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HPS CORRUGATED WEB GIRDER FABRICATION INNOVATIONS

FINAL REPORT

PART 4: LITERATURE AND EXPERIMENTAL STUDY OF STRAIN AGING IN HPS AND OTHER BRIDGE STEELS

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Summary

An extensive literature covering the last 50 years has shown that all structural and bridge steels are potentially susceptible to strain aging. The most damage is done by cold strain itself. Strains in the 5% to 18% range can typically increase yield strength by 70% and typically increase tensile strength by 35%. Over the same strain range, tensile elongation will typically decrease by 30%. The Charpy V-notch impact transition temperatures will typically increase by 65°F after similar strain. Aging by heating in the 500°F to 800°F range after cold strain will not increase the yield or tensile strength nor further reduce tensile elongation. Aging after cold strain will typically cause an additional 35°F increase in the transition temperature.

Heating strained or strained and aged material in the 1100°F to 1200°F range will decrease the yield and tensile strength and increase the tensile ductility again but not to their initial values. Similar heating of strained and strained and aged materials will also decrease transition temperatures again but not to their original values. Strain aging should not be a problem in bridge steels because cold strain levels during fabrication are typically low and post-strain heat treatments are not used. High Performance Steels, with their excellent initial notch toughness, can tolerate some potential strain aging loss and still meet stringent CVN toughness requirements.

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1.0 INTRODUCTION

1.1 Historical Background.

The discovery that the properties of steel could be changed by cold mechanical deformation is lost in prehistory; cold working to increase the strength and hardness of metals in general and steels in particular has been used for at least 4000 years. These changes occur simultaneously with deformation, provided the metal involved is worked at temperatures below approximately one-half to one-third their melting point on an absolute temperature scale. For irons and most steels, this means mechanical working at temperatures below about 1000^{o}F will usually result in permanent increases in strength and hardness, i.e. it is "cold strain." At temperatures above this level, the effects of cold strain are reversed by the process of annealing during which the grain structure of the metal distorted by deformation is replaced by new strain-free grains, and the metal becomes soft again.

The effects of annealing have also been known for thousands of years because one of the side effects of cold strain is a loss of ductility, and in working of metals into useful shapes, it is usually impossible to produce a tool or weapon by cold work without fracturing unless it is annealed periodically to restore its ductility, or it is "hot" worked above its annealing temperature where its ductility is instantaneously restored while deformation is occurring. Hot working, often followed by some cold working thus became a standard metal-working practice. Hot working was done for major shaping of tools and weapons because it allowed almost unlimited ductility but the final step was often some cold deformation to the surfaces to increase their hardness and strength.

Unknown until the early 1920's and 30's, however, was another important side effect of cold strain, a loss of toughness that, on occasion, resulted in brittle fractures. While it was understood that brittle fractures were associated with low toughness in steels, the causes and mitigation of these fractures was not very well understood until ground-breaking research on ship hull fractures was undertaken during World War II. From these studies came an understanding that steels underwent a transition in toughness with temperature and that this transition could be measured by a standardized test, the Charpy impact test.

Subsequent use of this test by many investigators demonstrated that the impact toughness of a steel was a function of its composition, steel making process, strength, and, among other things, the amount of cold deformation applied. Thus the first element in the loss of toughness in steels in strain aging was identified, cold strain. Indeed, as the data will later show, in some steels the significant loss in toughness attributed to strain aging, as measured by increase in transition temperature, occurs as a result of the effects of strain alone. The investigations also demonstrated that many steels used in pressure vessels and structures, including bridges, were susceptible to loss in toughness by cold strain, the first element in strain aging.

The second major factor in toughness loss in cold deformed steels is through what has been called "aging." This phenomenon was first identified in the 1920's as a non-uniform yielding in deep drawing of steel sheet, especially noticeable in the auto bodies and other consumer products.

This sheet was typically cold rolled and annealed prior to final drawing into the finished shape. This sometimes resulted in surface roughness and stretch lines (called Lüder lines) on the surface of the product. While these had no adverse effect on the mechanical properties of the product, their appearance was unacceptable.

It was found that a small amount of cold deformation by rolling after annealing would eliminate this effect and at the same time it eliminated the sharp yield point in the stress-strain curve, replacing it with a "round-house" (gradual yielding) curve. However, when there was a significant time gap between the final rolling and the deep drawing fabrication process, the sharp yield point effect would return, and with it the non-uniform yielding stretch lines. This was referred to as "aging." Experimentation showed that the return of the yield point and the stretch lines depended on both time and temperature; at room temperature it returned in days or weeks, at temperatures of 300^{o}F to 500^{o}F, it returned in hours, while at 800^{o}F, return was almost immediate. It was also found that the effect was related to composition. Steels deoxidized with aluminum appeared to be more resistant to the phenomenon, while silicon deoxidized steels were less so.

At the time, these findings seemed to be merely academic as far as steels used for bridges and other structural applications were concerned. However, research done in the 1950's showed that the strain aging phenomenon could occur in pressure vessel steels where the primary effect was decreased impact toughness, usually seen by shifts in transition temperature to higher ranges and sometimes resulting in low impact toughness at operating temperatures. Since the many of the steels used in pressure vessels were similar to those used in bridges, for example, ASTM A514 used in structures and ASTM A517 used in pressure vessels, there was a continuing concern with the possibility that this phenomenon might have wider implications.

It is now known that these two effects can work in concert to significantly reduce the Charpy impact toughness of bridge steels, i.e. they are susceptible to strain aging. The purpose of the literature survey and research reported here is to summarize what is known about strain aging in bridge steels and to relate it to the data developed for strain aging in HPS 70W steel. In addition to the data in open literature, Lehigh University and the ATLSS Center have been conducting research on strain aging in structural steels for over 50 years, and this creates a large body of data to compare with the results of the recent tests on HPS 70W.

1.2 Theory of Deformation in Metals.

A large body of research has been published on the causes for strain aging, some of it quite detailed with respect to submicroscopic phenomena. For the purposes of this report, only a summary will be provided. If, however, a more detailed review is desired, the papers by Baird, although done in 1963[1] and updated in 1971[2], are still the most comprehensive and are recommended. The 1971 paper is especially valuable because it contains not only a discussion of the causes for strain aging but also includes substantial data on the effects of strain aging on the toughness of a number of steels.

The effects of strain aging in steels were already attributed to the way in which alloy elements can influence how they plastically deform as early as the 1940's[3]. At the crystal structure level, metals consist of arrays of atoms stacked together in patterns dictated by their atomic size, electron structure, temperature and the alloying elements they contain. As a result of this internal stacking, the atoms lie in layers at various orientations within the individual crystals, or grains. When sufficient force is applied to the crystals in a favorable orientation, the layers or sheets of atoms slide over one another, causing the phenomenon referred to as "slip."

This is similar to the deformation occurring in a deck of cards when subjected to shearing force on the top and bottom cards in the deck; the cards slide over one another. This analogy, though an oversimplification, provides some insight into the factors that affect the force necessary to cause the atom layers to slip over each other and the resulting behavior of its grains. If the cards are smooth, only a small shearing force is necessary to cause the slip and to continue to slip. If they are rough, the necessary force is greater. If the cards are partially glued together, the force is much greater and the failure of the deck will be by a mixture of modes, some local slipping, some tearing through the cards and perhaps some delamination of the individual cards themselves.

