NIOBIUM-BEARING HSJA STEEL SHEET AND STRIP PRODUCTS

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Introduction

Considerable interest has been expressed in the automotive, agricultural, construction, and other industries in sheet and strip HSJA steels because they offer many opportunities to improve component strength and/or reduce component weight with minimum loss of fabrication ease and with cost effectiveness.

Hot rolled products have been generated with yield strengths ranging from *40* to 80 ksi (276 to 550 MPa), strengthening being achieved by controlled rolling, giving various degrees of precipitation hardening, grain refinement, and substructural strengthening, depending on the strength level. Cold rolled sheet products, used primarily by the automotive industry, have been developed more recently and are produced mostly by batch annealing and galvanizing in North America and by continuous annealinp in Japan, with strengths ranging from 37 to 220 ksi (276 to 1517 **MPa).** Niobium steels are produced mainly for the lower strength levels, applications ranging through door panels, hoods, and sundry structural parts such as rails, cross members, etc.

Tests of corrosion resistance of these steels have revealed that no change in performance is to be expected. Thus, whenever protection has been considered necessary for the low strength products, it is also necessary for the HSLA steels. In addition, since many applications involve thickness reductions, corrosion protection not previously required may become vital. A full range of galvanized HSLA steels has, thus, been made available.

Hot Rolled Steels

Production

Hot rolled high strength sheet and strip products are usually made on continuous hot strip mills, where time from slab to coil and between successive reductions is very short. Properties are predominantly controlled by composition, finish rolling and coiling temperatures, and to a lesser extent by control of reduction per pass. Slab reheat temperatures and times are also chosen to ensure complete solution of niobium carbides and, thus, obtain the maximum strengthening effects.

Strengths up to 80 ksi (550 MPa) are available, this being close to the limit normally obtainable for ferrite-pearlite-niobium steels. Higher strength levels can be achieved by supplementing the niobium with extra precipitation hardening, such as by the addition of vanadium or by inducing bainitic-type reactions during cooling by resorting to alloying elements such as Mo.

The main strengthening mechanism in these steels is thought to be grain refinement. Manganon and Heitmann (1) reported that for hot strip mill processing, niobium up to 0.05 percent is only available for ferrite grain refinement, i.e. for strength levels up to about 65 ksi (448 MPa). Precipitation hardening increases its contribution as the strength is raised beyond 65 ksi (448 MPa). Typical compositions of hot rolled HSLA steels are given in Table I and typical mechanical properties in Table 11.

Because of reduced formability and increased sensitivity to the presence of stringer sulfide inclusions as strength is increased, many of these steels are given inclusion shape control treatments. Addition of rare earth or zirconium during steelmaking creates high yield strength complex sulfides which resist elongation during rolling and, thus, stay globular, eliminating the planes of weakness associated with stringers.

Table I. Typical Hot Rolled HSLA Steels

Yield Strength	Composition				
	C	Mn	Nb	S	P
350 MPa	0.08	0.60	0.03	0.015	0.008
420 MPa	0.08	0.60	0.05	0.015	0.008
490 MPa	0.08	1.0	0.07	0.015	0.008
550 MPa	0.08	1.2	0.10	0.015	0.008

Table 11. Typical Properties of HSLA Steel

Specified Minimum Yield (MPa)	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (% in 2")	n Value	r Value
350	385	490	31	0.20	1.0
420	455	550	28	0.17	1.0
490	525	620	26	0.15	1.0
550	585	655	22	0.12	1.0

Fabrication

The major problems with fabrication of parts from HSLA steels have resulted from the reduced formability associated with higher strength, variation in springback, and reduced or different weldability.

A considerable amount of information is now available on the formability of HSLA steels showing that, despite reduced levels, many complex parts can be successfully stamped. Most of this information has been obtained from the tensile tests with the "n" value (work hardening rate), "m" value (strain rate hardening), and "r" value along with elongation (uniform and total) being the properties of concern. Table II gives typical values. The stretchability of steel given by "n" and "m" values and elongations clearly decrease with increased strength, while deep drawability as measured by "r" value is unaffected.

An additional concern is bendability, a condition which occurs in most pressings and often in combination with stretching. These latter conditions can involve plane strain or positive biaxial strains so that performance of a specific steel may be inadequately described by tensile test data. Bendability without stretching is usually evaluated in the transverse direction and is usually normalized in terms of the bend radius divided by the sheet thickness to which a steel sample, usually with sheared edges, can be bent without exhibiting surface or edge fractures. Typically, niobium strengthened steels do not exhibit a serious deterioration in bendability, compared to mild steels, until strength levels of 70 ksi (480 MPa) are reached. Table IV details minimum values specified for fully killed hot rolled steels without inclusion shape control.

Tensile test data do not fully represent formability. Many pressings are formed with strain paths resulting in conditions close to plane strain. Tensile test ductility does not always predict behavior under these conditions, hence, development of the limiting dome height (LDH) test, which is a cup test conducted so that plane strain occurs. Typical values from tests conducted in one laboratory are given in Table III. The test combines an assessment of plane strain deformation behavior with surface effects and gives, therefore, a more realistic measure of formability.

Table III. Limiting Dome Height Results for Selected Cold Rolled Sheet Steels

Steel Type	Limiting Dome Height mm
Rimmed Drawing Quality	27.9 - 29.9
Killed Drawing Quality	29.5 - 33.0
HSLA - 40 ksi Yield	23.6 - 30.5
HSLA - 50 ksi Yield	23.0 - 26.0
HSLA - 60 ksi Yield	19.8 - 22.0

Table IV. Minimum Bend Radii for High Strength Steels

Steel	Yield Strength (MPa)	Yield Strength (ksi)	Bend Radius
AKDQ	175	25	0.2 T
DQ	210	30	0.2 T
CQ	245	35	0.5 T
HSLA 40	280	40	1 T
HSLA 50	350	50	1 T
HSLA 60	420	60	1 T
HSLA 70	490	70	1 T
HSLA 80	550	80	1 T

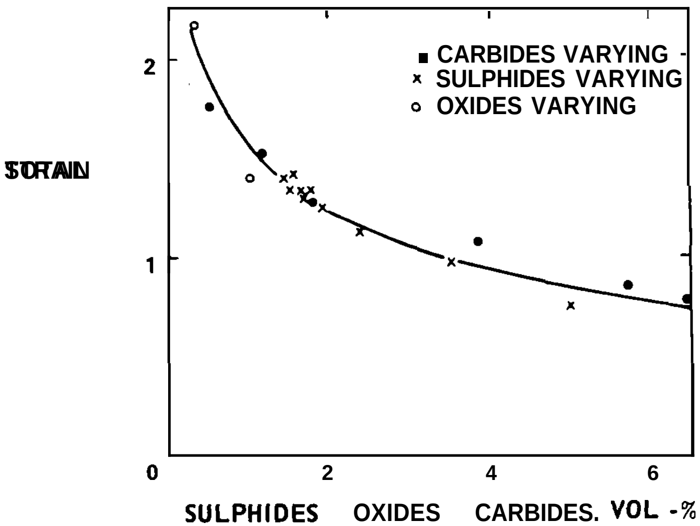

Figure 1. Effect of Second Phases on Ductility.

