## 8306-091

# RESTRICTED YIELD STRENGTH VARIATION IN HIGH STRENGTH LOW ALLOY STEELS

**Emil G. Hamburg**
Jones & Laughlin Steel Corporation
Pittsburgh, Pennsylvania

Variability in the yield strength of High Strength Low Alloy sheet steel is a major concern of the automotive industry and other industries involved in forming sheet metal. In order to have a material with a more consistent forming behavior, restrictions have been imposed on the permissible yield strength variation.

Achieving uniform properties requires identifying those components of the processing sequence that may have significant effect on yield strength variability of the product. Alloy design is examined and optimized with regard to steelmaking, hot strip mill processing capabilities, batch and galvanize line annealing capabilities. The use of low carbon steels containing columbium or columbium and vanadium together with silicon for solid solution strengthening achieves a family of steels that minimize yield strength variation. Cold rolled steels utilize that portion of the annealing cycle that achieves a fully recrystallized structure for steels with yield strengths of 50 ksi (345 MPA) and 60 ksi (414 MPA) and a recovered structure for steels with minimum yield strength of 70 ksi (483 MPA) and 80 ksi (552 MPA).

VARIABILITY IN THE YIELD STRENGTH of High Strength Low Alloy sheet steel is a major concern of the automotive industry and other industries involved in forming sheet metal. In order to have a material with a more consistent forming behavior, restrictions have been imposed on the permissible yield strength variation. For the steel supplier, this translates into identifying the area where improved control of composition and processing will result in a product that will meet new and more restrictive specifications.

The present goal of the steel supplier is to be able to ship product on a routine basis that does not vary more than 0 ksi below the minimum yield strength and not more than 15 ksi above the minimum yield strength.

Achieving uniform properties requires identifying those components of the processing sequence that may have an effect on yield strength variability of the product. The first step in this process is the question of optimum alloy design. The goal is to chose an alloy system that exhibits the least amount of sensitivity to processing parameters.

For example, skid marks, acquired during reheating, can result in regions of the slab being 50 to 100°F (28 to 56°C) cooler than the remainder of the slab. Since these regions have a different thermal history than the remainder of the slab, they are a source of variability in strength. Similarly, the coiling temperature on some hot strip mill facilities can vary as much as 150°F (83°C). The sensitivity of yield strength to coiling temperature for certain compositions can be quite large as illustrated in Figure 1. Two compositions containing 0.4% Mn and 1.5% Mn with varying amounts of Ti were subjected to a coiling temperature of 1100°F (593°C) and 1300°F (704°C). For the steel containing 0.4% Mn, the variation in yield strength was small while the variation in yield strength of the steel with 1.5% Mn was large (approximately 15 ksi). Qualititatively, this can be explained with a schematic of a continuous cooling diagram (Figure 2). High manganese steels transform over a wider range of temperature than low Mn steels. Interphase precipitation, grain size and transformation products take place over a wider range of temperature resulting in large variation in strength. The steel with low Mn transforms over a narrow range of temperature resulting in similar microstructures for both slow and fast cooling rates. On this basis, steels with high Mn will exhibit greater variation in yield strength if there is a lack of coiling temperature control on the hot strip mill.

PROCESSING - A key to minimizing variability of high strength steels is identifying key process steps that must be controlled. Those steps in the processing sequence that cannot be optimized must be circumvented by alloy design. Table I outlines those control points considered essential.

Ladle chemistry control can be achieved with a ladle trim station. Carbon is controlled with 0.03%, manganese is controlled within 0.3%, silicon within 0.2% and microalloying elements such as Cb and vanadium within 0.015%.

