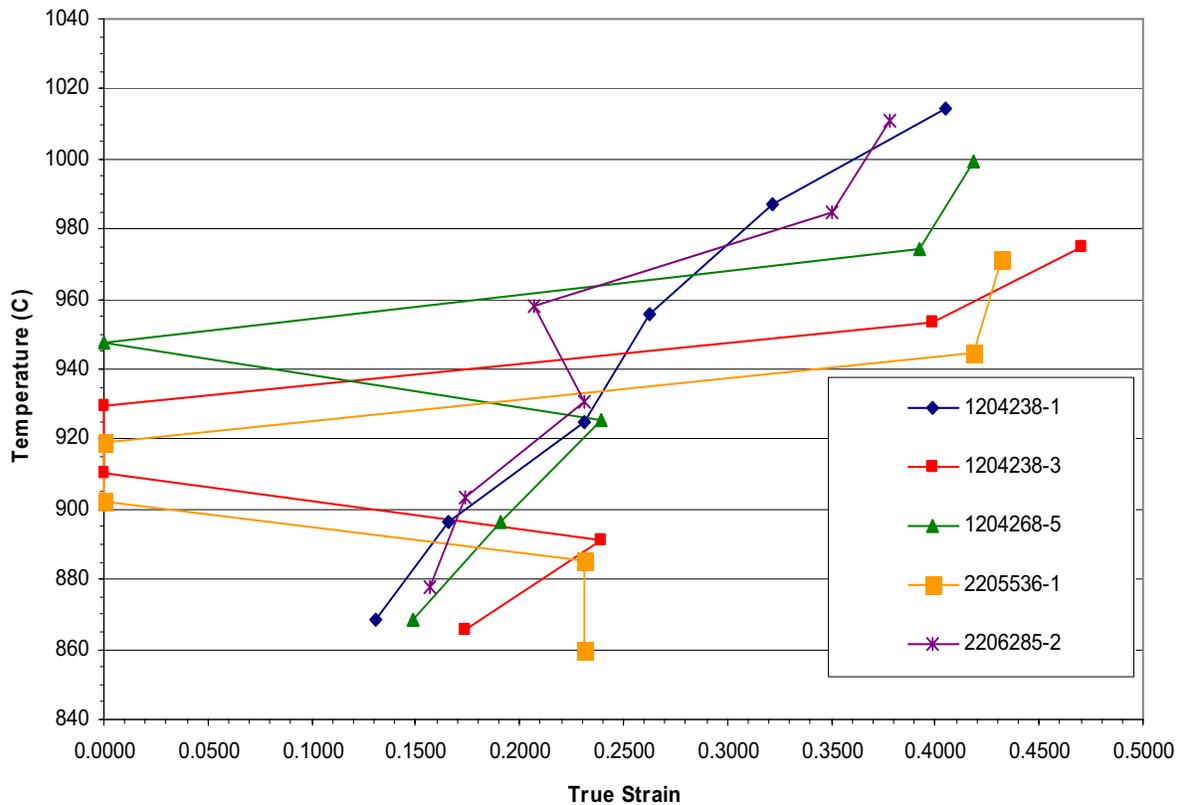


Figure 10. T – ε pass sequence data.

Furthermore, these heavier passes are also sufficient to overcome an important, but neglected, additional cause of the mixed grains found in this kind of product; the grains that are poorly oriented for plane strain hot deformation. Hu, in a classical study of cold rolling and annealing of single crystals of silicon-ferrite at room temperature, showed that the substructure observed after deformation was strongly dependent on the orientation of the single crystal relative to the deformation axes (as below). When the crystals had initial orientations near $\{001\}\langle 110\rangle$, they showed a homogeneous distribution of dislocations in the form of uniform cells. These crystals did not recrystallize very easily during subsequent annealing. On the other hand, crystals with

orientations near $\{001\}\langle 100\rangle$ exhibited a very heterogeneous dislocation structure comprised of broad, low density deformation bands separated by narrow, microbands or transition bands that contained extremely small dislocation cells and a very high local dislocation density [10]. These crystals showed rapid recrystallization during subsequent annealing because of the high local stored energy and sharp orientation change at the microbands. The reason for the difference in behavior is that the first crystal orientation had no grain interior nucleation sites for static recrystallization, while the second had many nucleation sites. HSLA austenite is believed to behave similarly, as shown in Figure 11, where it is obvious that some grains show deformation bands and some do not [11]. As the pass strain increases, more of the poorly oriented grains will show a sufficiently high enough dislocation density that they will exhibit nucleation and recrystallization, grain refinement and subsequent uniform final microstructure.