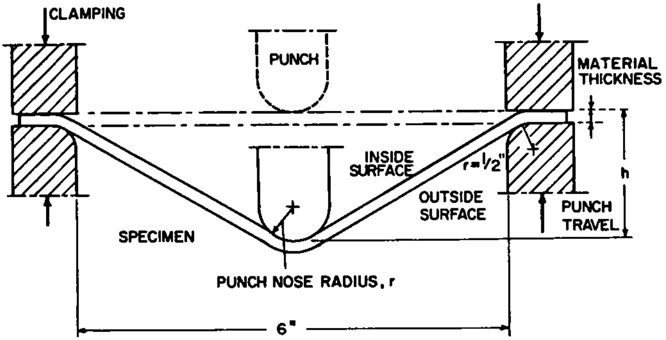

Figure 2(a). Angular Stretch Bend Test.

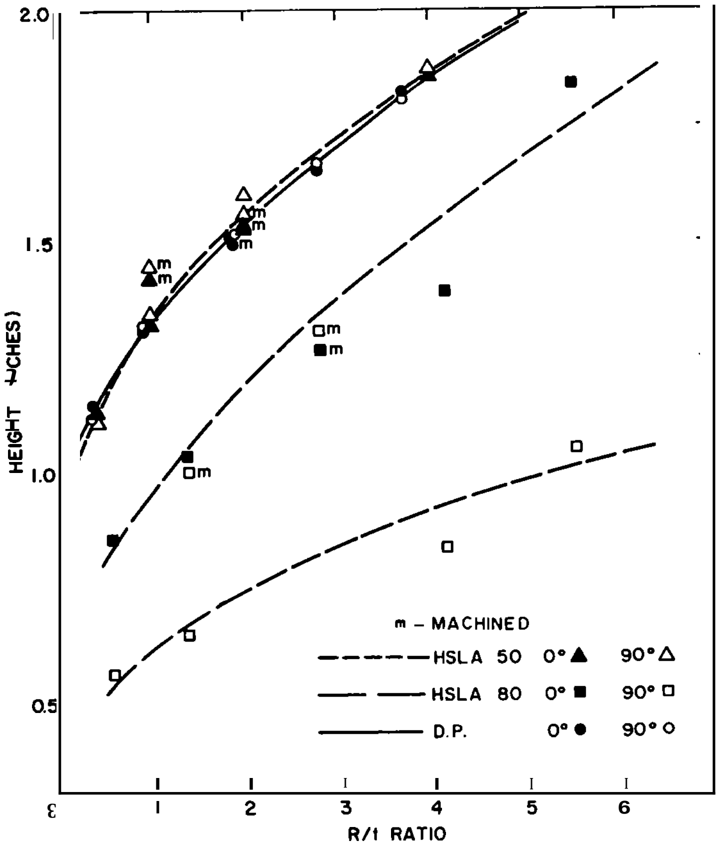

Figure 2(b). Stretch Bend Test Results for Various Steels and Different Punch Geometries.

In addition to predicting formability from a series of tests such as those described, Forming Limit Diagrams (FLDs) have been used to assess press performance and obtain more predictive information. They show the maximum value of peak strain the sheet steel can withstand before failure occurs through localized necking. FLDs have now been determined for all the currently available HSLA steels and the relationships with basic mechanical properties well established. In general, FLDs have the same overall shape, as shown in Figure 3. Description of the effects of property changes are usually confined, therefore, to defining the influences of property variation on FLD_0. This is the limiting value of strain under plane strain conditions.

Decreasing "n" value as strength increases reduces FLD_0 according to the relationship shown in Figure 4. Secondly, increasing the thickness has been found to raise the FLD. Figure 5 shows this effect. Knowing these variables enables construction of FLDs for any strength and thickness of HSLA steel and, thus, provides a valuable tool for assessing press performance. Parts made with no safety margin (strain close to failure) can be identified before full-scale production begins and appropriate corrective actions taken.

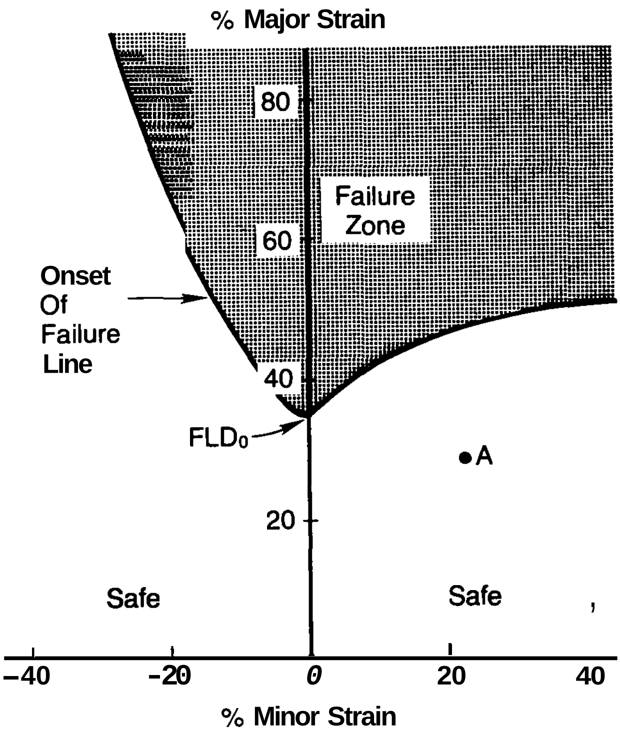

Figure 3. Typical Forming Limit Diagram.