Minimizing processing variation at the hot strip mill is essential for both hot and cold rolled products. Reheating time and temperature can be restricted only to those conditions that permit reasonable productivity. Steels strengthened with V and N are desirable from this standpoint as they require relatively long residence time for complete solution of the vanadium nitrides. Reheating furnace skids result in at least a 50°F (28°C) periodic variation in temperature along the length of the slab. For most hot strip mills, finishing temperature control within 50°F (28°C) can be achieved. Coiling temperature control within a 50°F (28°C) range is often difficult to achieve on existing hot strip mills. Minimizing yield strength variation by control of coiling temperature translates into controlling not only water end temperature but maintaining a uniform cooling rate during controlled cooling. Since finishing temperature is usually controlled by mill acceleration it is often difficult for existing control systems to insure that a uniform cooling rate is applied to the strip. In order to improve coiling temperature control, it is necessary to install modern computer control, both hardware and software. Water delivery systems are often inadequate for the required control. Updating coiling temperature control requires time for process analysis and acquiring the necessary hardware and software. For this reason, microalloyed steels that are not sensitive to coiling temperature are desired.

Batch annealing thermal cycles have in the past been designed to permit maximum throughput. The resulting stack temperature variability can be as high as 150°F (83°C). High strength cold rolled steels require the hot and cold spot difference be 50°F (28°C) to insure adequate uniformity. This can be achieved through restricted furnace temperatures, heat shields, hot spot control and modified heating cycles with an associated decrease in productivity.

Galvanizing line heating cycles often utilize a thermal head to insure rapid heating and high productivity. In order to achieve a 50°F (28°C) variation in temperature during the annealing cycle in a 0.050 inch (2mm) sheet, the gauge variation must be held to 0.003 inch (0.04mm). An alternative scheme would be to have the strip in equilibrium with the furnace for a short period of time negating the requirement for close gauge control, however, there is a significant production penalty with this method. Feedback control where the strip temperature is used to control line speed is the best method but requires capital expenditure and time to achieve.

ALLOY DESIGN - HOT ROLLED - From what has been briefly discussed above, hot rolled alloy design must specify alloy chemistries that are insensitive to reheating temperature and insensitive to variations in controlled cooling rate and coiling temperature.

The general guidelines for alloy design of hot rolled steels are that they must be formable, spot weldable, and able to be continuously cast. Consequently, the steels, if possible, must be low carbon (under 0.1%), low manganese, low phosphorous, have sulfide shape control and have restricted levels of microalloying elements to maximize castability. Within the family of hot rolled steels commercially available, are steels utilizing Cb, V, Ti, V+N and Cb+V. Ti offers the most cost effective approach to alloy design because it combines strengthening and sulfide shape control simultaneously. However, the well-known reactivity of Ti with O, N Si and C cause this microalloy to behave unpredictably. Figure 3 shows the results of mechanical testing through 6 coils of 50 ksi yield strength Ti-microalloyed steel at five positions (front, 1/4, middle, 3/4, back) and across the width at each position. The total variability was 18 ksi. Figure 4 shows the results of mechanical tests on 6 coils of a steel strengthened with Cb. The total variability was 8 ksi while at each position it was 4 ksi or less.

Additional studies comparing the effect of coiling temperature on the strength of Cb and Ti steels revealed that the strength is sensitive to the time between exiting of the strip from the finishing train until cooling water is applied to the strip (delay time). A ten-second difference in this delay time resulted in an 8 ksi difference in yield strength in a Ti-strengthened steel and a 4 ksi difference in a Cb-strengthened steel. In addition, cooling rate during transformation has a significant effect on the strength of Ti-strengthened steel but little effect on Cb-microalloyed steel.

Changing the cooling rate from 18°F per second (10°C) per second ) to 36°F per second (20°C) per second results in an 8 ksi difference in the yield strength of the Ti steel. Coiling temperature had no effect on strength when varied from 1100°F (393°C) to 1250°F (677°C).

An estimate of the effect of sulfur on the yield strength of Ti steels was obtained by varying sulfur between 0.003% and 0.032%. The variation in strength is shown in Figure 5. Increasing the sulfur from 0.01% to 0.02% results in a 5 ksi decrease in strength. The sensitivity of Ti steels to cooling rate, delay time and the interaction with O, S and N result in a composition where the yield strength behaves erratically in the hot rolled condition. The excellent uniformity exhibited by low carbon Cb steels and the relative insensitivity to controlled cooling variations make this the preferred composition.