In metals, the slip along the crystal planes is facilitated by the presence and motion of crystal defects called dislocations. If the force necessary to start a dislocation moving and to keep it moving freely along the crystal planes is relatively low, the metal will slip easily. Typically, this results in a low yield point in a tension test, the specimen will not show much strain hardening and will require only a modest increase in force to cause final fracture. This type of fracture is usually characterized by good ductility. If the force needed to initiate and sustain the motion of the dislocations is large, the yield point of the metal is higher and more strain hardening occurs requiring a large increase in force to continue deformation and to finally cause fracture. This type of fracture is usually associated with low ductility.

For a given metal, the number and motion of slip facilitating dislocations is mainly influenced by its crystal structure, how much prior deformation it has experienced, its grain size, its composition and its temperature. Relating this to the structural steels of interest in this research, the motion of dislocations is most influenced by alloy elements, grain size, prior deformation and temperature. The most obvious correlations are well known to engineers, alloyed metals are stronger than pure ones, fine grained metals are stronger that coarse grained ones, cold worked metals are stronger than annealed ones, and metals become softer at high temperatures. But it has long been known that alloy elements do not all affect dislocations in the same way[4], and that is important for understanding strain aging.

Structural steel alloy elements like manganese, nickel and chromium are close in size to iron atoms, and as a result, when placed in the iron based crystal structure of steel, locate themselves as substitutes for iron atoms in the slip planes. This causes some distortion of the plane, which requires somewhat more force to cause the dislocations to facilitate slip and accounts for why alloy elements increase strength. Other alloy elements like carbon, nitrogen and hydrogen, are too small to substitute for iron, and thus go into holes (interstices) between the larger atoms and defects in the structure, including dislocations.

As a result, they impede the motion of dislocations also by fixing or pinning the dislocations in place so they are not free to facilitate slip. It is the dislocation pinning action of carbon and especially nitrogen atoms that causes strain aging-phenomena.

1.3 Metallurgical Causes for Strain Aaging.

The alloying elements in the steel are dispersed into their characteristic microstructural constituents, predominantly iron and iron carbide. In the case of nitrogen and some of the carbon that is not absorbed in iron carbide, they are in the iron-rich phase as small individual atoms in interstices in the crystal structure. After the steel cools from rolling, over time, the carbon and nitrogen atoms migrate through the structure to the dislocations due to the distortion they create in the crystal lattice. The motion of these (small) interstitial atoms to the dislocations produces a stabilizing effect which increases the force necessary to cause the dislocation to allow slip. It now takes greater force to deform the steel, raising its strength. If both carbon and nitrogen are present, iron-carbon-nitrogen compounds (carbonitrides) can form that also restrict the motion of the dislocations and raises the strength of the steel.

The effect of temperature is important on the “aging” phenomenon in structural steels. Structural steels are more complex that sheet steels in that they contain relatively more carbon and alloy and have a more complex microstructure. As a result, the aging of the steel as measured by increases in strength and loss in toughness does not occur at room temperature. In general, temperatures in the 300 ^{o}F-700^{o}F range for periods of 1-5 hr are necessary to develop aging effects.

A second strengthening mechanism occurs when cold deformation (alone) is done to steels. When dislocations break away for their pinning interstitial atoms and begin the movement causing slip they begin to intersect with each other. A complex series of interactions between the dislocations occurs, causing them to pin each other, decreasing their mobility. The decreased mobility also results in higher strength, lower ductility and lower toughness. As a result, cold deformed steels already have lowered ductility and toughness before any strain aging occurs and when heating follows cold deformation, the loss in ductility and toughness is greater. It is this combination of events that is the most damaging to the toughness of structural steels.

It is these two effects, the increased strength and reduction in ductility and toughness from cold strain followed by an additional strength increase and toughness loss through aging, that are the primary elements in strain aging.

1.4 Effects of Strain Aging on Strength and Toughness.

This explanation of the causes of strain aging fits quite well with the “aging” effects observed in steel products. The phenomenon was first observed in steels that were rolled and annealed. After being stored for weeks or months, during which time the interstitial atoms migrated to the dislocations, the yield point increased significantly and the ductility decreased. The material appeared to have “aged.” For structural or pressure vessel steels, materials that were cold formed during fabrication by bending or rolling had increased strength and decreased ductility and toughness.

When heated after forming, for example by preheating before welding or in low temperature stress relief, their strength was further increased and its ductility and toughness further degraded.

1.5 Control of Strain Aging

There are some well-established methods for control of strain aging but most are neither entirely effective nor practical. The first approach is to eliminate the presence of the interstitial elements, particularly the carbon and nitrogen that can cause this phenomenon. Since these elements are almost always present in structural steels and only small amounts are required to cause strain aging, this has proven to be either difficult or expensive to do on a regular basis. Special steelmaking procedures, such as vacuum degassing, i.e., subjecting the molten steel to reduced atmospheres to eliminate hydrogen and some nitrogen in the steel, should eliminate or reduce strain aging. This is both expensive and not entirely effective.

Another approach is to deoxidize the steel with aluminum as well as silicon. Aluminum-silicon deoxidation is intended to not only remove dissolved oxygen from the steel as oxides but also to combine aluminum with nitrogen to form aluminum nitrides that help to control grain size during and after heat treatment. This should remove free nitrogen from the steel in the form of nitrides and eliminate one cause of strain aging. As the research cited below will demonstrate, some aluminum-deoxidized steels still appear to be susceptible, thus this approach has also not proven to be entirely effective. Finally, it might be expected that steels containing strong carbide–forming alloy elements such as chromium, vanadium and molybdenum would be less susceptible to strain aging, research shows that this has not proven to be the case either.

A procedure that is sometimes effective in reducing the toughness loss in strain aging is to apply a heat treatment after straining to cause “overaging” of the steel. This process is virtually the same as used to stress relieve weldments and requires heating the strained material to temperatures in the 1000^{o}F to 1150^{o}F range. While this procedure is routinely applied to some products, for example some classes of pressure vessels, it is not often applied to bridges or other structures. Moreover, when applied to such large and complex structures, not only is this expensive but distortion and creep leading to shape change can occur, making this approach unrealistic. It has also been found in the research reviewed here that even this procedure is not effective for some steels; lost toughness is not always recovered during stress relief, probably due to other reactions and microstructural changes occurring during heating in this temperature range for extended periods of time, i.e., hours.

At the present time, although each of the steps outlined above can help to control or mitigate the effects of strain aging, there is no one procedure that will guarantee there will be no toughness loss due to strain or subsequent aging. One approach that is effective is to select steels that have sufficiently high toughness and low transition temperatures that losses in toughness by strain aging do not have a significant effect on service performance. The High Performance Steels that are designed with toughness levels that greatly exceed service requirements meet this requirement.

2.0 HISTORICAL DATA ON STRAIN AGING IN LOW CARBON STEELS.

2.1 Overview of Research Literature.

The effect of mechanical (cold) strain either with or without subsequent aging, especially the effect of toughness, was not experimentally explored until the late 1940's, and even then the emphasis was on steels used in ships, pipelines and storage tanks rather than those used in structures. Another driving force promoting toughness research and control was, as the result of some brittle fractures, the early adoption of Charpy "V" notch (CVN) impact toughness standards in the American Society for Mechanical Engineers (ASME) Boiler and Pressure Vessel Code for some pressure containing components. Additional failures of some pipelines and ship hulls created a heightened awareness of the need to incorporate fracture control plans requiring stricter toughness requirements into codes governing the manufacture of these structures. Creation of a rational fracture control plan requiring specified CVN toughness levels in bridges was not to become part of the American Society of Highway Officials (AASHO) steel bridge code until about 25 years later. A great deal of the research on strain aging used in the ASME Code was done in the then Department of Metallurgy at Lehigh University under the sponsorship of the Pressure Vessel Research Committee of the Welding Research Council, a body charged with providing research information for the ASME Code Committees. Their support of this research and other toughness related studies at Lehigh spanned 40 years.