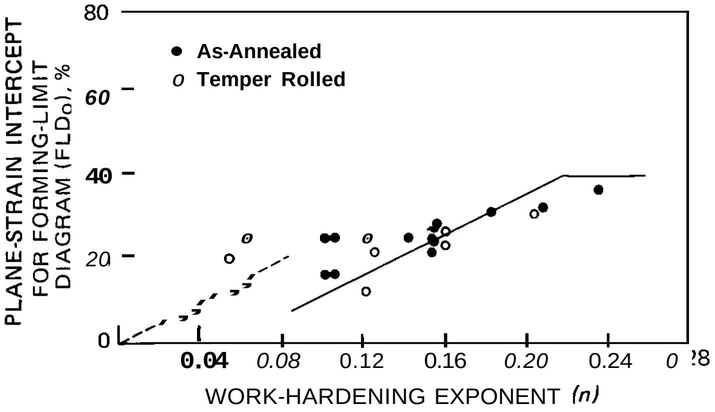

Figure 4. Dependence of FLD_0 on Work Hardening Exponent (n).

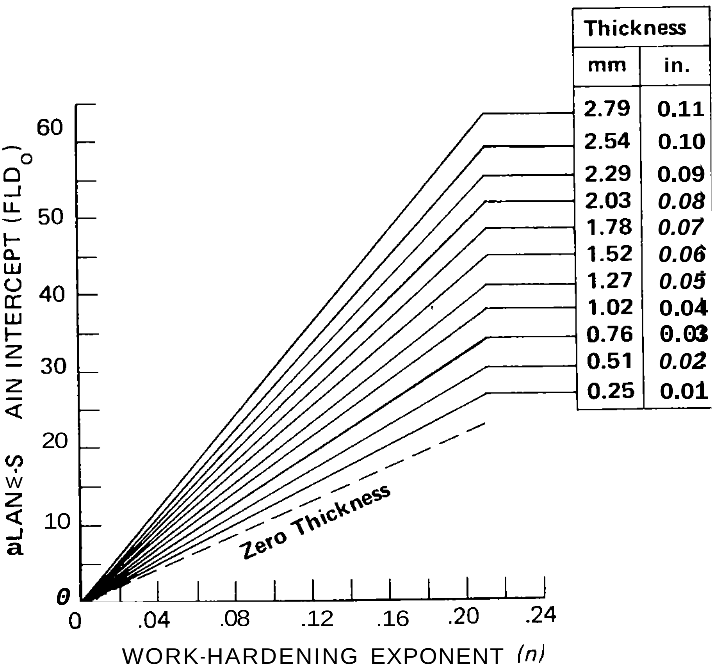

Figure 5. Dependence of FLD_0 on Work Hardening Exponent (n) for Various Sheet Thicknesses.

A recent publication by Keeler and Stephens (5) describes various techniques to assess the severity of sheet metal stampings. The FLD can be combined with the uniaxial strain path, controlled by the r value, to determine a minimum hole expansion limit for steels with inclusion shape control. The FLD combines the effect of thickness with the general formability described by the "n" value to establish a plane strain limit, while the left hand side of the FLD is considered to be a pure shear band (6). This results in the slope of the left hand side decreasing with decreasing plane strain limits. The intersection of the two curves predict the onset of necking, which, if the steel possesses adequate control of inclusions, should be obtainable. Steels without adequate inclusion control usually cannot approach this strain level.

The effects of a heavy prestrain such as prior cold work or burr from previous cutting operations can be allowed for by applying an appropriate safety factor to reduce the calculated strain to a suitable level. This approach has been successfully combined with the analysis developed by Wang and Wenner (7) to predict stretch flange limits for various sheet metals.

The prime cause of variability in stamping performance is scatter in yield strength values giving rise to variable springback. One attempt to quantify this effect was made by Davies, (8) who showed the relationship between springback in a simple bending operation and yield strength. This type of relationship, shown in Figure 6, has led to action from the steel companies aimed at improving control of yield strength. Greater use of laminar flow cooling and associated computer control to achieve more precise coiling temperatures is one example.

Differences in spot welding performance between HSLA steels and the low strength products they replace have been minimized by using low carbon content, minimizing other alloy additions, and avoiding surface oxides that would modify surface resistivity. Niobium has a negligible effect on weldability compared to other possible alloying elements.

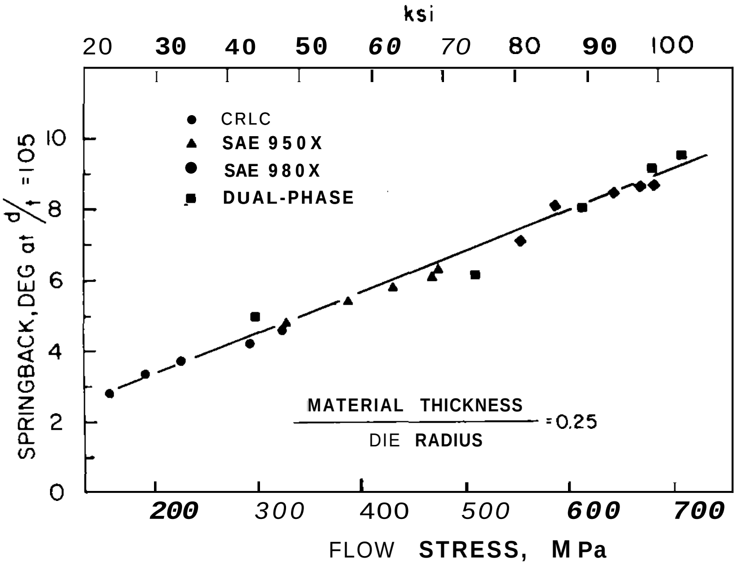

Figure 6. Effect of Yield Strength on Degree of Springback.

Fatigue Properties

Since many of the applications which are employed for hot rolled sheet steels involve cyclic loading conditions, a considerable amount of research on their fatigue properties has been conducted. Particular emphasis has been on strain controlled testing, since this is felt to give the best simulation of service conditions. Figure 7 demonstrates the concept. Strains giving rise to fatigue failures are usually in areas of stress concentration and are, thus, surrounded by materials subjected to lower strain. Elastic constraint of the critical areas, therefore, exists and is well simulated by strain controlled testing of smooth specimens. Figure 8 demonstrates information typical of that generated by this type of testing.