Vanadium-nitrogen strengthened steels exhibit sensitivity to coiling temperature and rate of cooling during controlled cooling. Figure 6 shows the variation in yield strength of an 80 ksi yield strength steel for coiling temperatures between 950°F (510°C) and 1300°F (650°C).[1] This steel exhibits approximately a 10 ksi variation in yield strength for a coiling temperature change of 100°F (56°C). Vanadium-nitrogen strengthened steels are sensitive to slab reheating practices and aluminum contents. The normal practice for reheating these steels is to establish a minimum reheat time by limiting push rate and limiting the maximum Al content in the steel. Lack of heating in the vicinity of the slab furnace skids can be a source of variability.

The within coil variability of 50 ksi minimum yield strength steel strengthened with vanadium is satisfactory for meeting the -0 ksi +15 ksi requirement; however, because of relatively high carbon (0.1%) and manganese (1.0%) the spot weldability does not satisfy automotive specifications.

Laboratory investigations and subsequent data from production trials of 70 ksi and 80 ksi minimum yield strength steels leads to the choice of Cb-V strengthened steel. Figure 7 shows the variation in yield strength associated with finishing temperature and coiling temperature. The lack of variation with coiling temperatures ranging from 1050°F (566°C) to 1200°F (650°C) is attributed to the competing reactions between V and Cb for C. This characteristic is essential for minimizing strength variation resulting from processing on existing facilities. Figure 8 shows the distribution in yield strength obtained from 100 coils of an 80 ksi minimum yield strength steel sampled from the front, center and back.

For the lower strength, 50 ksi and 60 ksi minimum yield strength steels, low carbon Cb-strengthened steel has proven to meet the aforementioned requirement. Table II outlines the chemical position of hot rolled steels that will meet the 15 ksi minimum yield strength variation requirement. Table III shows typical properties.

For 50 and 60 ksi minimum yield strength, low C-Cb steels best satisfy the requirements for minimum variability. For 70 ksi and 80 ksi minimum yield strength, the low carbon Cb-V microalloyed steels will meet the -0 +15 ksi requirements for variability.

COLD ROLLED AND GALVANIZED STEEL - Minimizing variability in cold rolled steels and galvanized steels starts with the hot band, i.e., variation in hot band strength either as the result of poor chemistry control or processing control will translate into yield strength variation in the cold rolled steel. The compositions therefore will be similar to the hot rolled compositions described above and for the same reasons, minimum variability, castability and spot weldability. Cold rolled (batch annealed) and galvanized steels are produced by either a full recrystallization anneal for steels exhibiting minimum yield strengths of 50 ksi and 60 ksi, by a partial recrystallization anneal for steels with minimum yield strengths of 70 ksi and 80 ksi and by a recovery anneal for steels exhibiting yield strengths of 100 ksi. These processes are illustrated in the annealing curve of a Ti microalloyed steel shown in Figure 9. The variability associated with temperature variation during annealing can be estimated from the slope of the curve. For a recovery anneal, temperature variations have a minimal effect on strength variation. With a full recrystallization anneal, that takes place away from the knee, temperature variation also has a minimum effect on strength. It is estimated that a 50°F (28°C) variation in annealing temperature will result in a 3 ksi variation in strength. The variability in yield strength encountered in 70 ksi and 80 ksi minimum yield strength cold rolled product produced by a partial recrystallization anneal can be as high as 10 ksi for a 10°F (6°C) variation in annealing temperature.

About the best performance that can be expected from a single stack box annealing furnace is a 50°F (28°C) variation in annealing temperatue between the hot and cold spot. In addition, the effective time at temperature is shorter for the cold spot. In terms of variability, this translates into an expected variation of 10 ksi for fully-recrystallized steels in the 50 ksi and 60 ksi range. Partially recrystallized steels are expected to exhibit a variation of 30 ksi for yield strengths of 70 ksi and 80 ksi.

Figure 10 shows a relationship between hot band strength and the final annealed strength of fully recrystallized cold rolled of galvanized steel. Galvanized annealing cycles typically run between 5 seconds and 30 seconds at temperature. In this short time, some of the precipitation strengthening present in the hot band is retained.[2] In order to make up for the precipitation strength lost during the batch annealing cycles, solid solution strengthening with silicon and manganese is used in the cold rolled product.