Kozasu, et al., studied the recrystallization of coarse-grained austenite in the early 1970s [12]. Figure 12 [12] shows that recrystallization of coarse-grained austenite can occur only with very large reductions, of the magnitude found when stands F3 and F4 are dummied, as shown schematically in Figure 10. The final microstructure that results from this new rolling practice is shown in Figure 13.

The uniformity of the microstructure results in higher strength and toughness and the absence of spurious UT reflections [6]. This new rolling practice is used for all heavy gauge strip and skelp produced by NSB.

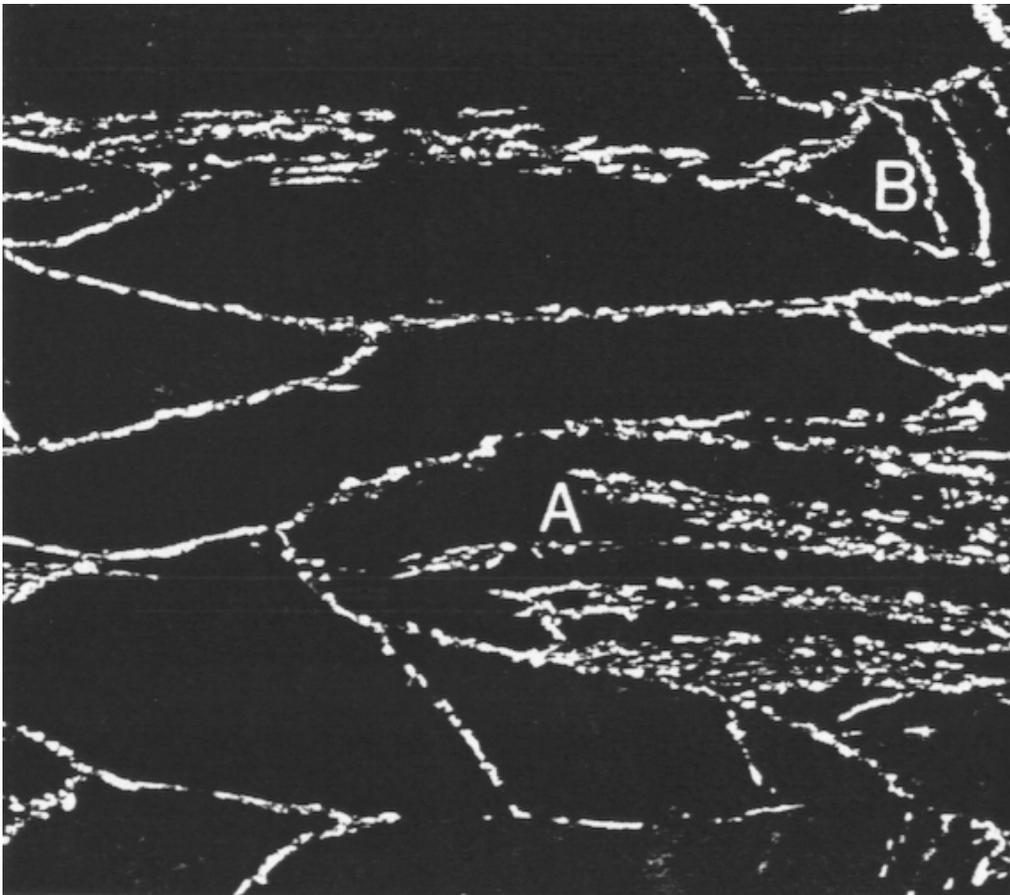


Figure 11. Dark field optical micrograph of nucleation of ferrite at deformed austenite grain boundaries, deformation bands (A), and annealing twins (B).