Smooth specimen test data have been found to correlate well with service performance, the superior fatigue resistance of the higher strength niobium steels having been demonstrated in many applications. In general, the superiority of the high strength steels is at long lives (> 2 X 10^6 reversals), with little difference being noted at short lives (10^3 - 10^4 reversals). Figure 8 gives typical results for an example of a niobium strengthened steel with a yield strength of 50 ksi (350 MPa).

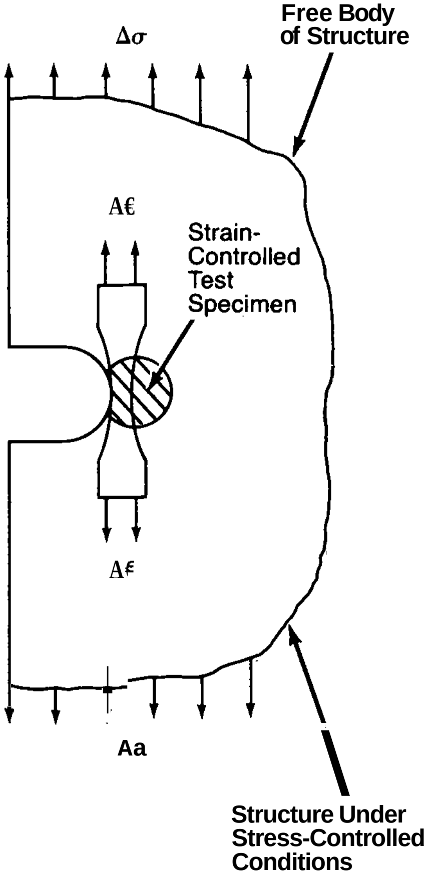

Figure 7. Illustration of Strain Controlled Fatigue Testing Concepts.

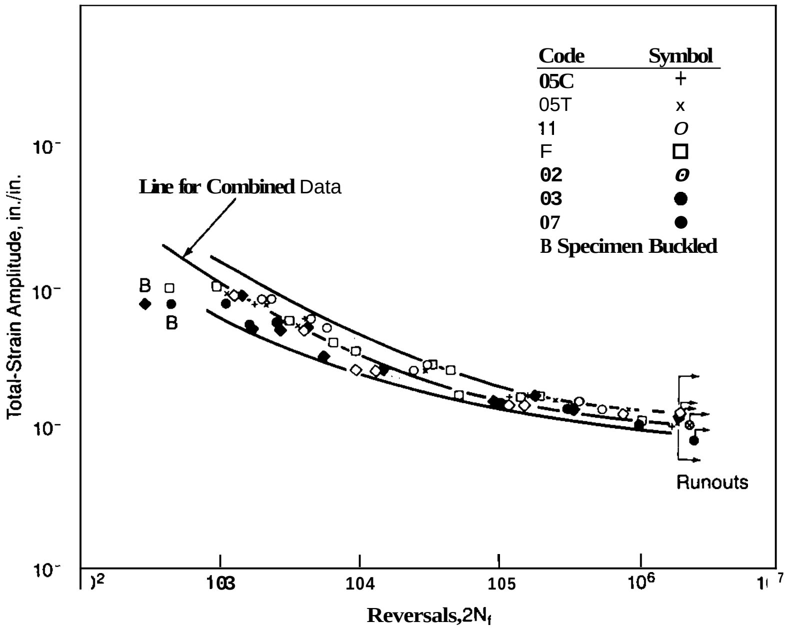

Figure 8. Strain Controlled Fatigue Curves for a Niobium Containing HSLA Steel with a Yield Strength of 350 MPa.

Despite the good results obtained with smooth specimen testing differences in response to notches in components have sometimes been noted for steels with similar fatigue test data. This is presumably related to varying responses to triaxial stresses. Notched tests are frequently run, therefore, to measure the sensitivity. One popular approach utilizes the Neuber analysis to rank notch sensitivity. Details of the approach have been described by Topper, et al (9). This simplified analysis gives a notch sensitivity factor, K_f, where values of 1.0 are for material unaffected by a notch to numbers as high as 2.0, or greater, where substantial loss of life is caused by the presence of stress concentrations. In general, the higher strength steels have higher K_f values than their low strength counterparts. Improved component life is still experienced, however, because the smooth specimen or matrix fatigue strength increase more than offsets the increased notch sensitivity. Table V gives typical K_f values for HSLA steels.

Table V. Typical K_f Values for HSLA Steels at a Life of 10^6 Reversals

Nominal Strength (MPa)	K_f
245	1.2
350	1.4
550	1.7

Data have also been presented to show that fatigue properties measured by conventional methods are not affected by the normal variations in inclusion content or degree of sulfide shape control. However, recent testing of a 80 ksi (550 MPa) yield strength steel by R. B. Wilson (10) has demonstrated that sheared edges can present a different situation. Different edge conditions were tested for steel with and without sulfide shape control. The results showed a drop in life with deterioration in edge condition (changing from machined to sheared) and a substantial improvement in fatigue life with the addition of sulfide shape control. These results show that treatment of the inclusions may be necessary for component performance, even if forming requirements do not dictate such action. Table VI summarizes these findings.

Table VI. The Influence of Edge Condition on Fatigue Life

	Average Life (Cycles)	
Condition	Longitudinal Test	Transverse Test
Steel 1 -		
Sheared	80,000	-
Machined	110,000	-
Steel 2 -		
Sheared	60,000	-
Rolled	100,000	-
Steel 1 -		
No Rare Earth-Sheared	-	32,000
With Rare Earth-Sheared	-	53,000

Many of the cyclic loading applications also involve exposure to corrosion. Investigations have, therefore, been conducted to determine the effect of corrosion on fatigue life (11). This work has shown that the loss in life caused by the pitting and general thickness loss that occurs in the northeastern snow belt of North America is comparable to the effects of typical design notches in components. The HSLA steels show similar sensitivity to the historically used low strength steels. Since weight reduction is usually associated with the introduction of an HSLA steel, extra corrosion protection is often applied to maintain the superior fatigue performance of the higher strength steel. Galvanizing by continuous hot dipping is the most popular method and has been shown to have an insignificant effect on fatigue strength (12). Deterioration in component life is delayed, therefore, for as long as the zinc coating survives.