European and Asian research followed the same pattern; research on the toughness was first addressed by professional bodies and agencies involved in the manufacture and operation of ships, pressure vessels and pipelines. The worldwide adoption of nuclear energy for power generation created a heightened concern for safety from fast fracture in nuclear pressure vessels and promoted corresponding research on strain aging both here and abroad. The results of these studies began to be applied to many new structures beside pressure vessels, notable examples being off-shore structures, liquefied gas storage containers and casks for nuclear waste materials transport. The bridge industry adopted toughness control much later in time, and thus has a shorter strain aging research history.

While the initial work was done on steels now obsolete or not intended for structural applications, much of the data obtained is still relevant since the response of the older steels has now been found to be applicable to more modern ones and to structural steels as well. Indeed, in the 1980's some structural steels were added to the pressure vessel steel programs because of an increasing understanding that structural supports were as important to the safe performance of many pressure and storage vessels, for example nuclear reactors, as the nuclear pressure vessels themselves.

It is interesting to note that toughness requirements are not yet used in many building structures. The exceptions are cases where bitter experience with fractures has highlighted the liability of low toughness steels or welds and the need for toughness control, at least in these situations. Examples of these experiences are fractures in roof members fabricated by the welding heavy-section wide-flange rolled sections and cracking of beam-to-column welded SMRF connections under earthquake loading.

The intent of this literature review is to summarize the procedures, data, and conclusions from research papers found in the literature that relate to possible strain aging in structural steels. In order to focus the review on information most relevant to strain aging in structural steels, limitations have been placed on the data which is presented in the tables extracted from investigations reviewed: (1) the investigations are those which had sufficient mechanical property data, especially toughness data, to provide meaningful trends and conclusions and (2) data for steels with applications unrelated to normal structural applications, for example nuclear or cryogenic service, are not included. There are a number of papers which appear in the bibliography that are not reviewed here because they do not meet the above criteria. The data in the tables in this review are listed in customary US units regardless of the units used by the original authors and are arranged in a manner that allows cross-comparison between investigations as much as possible.

2.2 Lehigh University Research on Strain Aging in Steels.

Because there was a extensive series of related research investigations done at Lehigh University from the 1940's to 1980's, these are reviewed and discussed first. By the 1980's there was a substantial number of strain aging studies on steels relevant to bridge structures by laboratories around the world as well. These will be reviewed in the following section of this report.

A. Osborn, Scotchbrook Stout and Johnson (1949

Some of the earliest work done at Lehigh University was published by C. J. Osborn, A. F. Scotchbrook, R. D. Stout and B. G. Johnson in The Welding Journal Research Supplement, v. 14. no. 8 pp. 337s-353s, 1949[5]. It consisted of both tension and CVN toughness tests on two steels, ASTM A70 and ASTM A201. Neither of these are listed as ASTM steels today. The most relevant of these materials is the A201, a silicon deoxidized steel. It had a yield strength of 32 ksi and a tensile strength of 63 ksi, similar to ASTM A7. Its elongation was 40%. The steel was given cold strains of 1%, 5%, and 10% after which its strength and CVN toughness were measured. Subsequent heat treatments for one hour at 500^{o}F, 800^{o}F, and 1100^{o}F were applied and properties measured again. Charpy V notch 40 ft-lb impact transition temperatures were measured for the same treatments. The composition of the A201steel and the results of the tests are seen in Table 1.

Table 1. Results of research of Osborn, Scotchbrook, Stout and Johnson

A. Composition of the A201 Steel (%)

C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Ti	V	Nb	Al	N
0.15	0.53	0.020	0.025	0.19	0.05	0.04	0.01	0.08	-	-	-	0.026	0.003

B. Tensile properties of A201 steel strained 1%, 5% and 10% and aged 1 hr at 500^{o}F, 800^{o}F and 1150^{o}F

Yield Strength (ksi)

Condition\ Strain	0%	1%	5%	10%
As Received	32	32	58	69
Aged at 500^{o}F	30	39	58	69
Aged at 800^{o}F	-	41	56	63
Aged at 1150^{o}F	32	36	44	47

Tensile Strength (ksi)

Condition\ Strain	0%	1%	5%	10%
As Received	63	59	66	72
Aged at 500^{o}F	62	61	67	75
Aged at 800^{o}F	-	62	68	76
Aged at 1150^{o}F	61	61	65	67

Tensile Elongation (%)

Condition\ Strain	0%	1%	5%	10%
As Received	40	38	29	23
Aged at 500^{o}F	40	41	28	24
Aged at 800^{o}F	-	37	33	25
Aged at 1150^{o}F	37	38	34	32

C. Charpy impact toughness of A201 steel strained 1%, 5%, and 10% and aged 1 hr at 500^{o}F, 800^{o}F and 1150^{o}F, 40 ft-lb CVN transition temperature (^{o}F)

Condition\ Strain	0%	1%	5%	10%
As received	15	40	70	80
Aged at 500^{o}F	40	40	85	130
Aged at 800^{o}F	-	40	80	100
Aged at 1150^{o}F	40	25	50	65

The yield strength of the A201 increased little after 1% strain but increased from 32 ksi to 58 ksi after 5% strain, reaching 69 ksi at 10% strain, an increase of 215%. The tensile strength of the A201 increased much less, from 63 ksi to 72 ksi when strained 10%, an increase of only 14%. Its elongation at 10% strain decreased from 40% to 23%, a reduction by 43%. The CVN 40 ft-lb transition temperature of the A201 shifted from 15^{o}F to 80^{o}F. Aging one hour at 500^{o}F had only a modest effect on strength and ductility but increased the 40 ft-lb CVN transition temperature to 130^{o}F, 115^{o}F above its initial value and into a range where brittle fracture of a pressure vessel (or a bridge) in ambient service could be a real possibility. Aging at 800^{o}F had only a slightly smaller effect than aging at 500^{o}F.

Heating for one hour at 1100°F restored the steel's tensile strength and ductility back toward its original values but the yield strength remained elevated by over 50% and its CVN 40 ft-lb transition temperature was still at 65°F, 50°F above its original value.

The reason this seminal 55 year old study is included in this review is that it demonstrates trends observed in much of the subsequent research done both at Lehigh and elsewhere. Both straining and aging, especially in the 500°F to 800°F range, can significantly elevate the yield strength of a pressure vessel (or structural) steel and decrease its CVN toughness. Tensile strength and tensile ductility are less affected. Post-strain stress relief at high temperatures may not fully restore the yield strength and toughness to their initial levels.

Although these trends were established quite early, as described above, the increasing understanding of the importance of notch toughness to the performance of structures, first in ships and critical pressure vessels but later to bridges and some buildings, made the possibility of strain aging degradation of toughness a topic of continuing research. As a result, strain aging research programs were performed at Lehigh University at approximately ten-year intervals over the next 50 years.

B. Rubin, Gross and Stout (1959)

The next Lehigh University program, published by A. I. Rubin, J. H. Gross and R. D. Stout in The Welding Journal Research Supplement, v. 24, no. 4, pp. 182s-187s, 1959[6], explored the effect of strain aging on nine steels either being used in, or intended for, pressure vessel service. Of these, three were similar to steels used in structures or intended for use in structures. The test plan was similar to that employed ten years earlier. The steels were cold strained 5% and then subjected to aging for 1 hour at 500°F, 700°F, 900°F and 1150°F or 1200°F. Tensile properties and CVN toughnesses were measured. Although data for only the three of the steels most relevant to bridge structures are discussed here, the same trends were observed in all nine steels. The heat treatments given to these steels prior the tests were non-standard. Plates approximately ½ in thick were used and were given one or two heat treatments, either rapidly (oil) quenched or slow cooled from the austenitizing temperature (1650°F) followed by a tempering at 1150°F or 1200°F. These two treatments simulated the commercial heat treatment of either a one or four inch thick plate. Unlike the steel in the previous study, the some of the ones studied here were aluminum- silicon deoxidized, i.e., they were fully killed. This means that the free nitrogen level (not measured) should therefore have been combined with aluminum and reduced, reducing the strain aging effects as well. The compositions and results of the tests for the three relevant steels are seen in Table 2..