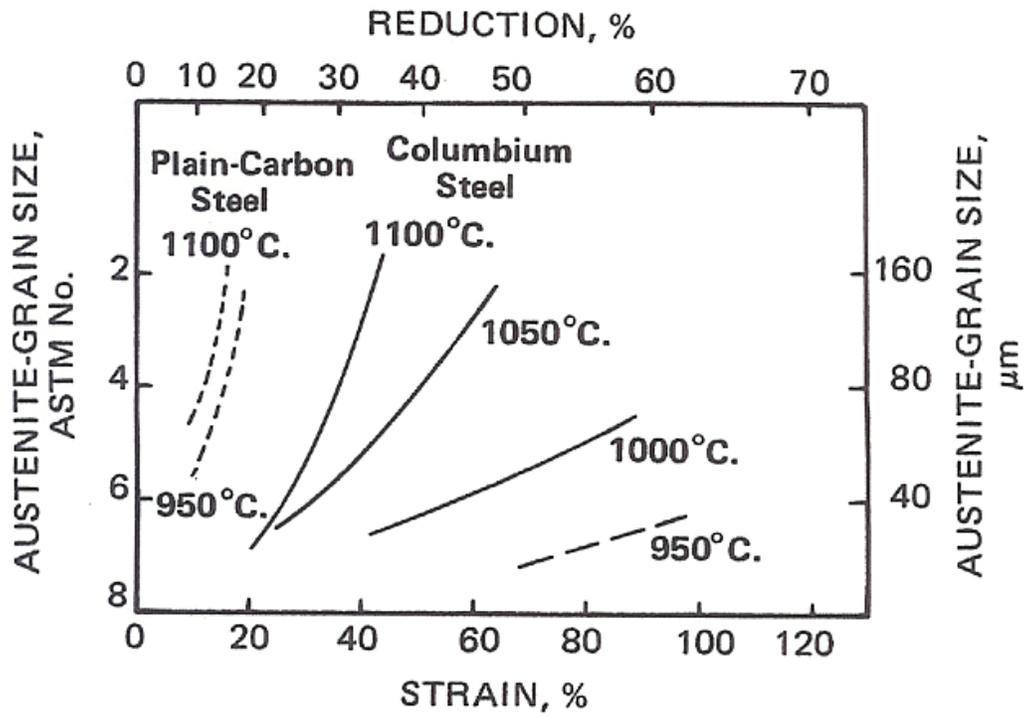


Figure 12. Effect of deformation temperature and initial grain size on critical amount of deformation required for completion of recrystallization in the plain-carbon and Nb steels.

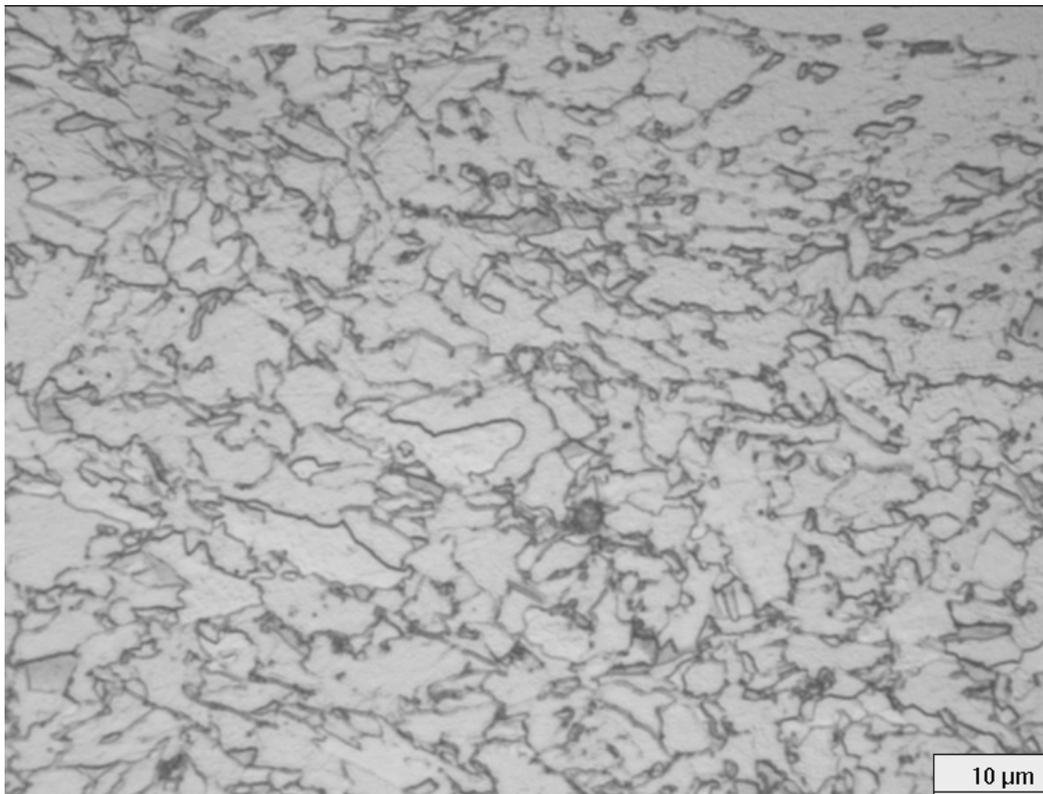


Figure 13. Optical micrograph of uniform acicular ferrite in 9.5mm thick X-70 using the new TMP path.