A key question for the designer centers on variability in properties, since the minimum life expected is the one that has to be designed to. Studies of scatter in fatigue life for SAE 950 and SAE 980 steels have shown a variation of about one order of magnitude (13), which is similar to the low strength steels they replace. The scatter has been found to be independent of mill processing, leading to the conclusion that fatigue behavior for a given strength level is insensitive to steel processing variables; and secondly, that testing in one location from a single coil is sufficient to characterize that grade.

Applications Experience

When substituting HSLA steels for low strength products, it has been clearly demonstrated that production practices have to be modified in order that the weight saving potential can be realized and also be cost effective. The approach is to identify the critical areas through experience and/or circle grid analysis. The latter provides a quantitative comparison and minimizes excessive reductions in design severity. Grid analysis also gives the degree of safety factor that exists. Experience has shown that material substitutions which appear acceptable in initial trials sometimes result in major difficulties once regular production is started. An adequate peak strain safety margin of up to 20 percent, depending on the quality of the try-out steel, is adequate for most applications.

Consideration must also be given to the true forming condition. Pure draw or simple bending is not likely to cause problems with high strength steels as long as minimum bend radii limits are observed. Conditions involving stretching are highly likely to require changes in both section geometry and bend radii. Edge stretching conditions also require consideration, and the previously described technique is recommended.

Another area of concern, particularly with relatively straight sided automotive structural members such as frame rails which are sufficiently complex to require a draw die, is side wall curl. Here, the sheet, initially the die cavity under tension. The resulting through thickness strain gradient produces an outward curl condition, as illustrated in Figure 9. The problem is worse at higher strength levels and is difficult to avoid. Usually, an extra "wiping" action is introduced to reduce the residual stresses. While one publication (14) has described the effect of several tooling parameters, continued work is necessary to resolve this issue if the U section parts are to be successfully produced.

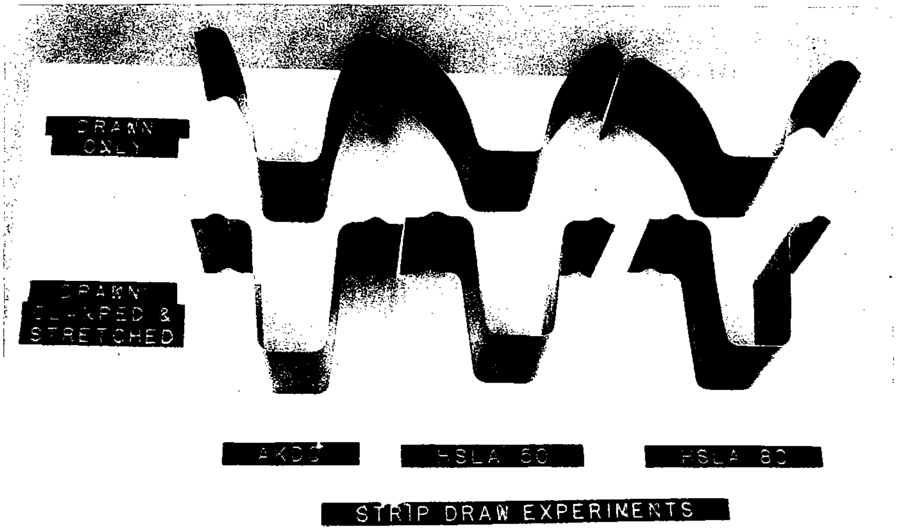

Figure 9. Illustration of Side Wall Curl for Three Classes of Steel.

Springback can be a serious problem, particularly since fitability issues affect final product quality. In general, parts which are heavily stretched show relatively little springback, contrary to the experience with simple bending. Bending springback is proportional to yield strength, bend radius, and the bend angle and, thus, is relatively easy to design for by either allowing open angles on flanges or by providing corrective operations. The latter usually requires additional press operations.

On automotive skin panels where fit is extremely important, the reduced strain hardening combined with higher loads (which tend to reduce the efficiency of lubricants) result in less uniform strain distribution and, thus, increased surface springback.

Wheels can now be made from 60 ksi (415 MPa) yield strength steels with from 10 percent to 15 percent weight savings possible. The manufacturing process for rims has to be modified in a number of ways; Figure 10 shows the steps involved. Heat input in the welding operation has to be tailored to the composition, such that a slightly harder weld zone than the parent metal is created. Failure to do this will result in fracture during forming because of concentration of strain in the weld. Composition (particularly carbon content) also has to controlled to give adequate hardenability. Greater control of fit-up during welding is necessary because of the reduced thickness being processed and because of greater sensitivity to mismatch. Careful control of inclusions is also necessary because clustered inclusions can give rise to planes of weakness perpendicular to the surface. These lines of weakness are generated during the upsetting operation after welding. Subsequent forming results in localized failure and generation of defects known as pinholes.

Another major application of HSLA steels has been twist axles such as those used by General Motors and Chrysler Corporation on their new front wheel drive cars. A schematic of the General Motors system is shown in Figure 11. The axle uses a 80 ksi (550 MPa) yield strength steel with full inclusion shape control being specified. Although not required for forming, the inclusion modification imparts superior fatigue performance, particularly since one of the highly stressed areas includes a sheared edge.

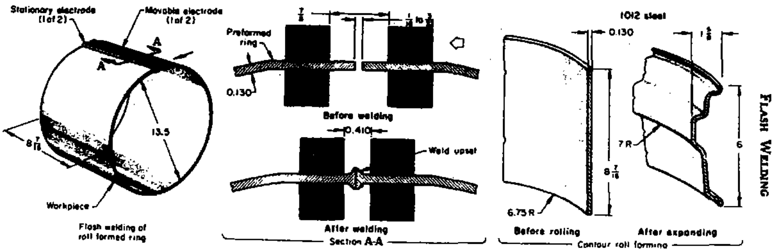

Figure 10. Illustration of Manufacturing Process for Automobile Wheel Rims.