Table 2. Results of Research of Rubin, Gross and Stout

A. Composition of the A212, HY65 and T-1 Steels (%)

Steel	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Ti	V	B
A212	0.28	0.70	0.010	0.021	0.24	-	-	-	-	-	-	-
HY65	0.12	0.48	0.013	0.032	0.21	2.16	-	0.39	0.70	-	-	-
T-1	0.15	0.93	0.015	0.022	0.27	0.89	0.48	0.44	-	-	0.06	0.003

B. Tensile properties A212, HY65 and T-1 steels strained 5% and aged 1 hr at 500^oF, 700^oF, 900^oF and 1150/1200^oF

Yield Strength (ksi)

Steel\Condition	Base	5% Str.	5% +500	5% + 700	5% + 900	5%+11/1200
A212	49	71	81	74	64	55
HY65	90	110	120	116	112	106
T-1	126	135	150	147	138	119

Tensile Strength (ksi)

Steel\Condition	Base	5% Str.	5% +500	5% +700	5% +900	5%+11/1200
A212	77	82	86	86	82	79
HY65	104	110	120	116	112	106
T-1	131	136	150	147	139	124

Tensile Elongation (%)

Steel\Condition	Base	5% Str.	5% + 500	5% + 700	5% + 900	5%+11/1200
A212	30	22	21	21	24	30
HY65	25	19	17	18	22	23
T-1	20	18	14	15	17	21

C. Charpy impact toughness of A212, HY65, and T-1 steels strained 5% and aged 1 hr at 500^oF, 700^oF, 900^oF and 1150/1200^oF, 15 ft-lb transition temperature (^oF)

Steel\Condition	Base	5%Str.	5% + 500	5% + 700	5% + 900	5%+11/1200
A212	22	36	92	78	26	26
HY65	-88	-42	-20	-65	-78	-28
T-1	-225	-170	-148	-170	-164	-180

The steel designated ASTM A212 is similar to ASTM A441 of the same era, while the steel designated T-1 is an early form of ASTM A514F/A517F (ASTM A709 Gr. 100). The steel designated HY65 is a nickel (2%) – copper (0.7%) steel developed by the U.S. Navy for use in submarines. It is included in this paper because it is similar in many ways to HPS 100W. The results are consistent regardless of steel composition or heat treatment. The initial 5% strain increases the yield strength substantially, but in proportion to the base strength level, 45% in the A212, 22% in the HY65 and 8% in the T-1. The high base strength of the T-1 is undoubtedly due to its high alloy content and the rapid cooling treatment. The tensile strengths of the steels are also increased, but to a lesser extent, and their tensile ductilities are decreased.

Aging heat treatments at 500°F elevate yield and tensile strength an additional increment, 20% for A212, 22% for HY65 and 10% for T-1. The decreases in tensile ductility were smaller but still substantial. Aging treatments at 700°F and 900°F result in elevations in strength and reductions in ductility with aging but are not as substantial as at 500°F. Treatments at 1150°F reduce strain induced strength increases and ductility decreases in the A212 and HY65, but not back to their initial levels. Only the T-1 steel, which was treated at 1200°F, returned to strength and ductility levels at or below the original ones.

The focus of the investigation was intended to be on the toughness response of the steels, and the results were consistent between steels and consistent with the 1949 study. As seen in Table 2, the initial CVN 15 ft-lb toughnesses of the steels varied substantially, with A212 being a level typical of structural steels (22°F), while HY-65 (-88°F) and T-1 (-225°F) were extremely tough even for pressure vessel steels. However, in spite of the deoxidation practice used which might have reduced their free nitrogen content, all of the steels had upward shifts in their CVN 15 ft-lb transition temperatures, both after straining and again after aging. The greatest shift occurred after straining and aging at 500°F, between 68°F and 78°F, depending on the steel. Moreover, in no case did the 1150°F and 1200°F treatments restore toughnesses to their original values.

The results of this research are similar to those obtained from the initial study but important additional information was developed. These tests demonstrated that changing steel microstructure over a wide range will not eliminate the strain aging susceptibility of the steel. The microstructure of the A212 steel is pearlite and ferrite while that of the T-1 is almost entirely tempered martensite. The HY-65 steel is a fine aggregation of ferrite and carbide with some possible Ni-Cu precipitates. All three are strain aging susceptible. Deoxidation practice did not eliminate strain aging but may have reduced its effects. The tests confirmed that aging at 500°F was more injurious to toughness than aging at 700°F or 900°F. They also suggested that strength level may have some effect on the extent of the property shifts. In terms of percentage change, the effects seem to be smaller for the higher strength steels. However, because the martensitic steel, T-1, is also the strongest, the effect of strength on strain aging susceptibility cannot be definitively separated from its microstructure. Finally, these results also demonstrate that, by selecting steels with low initial transition temperatures, the effects of strain aging can be mitigated since ambient temperature toughness may still be adequate even if strain aging has occurred.

C. Succop. Pense and Stout (1970)

A third Lehigh University study of strain aging was published by L. N. Succop, A. W. Pense and R. D. Stout in The Welding Journal Research Supplement V. 35, no. 8, pp. 354s-364s, 1970[7]. The focus of the study was multiple aging treatments following relatively low strains (1.25%) performed at 200°F. It included valid fracture toughness tests in addition to the usual tensile and CVN toughness tests. The test steels were ASTM A533, a manganese-nickel-molybdenum pressure-vessel steel and ASTM A516, a pressure-vessel steel similar to an ASTM A709 Gr. 50. Only the A516 steel data are presented in this review but represent the A533 steel as well.

The use of a relatively low plastic strain level, 1.25%, applied at a temperature of 200°F, was selected because this replicates the conditions when a fabricated pressure vessel is given the final proof test required by the ASME Boiler and Pressure Vessel Code.

The final proof test is done by pressurizing the vessel to 110% of its rated capacity and is typically done with heated water to prevent potential brittle fracture. The 1.25% plastic strain is typical of that which occurs at some locations in the vessel during this process and the 200^{o}F temperature is typical of the heated water. Since some of these vessels may be used in service at temperatures up to 500^{o}F after proof testing, strain aging in these vessels can occur either due to the 200^{o}F strain, or due to subsequent service. The aging ("service") temperatures used were 400^{o}F, 500^{o}F and 650^{o}F and the aging times used were 1000 hr and 3000 hr.

A final series of specimens were given a heat treatment at 1100^{o}F for 8 hr after strain aging at 650^{o}F to simulate the stress relief treatment sometimes given to pressure vessels after a period of service. While some of the parameters used in this research are not directly relevant to structural or bridge service, as will be discussed later, they clarify strain aging behavior that may be relevant to bridge materials under some circumstances.

The composition of the ASTM A516 steel and the data resulting from this research are shown in Table 3.