In order to reduce the yield strength variation at 70 ksi and 80 ksi levels, an alternate procedure to partial recrystallization is proposed, i.e., to recovery anneal a low yield strength steel given a carefully controlled amount og cold reduction (schematically shown in Figure 11).[3] The steel yield strength can be controlled to close tolerances for this strength level. Strength is strictly a function of the original hot band strength and cold reduction as shown by the relationship:

$$Y_{CR} = 0.9\ (Y_{HR} + \Delta Y_R)$$

$$Y_R = 4\ (\%R)^{0.7}$$

$Y_{CR}$ = Yield strength of cold rolled steel.

$Y_{HR}$ = Yield strength of hot rolled base steel.

$\Delta Y_R$ = Increase in strength due to work hardening during cold rolling.

$\%R$ = Percent reduction

The 70 ksi cold rolled steel is produced by utilizing a Ti-stabilized steel in the hot rolled condition, raising the flow strength to 90 ksi by cold reduction and recovery annealing. Figure 12 shows the yield strength distribution of steel produced by this procedure.

80 ksi minimum yield strength is achieved by utilizing a Ti-stabilized hot rolled base composition or utilizing the 50 ksi yield strength hot rolled steel with a cold reduction that raises the yield strength to 100 ksi and then recovery annealed. Steel produced by recovery annealing exhibits total elongation less than those exhibited by steels produced by partial recrystallization. The minimum gauge shown in Table V is dictated by the required cold reduction. Both the 70 and 80 ksi steels have been successfully applied to automotive application. The 80 ksi cold rolled steel utilizing the Cb-strengthened 50 ksi hot band with small cold reductions has a longitudinal total elongation similar to steels produced by methods such as partial recrystallization. Table IV outlines the composition adopted for cold rolled and galvanized applications. Table V shows typical properties of the high stength cold rolled product produced by the method described above.

In summary, a high family of high strength low alloys has been developed that meet present minimum yield strength range of 50 ksi, 60 ksi, 70 ksi and 80 ksi with a total variation in yield strength of -0 ksi, +15 ksi. The compositions are spot weldable and formable. These compositions and the associated properties can be applied to most part production in the automotive industry where springback control is critical.

## REFERENCES

[1] J. D. Grozier, "Production of Microalloyed Strip and Plate by Controlled Cooling," Microalloying 75, Union Carbide Corpration, 1977, p. 241.

[2] P. R. Pradham, "Annealing of Cold Rolled Rephosphorized Steels Containing Si and Cb," Journal of Heat Ttreating, Volume 2, Number 1, 1981, pp. 73-82.

[3] P. B. Lake and J. J. Grenawalt, "Properties and Applications of High Strength Cold Rolled Steels; Plain Carbon and Killed Low Alloy," Paper No. 740954, Society of Automotive Engineers, October, 1974.

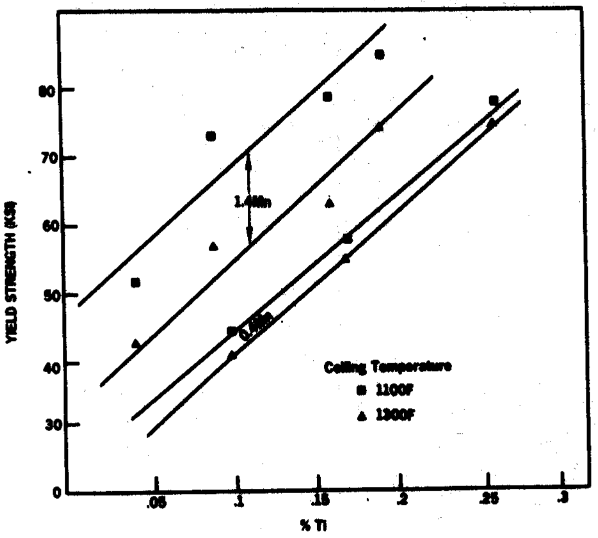

Fig. 1 - Effect of Mn and coiling temperature on the yield strength of Ti strengthened steel.