New Product Development at Nucor Steel Berkeley

Nucor Steel Berkeley (NSB) has been producing microalloyed HSLA sheet and skelp for nearly a decade in yield strength levels up to 560 MPa and in gauges up to 16mm. Examples of 2002 HSLA sheet/skelp production at NSB are shown in Figures 14-16. Figure 14 shows the final form of the products produced, Figure 15 illustrates the strength levels produced and Figure 16 shows the gauges available. It should be noted that HSLA hot band is available in yield strengths ranging from 310-550MPa(45-80Ksi) and API skelp from X-42 to X-70. The hot rolled gauges available range from 1.27mm to 16mm (0.050-0.625 in.) depending on strength level.

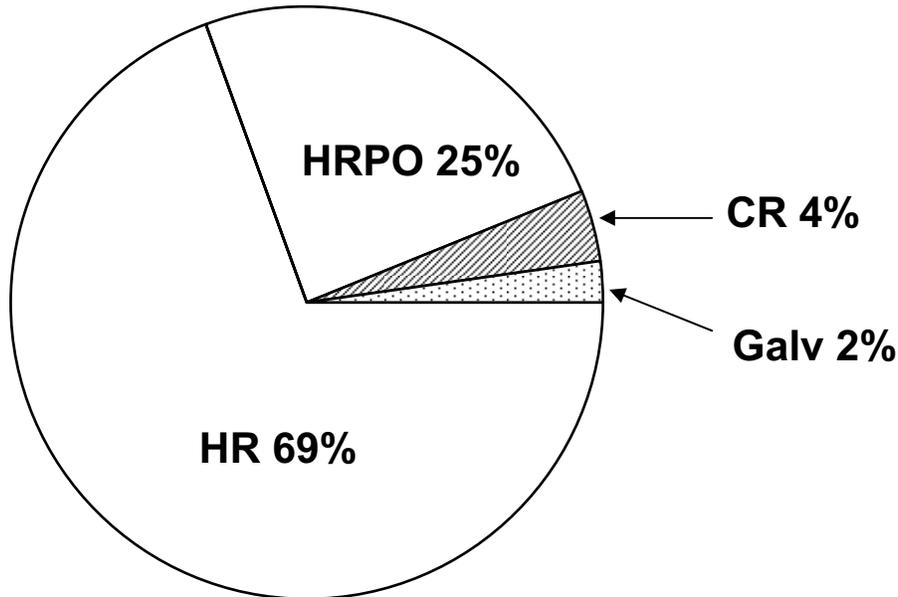


Figure 14. HSLA steel products produced at NUCOR Steel-Berkeley's CSP Plant, Charleston, South Carolina.

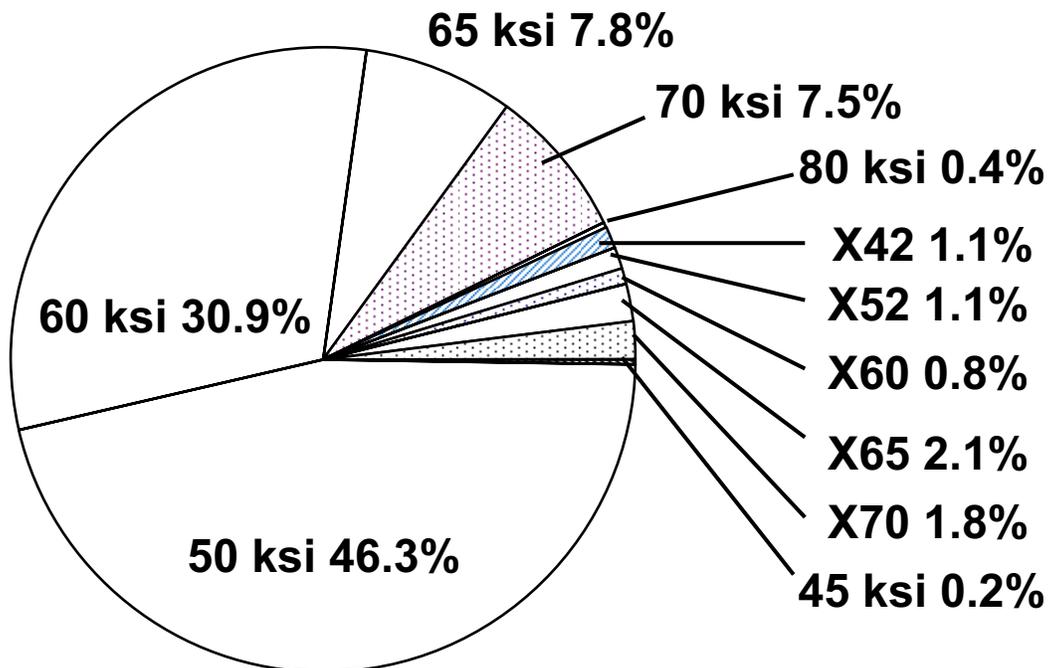


Figure 15- HSLA steel products produced at NUCOR Steel-Berkeley's CSP Plant, Charleston, South Carolina.