Table 3. Results of Research of Succop, Pense and Stout

A. Composition of A516 Grade 70 steel (%)

C	Mn	P	S	Si	Ni	Cr	Mo	Cu	V/Ti	Al
O.23	0.97	0.010	0.020	0.25	0.09	0.05	0.02	0.25	-	0.025

B. Tensile properties of A516 steel strained 1.25% at 200^{o}F and aged at 400^{o}F, 500^{o}F and 650^{o}F for 1000 hr[1] and for 3000 hr [2]

Property\ Condition	Base	1.25% Str.	Str.+400	Str.+500[1]	Str.+650[1]	+500[2]	+650[2]
Yield Strength (ksi)	48	52	58	56	57	86	68
Tensile Strength (ksi)	77	78	80	80	81	91	84
Elongation (%)	34	31	31	32	34	24	27

C. Charpy impact toughness of A516 steel strained 1.25% at 200^{o}F and aged at 400^{o}F, 500^{o}F and 650^{o}F for 1000 hr[1] and for 3000 hr[2]. Some specimens aged at 650^{o}F for 1000 hr[1] and 3000 hr[2]: also stress relieved 8 hr at 1100^{o}F, 15ft-lb transition temperature (^{o}F)

Base	1.25% Str.	Str.+400	Str.+500[1]	Str.+650[1]	+500[2]	+650[2]	SR 1100[1]	SR 1100[2]
-63	-41	-31	-32	-33	37	20	-28	-18

D. Fracture toughness at -250^{o}F (Ksi√in)

Base Value	5% Strain @ 200oF 650oF for 1000 hr	5% Strain @ 200oF 650oF for 3000 hr	5%Strain@200oF,650oF, 3000 hr, 1100oF, 8 hr
Av. 42	Av. 35	Av. 38	Av. 35

The small level of strain at 200°F (1.25%) had only a modest effect on the tensile
22°F. Aging at 400°F, 500°F or 650°F for 1000 hr produced a second upward shift of about 10°F, however aging for 3000 hr, typical of some pressure vessel service, produced an additional significant upward shift of 69°F if aging was at 500°F and 53°F if at 650°F. For material strained and aged at 500°F for 3000 hr the total upward shift was 99°F, from -63°F to 37°F. Stress relieving treatments at 1100°F decreased the transition temperatures again but did not restore them to their initial values; there was a residual transition temperature increase of 30°F to 45°F.

Yield and tensile strength rose in proportion to the toughness change, with yield strength of the material aged at 500°F for 3000 hr increasing by 77% and the tensile strength increasing by 19%. Material aged at other temperatures had smaller increases. As might be expected, tensile ductility decreased during straining and aging, the ductility declining after aging at 500°F for 3000 hr by about 30%.

An interesting feature of this investigation was a study of changes in plane strain fracture toughness as a result of these strain aging treatments. At the time these tests were run, elastic-plastic fracture toughness tests had not been developed, therefore all tests were run at -250°F, a temperature low enough to ensure plane strain (K_{Ic}) behavior in the specimens. The results of these tests are shown in Table 3. As can be seen, the base fracture toughness of the A516 steel was 42 ksi√in. After the 1.25% plastic strain at 200°F followed by aging 1000 hr or 3000 hr at 650°F, the fracture toughness decreased to 35-38 ksi√in. Specimens given stress relief at 1100°F for 12 hr still had a fracture toughness of 35 ksi√in, about 17% below its initial value. While the tests were conducted at a low temperature, they show that a loss in static fracture toughness can occur through strain aging and that recovery of toughness may not occur when high temperature stress relief treatments are applied. This result was later confirmed by others.

The findings of this study reinforce many of those from previous ones, for example identifying 500°F to 650°F range as the most deleterious aging temperature and confirming that post strain aging stress relief does not restore toughness. The new information developed was that even low levels of strain can be deleterious if the aging cycle is long enough. They also demonstrated that strain aging can effect plane strain fracture toughness. From the practical viewpoint, however, the long time aging cycles used in this investigation are not relevant to structural steel service and suggests that low level strains (1.25%) will not be significantly deleterious to their toughness.

D. Herman, Erazo, DePatto, Sekizawa, and Pense (1987)

The fourth strain aging study by Lehigh University researchers was published by W. A. Herman, M. A. Erazo, L. R. DePatto, M. Sekizawa, and A. W. Pense in Welding Research Council Bulletin no. 322, pp. 1-13, 1987[8]. This study was aimed at a series of structural as well as pressure vessel steels including ASTM A572 and A588, which are included in the current ASTM A709 Gr. 50 and Gr. 50W specifications. For this reason it must be considered the most directly applicably to modern structural and bridge steels. This review will focus on these bridge steels. Each of the steels was 1.5in thick and was tested in the as-rolled and the normalized condition. Normalizing is a heat treatment at 1150°F following rolling that produces a fine grained microstructure which usually results in improved toughness.

The yield and tensile strengths, tensile ductilities and 25ft-lb CVN toughnesses were measured both before and after strain aging treatments. The cold stain levels applied to the steels were 2%, 5% and 10% while aging as at 700^{o}F for 10 hr. Stress relieving heat treatments of 2 hr and 10 hr at 1150^{o}F were applied after straining and aging treatments.

A unique condition of the study was the fact that the specimens were tested in the transverse orientation. For the as-rolled steels (which do not normally receive much cross rolling) this results in an especially large difference in the base level CVN 25ft-lb transition temperature between the as-rolled and normalized conditions. The as-rolled condition base value transition temperatures are, on average, 118^{o}F higher than normalized ones and are in the 70^{o}F to 100^{o}F range. . Because of the way they were processed and tested, the toughness levels indicated for the as-rolled materials must be considered "worst case" rather than typical. The compositions of the steels and the data obtained in this research are in Table 4.

Table 4. Results of Research of Herman, Erazo, DePatto, Sekizawa, and Pense

A. Compositions of the A588A, A588B and A572(2) steels (%)

Steel	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	V	Al	N
A588A	0.14	1.03	0.012	0.020	0.45	0.20	0.60	0.05	0.31	0.072	0.030	0.011
A588B	0.13	1.17	0.020	0.017	0.38	0.21	0.44	-	0.31	0.041	0.048	0.012
A572(2)	0.16	1.19	0.010	0.023	0.23	0.19	0.12	-	0.27	0.040	0.040	-

B. Tensile properties of A588A, A588B and A572(2) steels strained 2%, 5% and 10% and aged 10 hr at 700^{o}F: also stress relieved at 1100^{o}F for 2 hr and 10 hr.

Yield Strength (ksi)

Steel and Condition	Base	Strain 2%	Strain 5%	Strain 10%	2% Str +700^o	5% Str +700^o	10% Str +700^o	5% Str + 2+1100^o	5%Str + 10+1100^o
A588A AR	56	-	83	-	-	87	-	68	67
A588B AR	55	74	81	87	73	83	88	60	59
A572·2 AR	54	-	76	-	-	78	-	62	60
A588A N	55	-	72	-	-	80	-	66	65
A588B N	48	53	70	80	59	76	85	60	59
A572·2 N	49	-	75	-	-	68	-	55	55

Tensile Strength (ksi)

Steel and Condition	Base	Strain 2%	Strain 5%	Strain 10%	2% Str +700^o	5% Str +700^o	10% Str +700^o	5% Str + 2+1100^o	5% Str + 10+1100^o
A588A AR	86	-	91	-	-	95	-	91	89
A588B AR	82	84	85	89	87	89	91	84	85
A572·2 AR	77	-	82	-	-	85	-	81	73
A588A N	79	-	83	-	-	88	-	83	86
A588B N	72	74	79	87	76	86	89	79	78
A572·2 N	71	-	75	-	-	80	-	75	75

C. Charpy impact toughness of A588A, A588B an A572(2) steels strained 2%, 5%, and 10% and aged 10 hr at 700oF: also stress relieved at 1100oF for 2hr and 10 hr, 25 ft-lb transition temperature (^{o}F)

Steel and Condition	Base	Strain 2%	Strain 5%	Strain 10%	2% Str +700^{o}	5% Str +700^{o}	10% Str + 700^{o}	5% Str + 2+ 1100^{o}	5 % Str + 10 + 1100^{o}
A588A AR	73	-	143	-	-	156	-	145	138
A588B AR	71	177	181	197	177	199	212	181	181
A572·2 AR	98	-	138	-	-	175	-	150	168
A588A N	-27	-	13	-	-	43	-	50	50
A588B N	-53	-3	-3	40	14	39	69	26	32
A572·2 N	-60	-	-29	-	-	17	-	14	14

The base level tensile properties of the steels indicate that the as-rolled yield and tensile strengths of the steels are a little higher than the normalized condition ones and the 25ft-lb CVN transition temperatures, as described above, are significantly higher for the as-rolled condition.