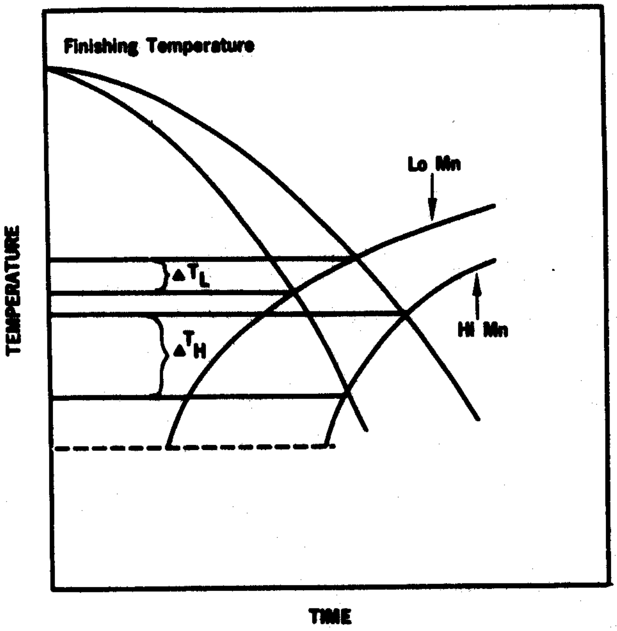

Fig. 2 - Schematic continuous cooling diagram showing the effect of Mn on the ferrite start temperature for a low and high cooling rate.

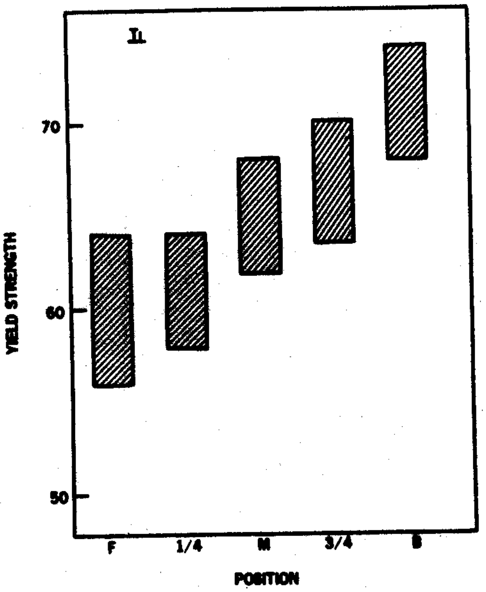

Fig. 3 - Variation in yield strength through a coil of a Ti strengthened steel.

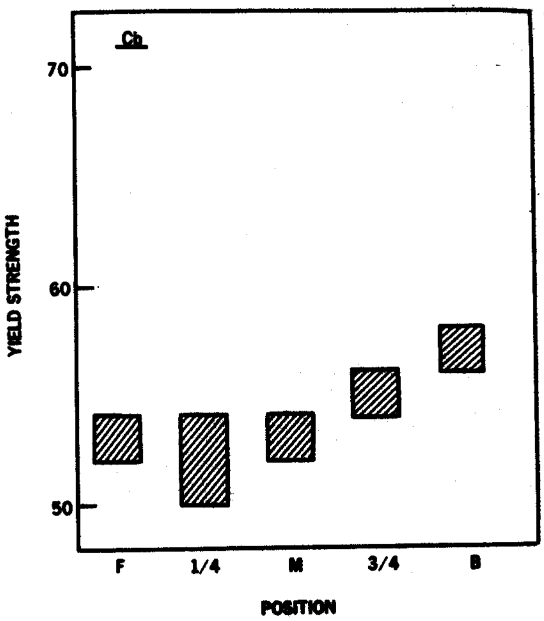

Fig. 4 - Variation in yield strength through a coil of a Cb strengthened steel.