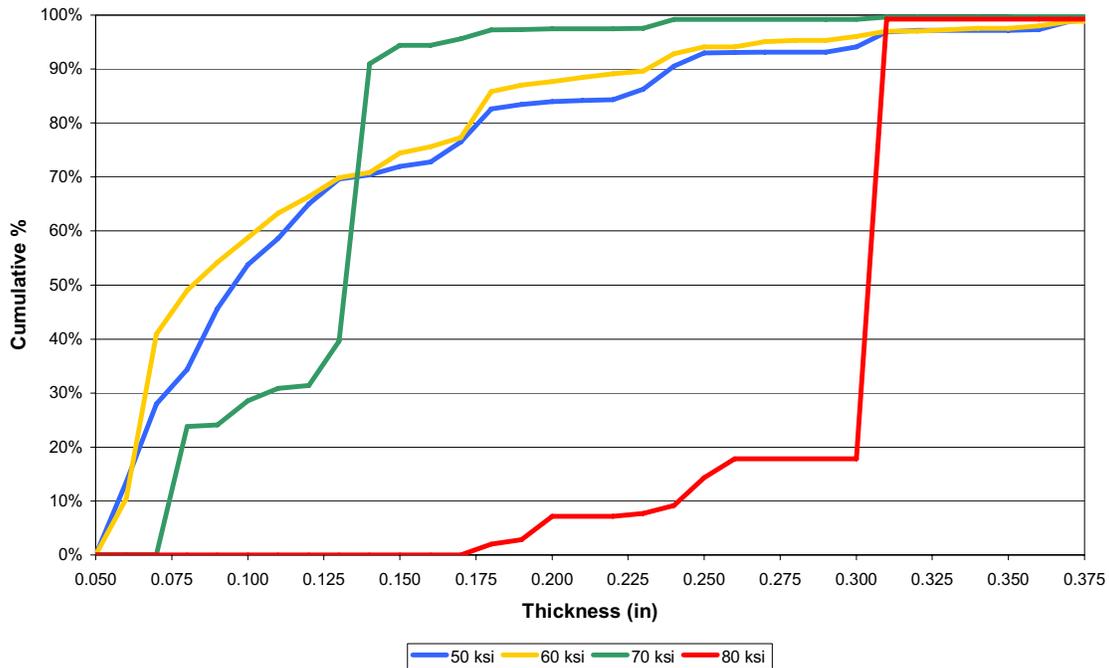


Figure 16. Production of hot rolled HSLA steels by thickness at NUCOR Steel - Berkeley's CSP Plant, Charleston, South Carolina.

These product lines have recently been reviewed [6] and discussed.

Since the Guangzhou Conference in 2002, NSB has expanded its high strength steel product line to include dual - phase (DP) and experimental complex phase (CP) steel. Furthermore, the addition of a vacuum degassing unit has enabled NSB to produce interstitial-free (IF), motor lamination and enameling steels.

The DP steels are produced either in the hot rolled or GI condition, and at UTS strength levels of 580 MPa. A 780 grade is under development in both conditions.

NSB currently produces two types of IF steels, fully stabilized and high strength re-phosphorized. The stabilized grades are stabilized either with Ti alone, or by Ti + Nb when produced on the CG line. It is now recognized that solute Nb aids coatability by increasing coverage and adherence. The high strength version is based on the Ti + P + B system.

NSB produces five grades of motor lamination steel. These are Types II, IV, V, VI, and VIII. These are all produced using vacuum degassing. They also produce two versions of enameling steels; types II (Low C) and III (ULC). This latter one is also vacuum degassed.

CLOSURE

Nucor Steel Berkeley has demonstrated that the CSP process is a very cost -effective method of making a broad range of high quality steel products. As mentioned above, steels ranging from Nb-bearing HSLA, DP, CP, IF, motor lamination and enameling steels can be successfully commercially produced using the CSP process. Practices that optimize the use of Nb in the appropriate members of this product line are being implemented.

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