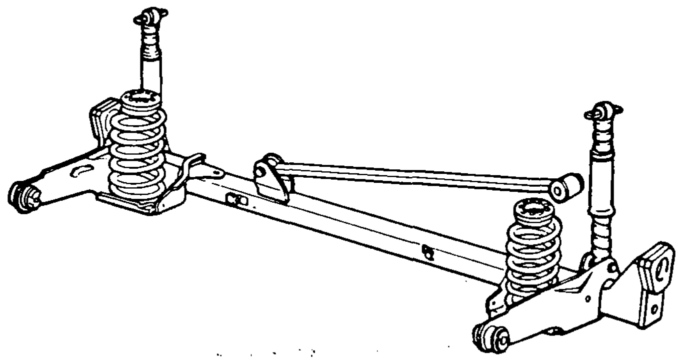

Figure 11. General Motors Twist Axle Arrangement which utilizes an 550 MPa Niobium Treated HSLA Steel.

Typical of other applications for niobium steels is the underbody truck hoist shown in Figure 12. Fifty ksi (345 MPa) yield strength steel is used €or this part. Ten percent weight saving and associated fuel cost reductions were achieved by changing from commercial quality steel to HSLA steel. Contrary to many other cases, no changes in fabricating procedures were necessary, despite a number of tight inside bend radii. No changes to welding practice were necessary either.

Cold Rolled and Galvanized Steels

Most of the interest in cold rolled high strength steels has come from the automotive industry because of its desire to reduce weight to improve fuel economy. Since many hot rolled applications are at the lower thickness limit available from hot strip mills, thickness reductions dictate a switch to cold rolled steel. In addition, many components are already made from cold rolled steel, hence, changing to HSLA steel means still mote need for cold rolled versions.

While individual predictions for the amount to be used vary from company to company, predictions (15) are that up to 50 percent of the automotive body weight could be high strength steel. One study (16) has stated that high strength steel sheet is one of the most cost effective approaches to improved fuel economy.

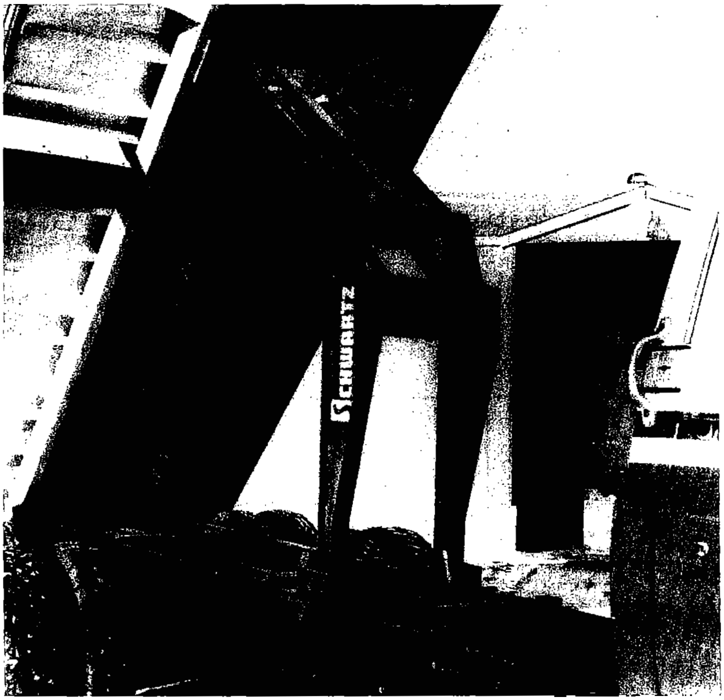

Figure 12. Use of a 345 MPa Niobium Treated HSLA Steel in an Underbody Truck Hoist.

Production

Achieving high strength in cold rolled and annealed steels is more difficult than in the hot rolled steels. Traditionally, the final annealing treatment has been by the box or batch annealing process involving slow heating, long times at temperature, and slow cooling. Such processing virtually destroys any strengthening by precipitation hardening, hence, the maximum strengths achievable are lower than in hot rolled products; Figure 13 deomonstrates the effect. To date, yield strengths up to 60 ksi (415 MPa) have been made commercially available from box annealed products. Typical properties of commercial batch annealed steels are given in Table **VII.**

Table VII. Typical Cold Rolled HSLA Steel Properties

Yield Strength (MPa)	Tensile Strength (MPa)	Total Elongation (% in 2")	Uniform Elongation
280	350	33	21
385	490	28	19
460	530	25	17

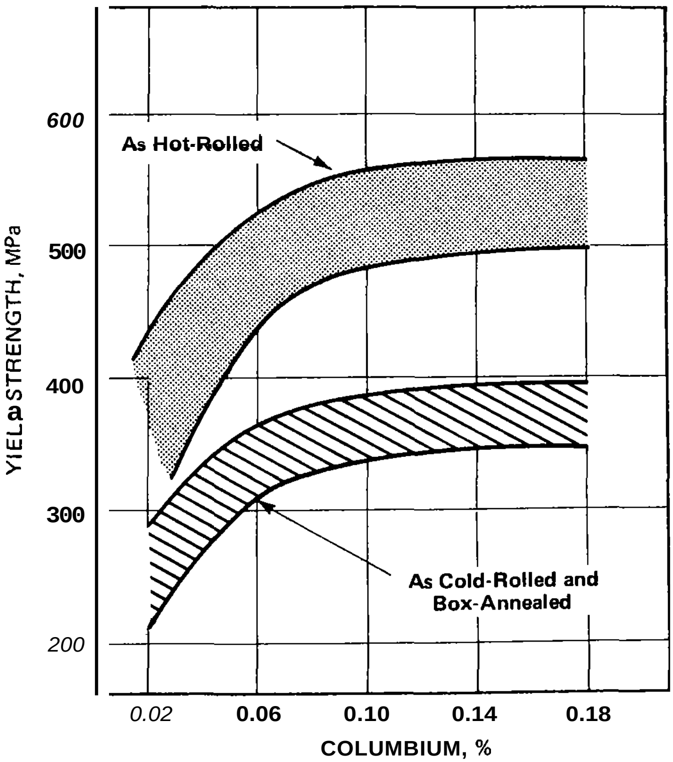

Figure 13. Comparison of the Yield Strength of Hot-Rolled and Cold-Rolled-Box Annealed Niobium Treated Steels.