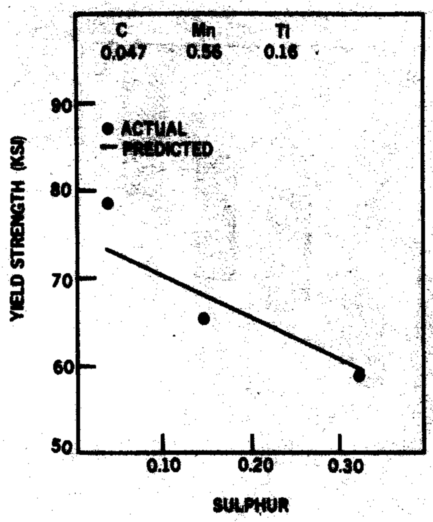

Fig. 5 - Effect of sulfur on the yield strength of a Ti strengthened steel.

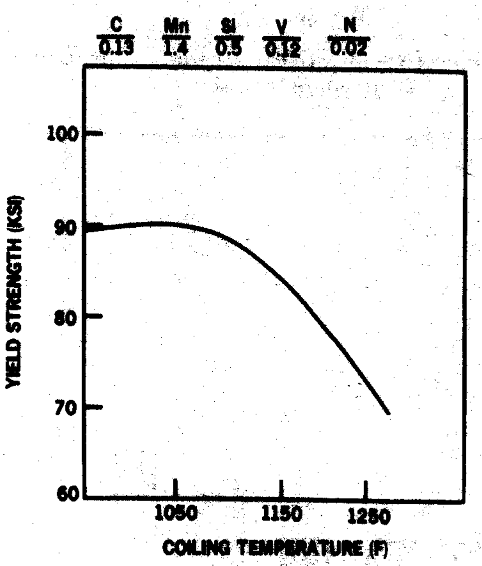

Fig. 6 - Effect of coiling temperature on the strength of a vanadium-nitrogen strengthened steel (1).

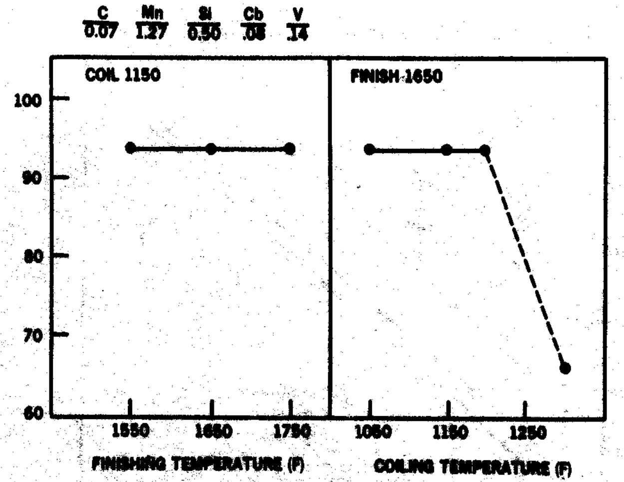

Fig. 7 - Effect of hot strip mill finishing temperature and coiling temperature on the strength of a Cb-V strengthened steel.

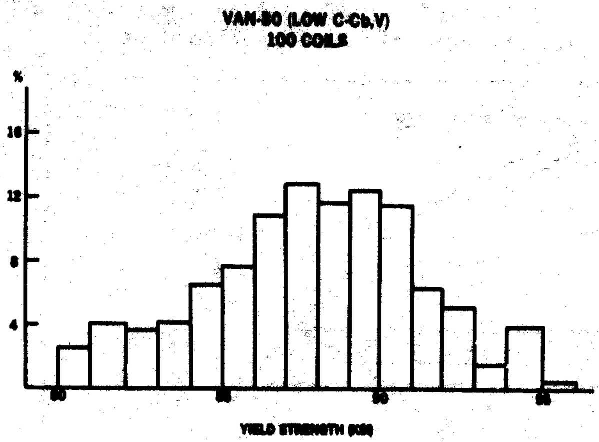

Fig. 8 - Variability in yield strength of a low carbon Cb-V strengthened 80 ksi steel.