As in previous studies, the yield and tensile strengths increase regularly with strain level as do the transition temperatures. Only the A588 B has a complete set of strain levels but these data confirm previous research that as strain level prior to aging increases, yield strength, and to a lesser extent, tensile strength, increases. In the case of yield strength, the increase can be 40% at 5% strain, about 60% at 10% strain. With aging at 700^{o}F, modest additional strength increases, up to 12%, occur. As expected, the tensile strength increases are smaller, about 5% - 10% for 5% strain, and about 10% - 20% for 10% strain. Aging at 700^{o}F increases tensile strength by about another 2% - 5%. Stress relief treatments again decrease yield and tensile strength but not to their original level.

The CVN 25 ft-lb transition temperatures increase with straining and aging, following the trends of yield strength, but are very large, over 90^{o}F for 10% strain and over 120^{o}F for 10% strain followed by aging at 700^{o}F. The stress relieving treatments for either 2 hr or 10 hr have only a modest effect on restoring toughness to its initial level. Even though the normalized steels have low initial transition temperatures, the final transition temperatures after straining or aging are in the ambient range.

The results of this investigation confirm trends of previous ones but are the first ones to include steels commonly used for bridges. It also shows potentially substantial shifts in transition temperature for relatively low strain levels, 2%, larger than those observed in previous studies unless long aging times follow the straining. Long aging times are not relevant to bridge applications but strains in the range of 2% are. An interesting aspect of this investigation is, based on their aluminum and nitrogen contents, these are killed steels and the nitrogen present should be at substantially combined with the aluminum, especially after the normalizing treatment. On the whole, however, there are no significant differences in strain aging response between the as-rolled and normalized conditions for the steels. In fact, the transition temperature increases with straining and aging mirror those in previous studies.

2.3 International strain aging research in the 1980's and 1990's

A. Khristenko (1987)

A strain aging study using low strain levels was published by I. N. Khristenko in Metallovedenie I Termicheskaya Obrabotka Metallov no.2 pp.19-20, in 1987[9]. This study was done on thin section steel specimens and the strain levels used were 2.5%, 5%, 7.5%, and 10%. The strain was performed in 2.5% increments each followed by aging at 480°F for 0.5 hr. One and two cycles of strain were applied.The results are given in Table 5.

Table 5. Results of Research of Khristenko

The effect of cycles strain and aging on the 50 J/cm^2 transition temperature of St3sp steel; a cycle consisted of 4 steps of 2.5% strain each followed by aging at 480°F for 0.5 hr (°F)

Step Cycles + Strain	Base Value	Step 1 2.5% Strain	Step 2 5% Strain	Step 3 7.5% Strain	Step 4 10% Strain
1st 2.5 - 10%	14	65	77	84	84
2nd 12.5 – 20%	-	-	95	104	114

Using a 50J/cm^2 impact energy transition temperature, the investigators demonstrated that low levels of strain, 2.5%, were not deleterious but repeated cycles of strain (x2, x3, and x4) caused increases in transition temperature. Above 5% strain, however, the effect began to level off and was constant at 10% strain. The 50J/cm^2 transition temperature (made on non-standard specimens) increased from 14°F to 65°F with the first 2.5% strain followed by aging at 480°F but increased to 73°F with the second cycle and reached 84°F at 4 cycles (10% strain and 2 hr aging). A second round of strain aging cycles, adding a second total of 10% strain and 2 hr aging, increased the transition temperature above the first cycle by 29°F for a total of 99°F. These transition temperature shifts are consistent those observed in the previous studies for high levels of strain.

B. Sorsa and Vierros

It was also in 1987 that another parallel study was published by Ilkka Sorsa and Paula Vierros in the Scandinavian Journal of Metallurgy, V16, pp. 134-139[10]. This research, performed in the Rautaruukki Oy Raahe Steel Works and the Imatran Voima Oy Central Laboratory in Finland, was focused on the deterioration of ductility and toughness of structural steels due to cold forming. Cold deformation between 5% and 26% was applied. Of particular interest to corrugated web bridge fabrication was the additional use of bending in radiuses of 1 x t and 2 x t to induce cold strain. Four steels were studied; (1) a normalized C-Mn steel, (2) a hot rolled C-Mn-Si-C steel, (3) a controlled rolled microalloyed steel and (4) a very low carbon microalloyed steel made with thermo-mechanically controlled processing (TMCP). Thicknesses ranged from 0.3in to 0.6in. The yield strengths ranged from 42 ksi to 61 ksi and the tensile strengths from 61 ksi to 79 ksi while tensile ductilities were from 31% to 36%.

The initial CVN 20ft-lb transition temperatures for the first three steels were between - 37°F and -58°F while that of the TMCP steel was -140°F. The testing sequence was complex and included a number of straining and single and multiple aging cycles. The strain and aging cycles (aging was only applied to steel 1) and major findings are summarized in Table 6.

Table 6. Results of Research of Sorsa and Vierros

A. Compositions of the steels (%)

Steel	C	Mn	P	S	Si	Ni	Cr	Cu	Nb	Al	N
1 C-Mn	0.11	0.83	0.019	0.029	0.21	-	-	-	-	0.047	0.006
2 C-Mn	0.16	1.40	0.015	0.012	0.41	-	0.21	0.04	-	0.001	0.006
3 C-Mn-Nb	0.11	1.08	0.015	0.010	0.18	0.03	0.03	0.01	0.028	0.035	0.007
4 C-Mn-Mo	0.03	0.37	0.003	0.009	0.05	0.13	0.07	0.08	0.015	0.044	0.013

B. Tensile properties of the steels strained 5%, 10%, 18%, and 26%

Yield Strength (ksi)

Steel \ Condition	Base	5% Strain	10% Strain	18% Strain	26% Strain
1 Hot Roll + Norm	42	57	65	75	83
2 Hot Roll	48	-	91	-	108
3 Controlled Roll	61	75	82	90	93
4 TMCP Treated	57	-	69	-	86

Tensile Strength (ksi)

Steel \ Condition	Base	5% Strain	10% Strain	18% Strain	26% Strain
1 Hot Roll + Norm	61	64	68	76	83
2 Hot Roll	79	-	92	-	112
3 Controlled Roll	74	77	82	93	96
4 TMCP Treated	68	-	74	-	-

Tensile Elongation (%)

Steel \ Condition	Base	5% Strain	10% Strain	18% Strain	26% Strain
1 Hot Roll + Norm	36	29	24	12	11
2 Hot Roll	31	-	15	13	10
3 Controlled Roll	31	27	18	14	9
4 TMCP Treated	31	-	17	13	10

C. Charpy impact toughness of the steels monotonic strain 5%, 10%, 18 and 26%; also bending strain of R/t = 1 and R/t = 2. 15 ft-lb transition temperature, (^{o}F)

Steel \ Condition	Base	5% Strain	10% Strain	18% Strain	26% Strain	R/t 1	R/t 2
1 Hot Roll + Norm	-58	-30	-13	14	8	-19	-40
2 Hot Roll	-37	-	23	-	28	-	-
3 Controlled Roll	-61	-30	-22	-20	-43	-8	-36
4 TMCP Treated	-140	-	-60	-	-52	-63	-

As might be expected considering the strain levels used, the yield strengths increased substantially. This study provided higher strains than employed in previous ones, up to 26% and at that strain the yield strengths of the normalized and hot rolled steels were increased by 100% or more and the yield strengths of the controlled rolled and TMCP steels were increased by about 50%. For strains of 10%, the controlled rolled and TMCP steels yield strength increases were between 20% and 30%, less that the 50% to 90% increase recorded by the others. Consistent with previous studies, the tensile strength increases are less than those of the yield strengths, however, at 26% strain, the tensile strength increased between 30% and 42%. At this strain level the yield and tensile strengths are about the same and elongations drop to as low as 9%.