An additional problem is encountered in achieving high strength cold rolled products and results from the frequently specified temper rolling operation after batch annealing. Elimination of yield point elongation and production of specific surface finishes for automotive skin panel applications are the reasons for temper rolling. Associated with yield point elongation removal, however, is a drop in yield strength. This drop is larger with finer grain sizes. For example, in a *40* ksi (275 MPa) yield strength product developed for autobody applications, the loss in strength from temper rolling was 7 ksi (50 MPa) (17). The problem was minimized by supplementing the niobium induced grain refinement strengthening with solid solution hardening from phosphorus. The phosphorus addition reduced the amount of temper rolling necessary for YPE removal from > 2 percent to < 1.5 percent because of its effect on strain hardening. This, in turn, meant less deterioration in formability from temper rolling in addition to more easily achieved strength. The amount of phosphorus that can be added is limited, however, by the effect on resistance spot weldability. Above 0.10 percent P, welds exhibit brittle behavior during peel testing and, thus, are often considered unsatisfactory. The strength contribution from phosphorus was limited, therefore, to that obtained from 0.07 percent aim levels, i.e. 7 ksi *(49* **MPa).** Since the same welding restrictions apply to higher strength levels, the same limitations on phosphorus apply.

Formability

As with hot rolled steels, formability decreases as strength is increased, Table VII demonstrating the effects as measured by tensile test data. Steels strengthened with niobium do not normally develop high r values and, thus, do not demonstrate the deep drawability of aluminum killed drawing quality steels. Performance in this type of operation is, however, comparable to rimmed and capped steels and, thus, is adequate €or the majority of applications.

All of the descriptions of formability assessment for hot rolled steels also apply to their cold rolled versions. The same need for inclusion shape control has been encountered for parts requiring edge stretching, and the same deterioration in formability associated with thickness reductions has been noted. Forming Limit Diagram analysis of cold rolled steels has shown the same dependence on properties and thickness.

As with hot rolled steels, the major forming concern has been control of variability. The higher strength steels, being more difficult to form, show greater sensitivity to material property changes than their low strength counterparts. Process control to minimize variability is concentrating on steelmaking modifications to increase control of composition, give more precise control of hot rolling parameters (reduction per stand and temperatures), and improve the annealing processes. Modifications to the batch annealing process are aimed at better temperature control and reducing temperature differences throughout the coils. These goals are being attained by use of improved gas flow, insulating plates to avoid hot spots, and better convector plates between coils. Some steel companies are installing continuous annealing lines which subject every part of a coil to the same thermal cycle and, thus, give the minimum amount of variability. These lines also increase the upper strength level achievable because of the short times at temperature (one minute) and rapid cooling rates.

In addition to process control being necessary for consistent forming behavior, limits to strength variation are being specified for crash worthiness considerations. Vehicles have to collapse in a controlled manner to protect passengers. Excessive strength in some parts can, therefore, lead to the incorrect order of component failure in a crash. All of the previously mentioned efforts to improve product consistency are, therefore, also directed toward this goal.

Where zinc is applied by continuous galvanizing, in-line annealing is usually carried out. More precise control of this process by careful attention to temperature measurement and control has been pursued by many steel companies.

Electrolytic deposition can be used instead of hot dip galvanizing. Thus, the advantage of minimal effect on formability, along with excellent one-side capability, is available. This is important if galvanizing is to be successfully applied to outer skin samples. This process is also capable of providing alternative alloy coatings, which may have potential for providing the required protection at lower coating weights, positive attributes where either paintability or weldability are involved.

Weldability

Resistance spot weldability has been a major concern with cold rolled HSLA steels. The most common method of assessment has been to use the welding lobe, as shown in Figure 14. Data for the lobe are obtained from peel tests, which give the size of weld retained after peeling apart the two sheets of steel which have been joined. The objective is to produce steels with a wide lobe (2000 amps) so that sensitivity to variation in production welding conditions is low. A second objective has been to have the position of the lobe similar to low strength steels, if possible. Similar lobe positions for different versions of steels at the same strength level is essential, since identification of formed parts at this stage of fabrication does not differentiate between suppliers. Welding requirements must, therefore. be the same.

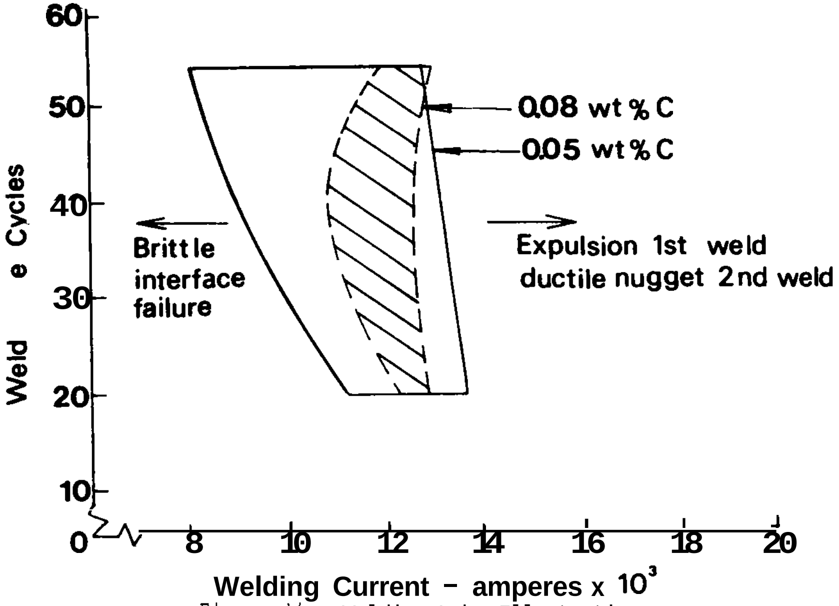

Figure 14. Welding Lobe Illustration.

Providing carbon and phosphorus levels are minimized, adequate spot weldability is usually achieved with niobium strengthened cold rolled steels, although weldability becomes more difficult with both lower gauge and higher strength. Phosphorus and carbon have similar detrimental effects on welding performance as measured by the peel test. Addition of 0.01 percent of either element has the same effect on weldability. Most of the other performance parameters such as tensile strength, cross tension and shear strengths, and fatigue strength are not as drastically affected by carbon and phosphorus.

A paper by T. E. Fine and R. B. Wilson (18) compared the fatigue strengths of spot welded cold rolled HSLA steels and drew the following conclusions. At lives less than 10^6 cycles, HSLA steels show superior fatigue strength. Beyond 10^6 cycles, no improvement was noted. Even when poor peel test results were obtained, fatigue strength was good. If better fatigue performance is required, larger spot welds can sometimes be used.