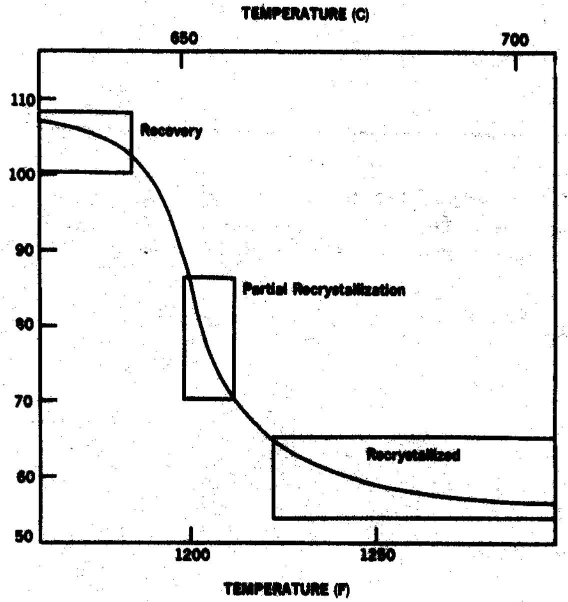

Fig. 9 - Schematic of the annealing response of a Ti strengthened steel.

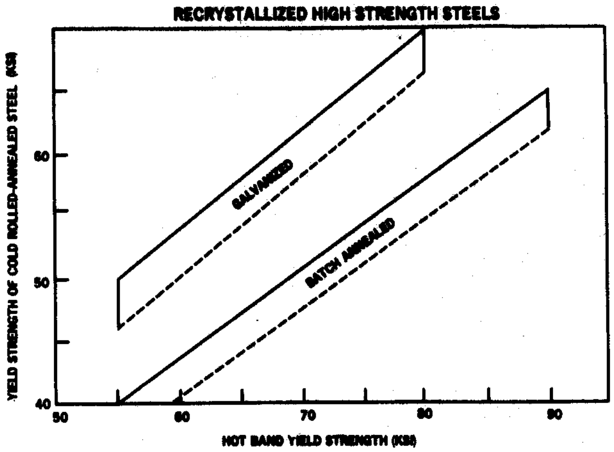

Fig. 10 - Relation between the yield strength of cold rolled batch annealed steels or cold rolled galvanized steels and the original hot rolled strength of the steel.

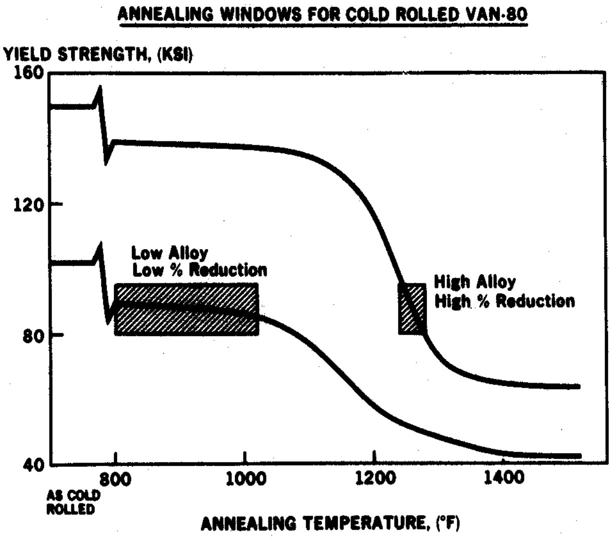

Fig. 11 - Schematic diagram comparing the annealing response of a partially recrystallized steel and a recovery annealed 80 ksi (552 MPA) steel.

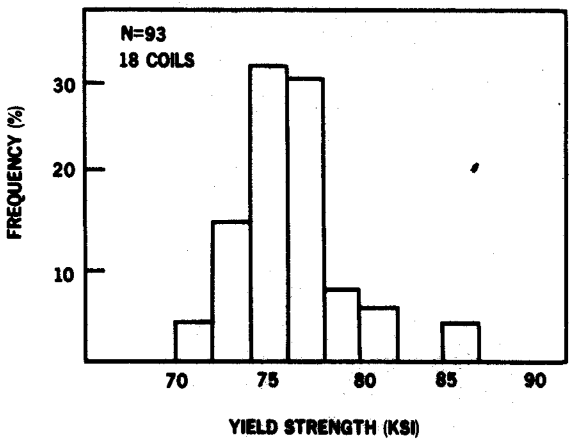

Fig. 12 - Distribution in yield strength from 18 coils of a 70 ksi (483 MPA) recovery annealed steel.