The toughnesses of the steels followed the same trends as the yield points, however, for the two steels for which the 20 ft-lb CVN transition temperatures were measured after 26% strain, the loss in toughness is the greatest at 18% and it recovers somewhat at 26%. The total increase in transition temperature between the base condition and 10% strain is between about 40^{o}F and 50^{o}F for all but the TMCP steel where it is about 80^{o}F. However, this steel had a very low initial transition temperature, about -140^{o}F. A special feature of this study is a comparison of transition temperature shifts between specimens given uniform strain and those given bending strain. This comparison is also seen in Table 6. Bending applied to the normalized and controlled rolled steels (which are both 0.6in thick) to an R/t of 1, had the same effect on transition temperature as something between 5% and 10% uniform strain. Bending the same steels to an R/t of 2 had an effect somewhat less than that of 5% uniform strain.

The aging experiments were done only on hot rolled and normalized steel no. 1 and employed temperatures higher than used in previous research studies, up to 1300^{o}F. Aging at 480^{o}F, which was the most sensitive aging temperature, increased the transition temperature of the steel with 18% strain by 62^{o}F for a total of 106^{o}F. Other combinations of strain and aging resulted in smaller transition temperature increases. Consistent with other studies, aging at 930^{o}F reduced the toughness loss from straining while aging at 1300^{o}F restored most of, but not all of, the original toughness.

The compositions listed for the steels used in the study included nitrogen and aluminum content. The TMCP steel, no. 4, had the highest nitrogen and aluminum contents of the group and also had the largest increase in transition temperature with strain. Steel no. 1, with a low nitrogen and high aluminum content, was still sensitive to straining and aging.

An additional important aspect of this research not included in these tables was an experimental study of the effect of strain aging on fatigue behavior. The researchers determined that strain aging did not change fatigue behavior of beams with welded attachments made from strain aged steel plates. They concluded that this was because initiation of fatigue cracks in the beams is controlled by the geometry of the welded connections, not the mechanical properties of the plates. Parallel fracture mechanics studies on several of the steels demonstrated that their fatigue crack growth rates were not materially altered by strain aging of the samples prior to testing.

The Sorsa and Vierros paper reviewed above included a TMCP steel in its strain aging investigation, the first found in the literature.

C. Yurioka (1994)

A second study to include strain aging in TMCP steels was performed by N. Yurioka, a researcher in the Japanese Welding and Joining Centre, and published in 1994 in Welding in the World (International Institute of Welding Document 1251-94)[11]. The paper is a comprehensive study of the history, composition, heat treatment and properties of TMCP steels. A part of the research was a study of the effect of strain aging on the fracture appearance transition temperature of TMCP steels compared to conventional ones. Yurioka studied transition temperature changes in as-rolled, controlled rolled and TMCP steels which were strained 5% and aged at 480^{o}F for 1hr. He concluded that the TMCP steel responded to strain aging to about the same extent as the other steels and their primary advantage is that they can offset toughness losses due to strain aging by their much lower initial transition temperature. The same could be concluded from the work by Sorsa and Vierros cited above.

D. Dobi, Kocak, Petrovski and Hanus (1994)

A similar program focused on a 0.8 in thick TMCP steel was also published in 1994 in The Proceedings of the 13th International Conference on Offshore Mechanics and Arctic Engineering[12] 1994. pp. 315-325, by D. Dobi, M. Kocak, and B. Petrovski of the GKSS Research Centre in Geesthacht and F. Hanus of the Dillingen Hutte AG Welding Research Laboratory in Saar, Germany. The reason for the research was increased interest in TMCP material for use in offshore structures because of their favorable cost in relation to their strength and weldability. The investigation examined the effect of strain and stress relief at 990^{o}F on the strength and toughness of the steel. There was no intermediate temperature aging treatment. An unusual aspect of the research was measurement of the effects of strain on CTOD crack toughness. This test typically uses a sharp notch in a slow loaded bend specimen. The crack root strain is calculated from the opening of the crack mouth during the test. When fracture occurs, the Crack Tip Opening Displacement is measured. Fracture control criteria for offshore structures often use the CTOD toughness measurement. The results of this research are seen in Table 7.

Table 7. Results of Research of Dobi, Kocak, Petrovski and Hanus

A. Composition of the 450 MPa yield strength TMCP steel (%)

C	Mn	P	S	Si	Ni	Cr	Mo	Cu	V	Nb	Al	N
0.09	1.34	0.013	0.001	0.34	0.040	0.025	0.009	0.014	0.001	0.031	0.044	0.004

B. Tensile properties of the 450 MPa steel strained 0%, 5% and 10%, and strained 0%, 5% and 10% followed by aging at 990^{o}F for 1 hr.

Property \ Condition	0% Strain	5% Strain	10% Strain	0%+990^o	5%+990^o	10%+990^o
Yield Strength (ksi)	66	78	88	60	70	73
Tensile Strength (ksi)	79	82	88	76	82	83
Elongation (%)	29	25	19	30	30	28

C. Charpy impact toughness and CTOD values for the 450 MPa steel strained 0%, 5%, and10%, and strained 0%, 5%, 10% and aged at 990^{o}F for 1 hr. 75 ft-lb transition temperature.

Property \ Condition	0% Strain	5% Strain	10% Strain	0%+990o	5%+990o	10%+990o
Transition Temp (oF)	-135	-96	-	-135	-119	-87
CTOD (mm)	1.3	0.8	0.5	1.4	0.9	0.8

The yield strength of the steel increased by 18% for 5% strain and by 33% for 10% strain. The tensile strength increases were smaller. Tensile ductility also decreased regularly with strain. The 75 ft-lb CVN transition temperature increased 39^{o}F for 5% strain while the CTOD toughness declined from 1.3mm to 0.5mm. Stress relief at 990^{o}F had the effect of ameliorating the strain aging changes but none of the properties except tensile elongation returned to their prestrained values. Thus this research confirmed what had observed in prior research on a TMCP steel, they are also susceptible to strain aging, however their low initial transition temperature precludes brittle fractures under most, if not all, structural applications even with substantial cold strain.

E. Ule, Vojodic-Gvardjanic and Lovrecic-Sarzin

A paper also reporting an analysis of the effects of strain aging on 9 steels with different processing and microstructure was published by B. Ule, J. Vojodic-Gvardjancic, and M. Lovrecic-Sarazin in the Canadian Metallurgical Quarterly, V. 35, no. 2, pp. 159-168 (1996)[13]. The steels were strained by a 10% cold reduction in thickness followed by aging at 480^{o}F for 0.5 hr. The use of cold reduction in thickness rather than cold tensile strain is a unique aspect of this investigation. The results of strain aging on the yield strength and the 30 ft-lb transition temperature of the 9 steels tested, along with their compositions, thicknesses and heat treatments indicated, are seen in Table 8.