Applications Experience

As previously mentioned, most of the experience with cold rolled HSLA steels has been in the automotive industry. Forty ksi (275 MPa) steels have been used extensively for skin panels with moderate formability requirements such as hoods, doors, trunk lids, etc. The major requirement has been comparable dent resistance to the thicker panels made from low strength steel. Improved corrosion protection when required has been achieved by the use of one-side prepainted zinc-rich primer coatings (ZINCROMETAL). However, with increasing corrosion protection requirements, there is a distinct possibility that a one or two-side galvanized coating for skin panels may be required. For these applications, the effect on formability will have to be minimized if these applications are to remain feasible in higher strength steels. Extensive use of 50 ksi (350 MPa) yield strength steel for structural body parts is reported and predictions are that many applications will be introduced.

Stamping experience with many parts formed from high strength steels has been similar to the hot rolled. Significant changes in both part design and the stamping process are usually required if the use of the higher strength steel is to be successful.

Part design modifications require understanding of the probable stamping process to determine the areas that are most likely to be critical. Areas toward the outside of the part that can involve controlled metal flow can be less difficult than interior areas where stretching without significant metal flow may occur. Further, areas that involve pure draw are less critical than those involving a combination process.

The experience of one automotive manufacturer on a major high strength steel substitution study showed that edge tearing was the most predominant failure mode. While the use of inclusion shape control, or similar practices, will reduce the problem, reduction in the degree of edge expansion is the only basic approach to account for the combined effects of reduced ductility and thickness. The previously described technique to predict both the failure limit and the design limits has been successfully used on a variety of sheet metals. Providing more metal in the critical area is also an effective way to reduce edge tearing.

Stamping process selection and die design are also significant steps if high strength steels are to be successfully pressed. For instance, and as previously discussed, drawability is largely unaffected by strength level, while the reverse occurs with stretching. Thus, stamping processes and die designs and adjustments that promote metal flow are favored. Figure 15 illustrates a HSLA 50 cold rolled seat back stamped on experimental dies using two different die developments. The part on the right used a stretch draw development as usually used for mild steel and resulted in a negative safety factor, while the part on the left encountered primarily draw strains with a minimum of stretching, resulting in a positive safety factor. Production tool patterns after the "draw" operation have been successful in production. Multiple operations that avoid excess strains by progressively working different areas also promote the more uniform strain distributions that are required with high strength steels.

As with hot rolled steels, increased springback is a problem. Over bending by part tipping, or positioning, is the most common correction technique on flanges with geometrical stiffening. Tight bend radii minimize springback, but the more limited formability restricts use of this approach.

Bending along curved lines also can cause considerable springback due to the compressive or tensile stresses along the length of the flange. Either part overcrown or stress eliminators such as darts or take-up beads in compression flanges and metal gains in stretch flanges can be used. Side wall curl, as previously described, is also a significant problem in cold rolled steels.

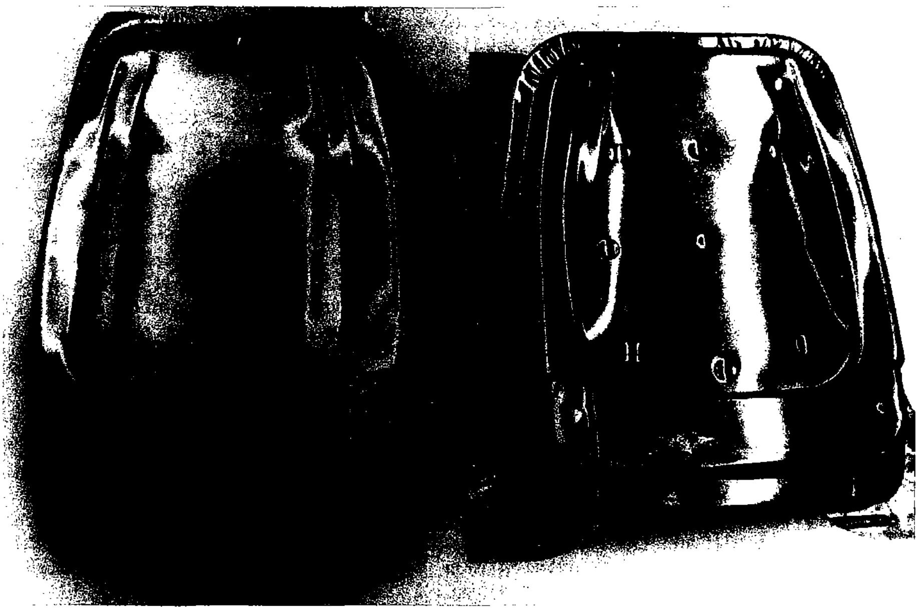

Figure 15. Seat Rack Stamping made from Cold Rolled HSLA Steels.

Draw beads are flow restrictors used in draw dies for complex stampings to avoid excess metal or wrinkles in the finished part surface. High strength steels require proportionally more retarding force than mild steel, since they cannot tolerate very sharp radii. Larger bead radii are, therefore, common. These larger bead radii, in turn, reduce the retarding force, often creating the need for additional beads. The increases blank size requirements and, thus, part cost. The analysis of draw beads and the test apparatus described by Nine (19) can be used to evaluate draw bead geometry effects.

Despite all the aforementioned problems, many parts have been successfully produced from high strength steels.

Limited use of recovery annealed high strength steels has also been introduced. Strength levels up to 140 ksi (965 MPa) are being supplied for various applications where forming is limited. Typical of these are bumper reinforcements and door intrusion beams where stretch requirements are minimal. At the higher strength levels, niobium can be used to inhibit recrystallization and reduce sensitivity to annealing temperature.

Summary

Niobium is being used in a large range of hot and cold rolled and galvanized high strength steel products. If modifications to manufacturing \ processes are made, then the superior strength properties of the HSLA steels can be utilized. The major barriers to further use have been development of a better understanding of property performance relationships and control of variability. Since both of these factors are being attacked vigorously, further growth in the market for HSLA sheet and strip products is expected.

Many parts, particularly in the lower body, require corrosion protection, hence, galvanized steel is frequently used. A substantial growth in the production volume for coated high strength steels is, therefore, to be expected.

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