## TABLE I
## MINIMIZING VARIABILITY IN PROCESSING

A. LADLE CHEMISTRY

B. HOT MILL PRACTICE
- REHEATING TEMPERATURE AND TIME
- FINISHING TEMPERATURE
- COILING TEMPERATURE

C. BATCH ANNEALING
- OPTIMIZE PRACTICE FOR STACK TEMPERATURE UNIFORMITY

D. GALVANIZING
- GAGE CONTROL (SPEED CONTROL–THERMAL FEEDBACK)

## TABLE II
## COMPOSITION OF HOT ROLLED STEELS

| MINIMUM YIELD STRENGTH (KSI) | COMPOSITION (%) C | Mn | Si | Cb | V |
|---|---|---|---|---|---|
| 50 | 0.05 | 0.4 | — | 0.02 | — |
| 60 | 0.05 | 0.6 | — | 0.05 | — |
| 70 | 0.07 | 0.8 | 0.4 | 0.03 | 0.05 |
| 80 | 0.07 | 1.0 | 0.4 | 0.05 | 0.12 |

TABLE III

TYPICAL MECHANICAL PROPERTIES OF HOT ROLLED HIGH STRENGTH STEELS

| MINIMUM YIELD STRENGTH | YIELD STRENGTH | | TENSILE STRENGTH | | ELONGATION IN 2 INCHES | |
|---|---|---|---|---|---|---|
| KSI | KSI | MPA | KSI | MPA | UNIFORM % | TOTAL % |
| 50 | 57.6 | 397 | 65.8 | 454 | 20 | 28 |
| 60 | 67.7 | 467 | 77.9 | 538 | 17 | 26 |
| 70 | 77.6 | 535 | 89.0 | 614 | 15 | 23 |
| 80 | 83.0 | 573 | 96.0 | 662 | 14 | 22 |

TABLE IV

COMPOSITION OF COLD ROLLED HIGH STRENGTH STEELS

| MINIMUM YIELD STRENGTH | COMPOSITION (%) | | | | | | MINIMUM GAUGE | |
|---|---|---|---|---|---|---|---|---|
| KSI | C | Mn | Si | Ti | Cb | V | INCHES | MM |
| 50 CR | 0.05 | 0.6 | 0.4 | - | 0.05 | - | 0.025 | 0.64 |
| 50 GALVANIZED | 0.05 | 0.4 | - | - | 0.02 | - | 0.025 | 0.64 |
| 60 CR | 0.07 | 1.0 | 0.4 | - | 0.05 | 0.12 | 0.025 | 0.64 |
| 60 GALVANIZED | 0.05 | 0.6 | 0.4 | - | 0.05 | - | 0.025 | 0.64 |
| 70 CR, GALVANIZED | 0.02 | 0.3 | | 0.2 | - | - | 0.037 | 0.94 |
| 80 CR, GALVANIZED | 0.02 | 0.3 | - | 0.2 | - | - | 0.025 | 0.64 |
| 80 CR, GALVANIZED | 0.05 | 0.4 | - | - | 0.02 | - | 0.048 | 1.22 |

TABLE V

TYPICAL MECHANICAL PROPERTIES OF HIGH STRENGTH COLD ROLLED STEELS*

| MINIMUM YIELD STRENGTH | YIELD STRENGTH | | TENSILE STRENGTH | | ELONGATION IN 2 INCHES | |
|---|---|---|---|---|---|---|
| KSI | KSI | MPA | KSI | MPA | UNIFORM % | TOTAL % |
| 50 | 57.2 | 395 | 69.1 | 477 | 18 | 26 |
| 60 | 66.0 | 455 | 72.9 | 503 | 17 | 25 |
| 70 | 73.4 | 506 | 82.3 | 568 | - | 10 |
| 80 | 87.3 | 602 | 94.4 | 651 | - | 12 |

*NOMINAL GAUGE 0.050 INCH (1.3 MM).