Table 8. Results of Research of Ule, Vojvodic-Gvardjancic and Lovrecic-Sarazin

A Compositions of the steels (%)

Steel and Treatment	C	Mn	P	S	Si	Ni	Cr	Mo	V	Nb	Al	N
1 H R, AC	0.19	1.49	0.013	0.005	0.42	0.10	0.13	0.04	0.07	0.05	0.087	0.006
2 H R, AC	0.14	1.53	0.014	0.005	0.33	0.15	0.16	0.01	0.07	0.04	0.026	0.006
3 Q&T	0.11	0.27	0.009	0.007	0.28	2.80	1.07	0.26	0.06	-	0.043	0.007
4 Q&T	0.11	0.34	0.009	0.003	0.37	2.63	1.03	0.27	0.08	-	0.050	0.007
5 Q& T	0.14	0.51	0.017	0.009	0.24	2.76	1.64	0.42	-	-	0.054	0.006
6 HR, CC	0.05	0.42	0.011	0.004	0.35	0.29	0.75	0.33	-	0.06	0.057	0.007
7 HR, AC	0.17	1.28	0.020	0.009	0.32	0.23	0.21	0.05	-	-	0.045	0.009
8 HR, AC	0.18	1.29	0.036	0.004	0.46	0.15	0.30	0.03	-	-	0.043	0.008
9 HR, AC	0.21	0.51	0.011	0.025	0.25	0.04	0.02	0.01	-	-	0.027	0.006

B. Mechanical properties of the steels cold rolled 10% and aged at 480^{o}F for 0.5 hr. 30 ft-lb transition temperature (^{o}F)

Steel and Treatment	Thick (in)	Yield Stength Base (ksi)	Yield Strength Str Aged (ksi)	Trans Temp Base (oF)	Trans Temp Str Aged (oF)
1 Hot Roll, Air Cool	0.8	60	94	-112	-40
2 Hot Roll, Air cool	2.5	60	98	-40	-4
3 Quench & Temper	0.8	107	128	-202	-185
4 Quench & Temper	2.0	105	130	-140	-75
5 Quench & Temper	2.0	145	166	-13	46
6 Hot Roll, Cont Cool	2.4	68	84	-185	-91
7 Hot Roll, Air Cool	1.0	56	85	-75	46
8 Hot Roll, Air Cool	3.1	51	91	-40	78
9 Hot Roll, Air Cool	1.2	38	70	-	-

The hot rolled materials had substantial yield strength increases of between 51% and 84% but the quenched and tempered steels and the especially accelerated-cooled steel had much smaller increases, between 14% and 24%. The increases in transition temperature in the hot rolled steels varied between 40^{o}F and 121^{o}F, with most in higher part of the range.

The quenched and tempered steel had more modest increases, in the 17^{o}F to 65^{o}F range. However, the quenched and tempered steels in the study had very high yield strengths, higher than any of the steels included in prior research programs except for the T-1 quenched and tempered steel in the Lehigh 1959 investigation by Rubin, Gross and Stout. That steel also had more modest increases in yield strength, 20%, and in transition temperature, 77^{o}F for 5% strain and aging at 500^{o}F. Because so few high strength steels are in the data base, it is not clear that this is a trend.

F. Homma Miki and Yang (1998)

An investigation exploring the combined effects of strain and aging on critical regions of weld heat affected zones in welded and bent structural plates was performed by K. Homma, C. Miki, and H. Yang, investigators in the Department of Civil Engineering, Tokyo Institute of Technology, and reported in Engineering Fracture Mechanics, V. 59, no. 1, pp. 17-27 (1998)[14]. The research program used the strain levels associated with the tension surface in minimum radius cold bends allowed in steel plate under the Japan Road Association (15 x plate thickness) and American Association of State Highway and Turnpike Officials (7 x plate thickness) design codes in the test matrix. They listed these strains as 3.0% and 7.5%.

There test specimens were taken from plates in which they simulated the microstructure of important regions in multipass weld heat affected zones by special heat treatment and then applied tensile strains of 3.0% and 7.5%. Two regions of the weld heat affected were studied; one located in a zone at the intersection of weld passes twice heated to about 2600^{o}F, called the intercritically reheated coarse grained heat affected zone (IRCG HAZ), and one heated to just below the lower steel transformation temperature (about 1300^{o}F) called the subcritical heat affected zone (SC HAZ). The IRCG HAZ was expected to have the lowest toughness in the weldment while the SC HAZ was expected to have some of its highest toughness. The conditions tested were plates either without strain (0.0%) or with 3.0% or 7.5 % strain and aged at 480^{o}F for 0.5hr. Also tested were plates with one of the two simulated heat affected zones only, and, finally, plates strained and aged at 480^{o}F for 0.5hr and then given one of the two heat affected zone simulations. The toughness response of the specimens to these treatments was determined by measuring CTOD toughness at -22^{o}F (-30^{o}C), 14^{o}F (-10^{o}C), and 32^{o}F (0^{o}C). The results of the experiments are seen in Table 9.

Table 9. Results of Research of Homat, Miki and Yang

A. Composition of steel SM490YB (%)

C	Mn	P	S	Si	Nb
0.17	1.37	0.025	0.004	0.44	0.02

B. Mechanical properties of the SM490YB steel

Yield Strength (ksi)	Tensile Strength (Ksi)	Elongation (%)	CVN (ft-lb) @ 32^{o}F
49	66	24	30

C. CTOD toughness of base material and simulated heat affected zones after being strained 3% or 7.5% and aged at 480^{o}F for 1 hr.

As Received Steel	CTOD (mm) at -22^{o}F	CTOD (mm) at -14^{o}F	CTOD (mm) at 32^{o}F
Strained 0% & Aged at 480^{o}F	0.7	1.2	2.6
Strained 3.0% & Aged @ 480^{o}F	0.5	0.7	0.9
Strained 7.5% & Aged @ 480^{o}F	0.3	0.5	0.6

Simulated Subcritical Heat Affected Zone	CTOD (mm) at -22^{o}F	CTOD (mm) at -14^{o}F	CTOD (mm) at 32^{o}F
Subcritical HAZ treatment only	4.6	4.5	5.5
Strained 3.0% & aged @ 480^{o}F	0.7	0.8	1.3
Strained 7.5% & aged @ 480^{o}F	0.2	0.4	0.7

Simulated Intercritical Reheated Coarse Grained Heat Affected Zone	CTOD (mm) at -22^{o}F	CTOD (mm) at -14^{o}F	CTOD (mm) at 32^{o}F
I R Coarse Grained HAZ Only	0.4	0.2	0.6
Strained 3.0% & aged @ 480^{o}F	0.2	0.3	0.6
Strained 7.5% & aged @ 480^{o}F	0.1	0.1	0.7

CTOD measurements, although ductility-based rather than energy-based, show the same transition behavior as CVN tests. However, because they employ a sharp notch, the ductile to brittle transition temperature normal to structural steels is shifted to higher temperatures. In the experiments performed here, for example, the only material that shows a sharp transition in toughness over the range of temperatures tested was the as-received steel in the untreated condition. This transition occurred above 14^{o}F. One of the implications of this result is that the steel is being tested mostly below its ductile-brittle transition temperature, (even though the range of test temperatures is a reasonable one of service for most structures) and it is the toughness of the lower shelf of the transition curve that is being measured. As a result, the changes in toughness with temperature are gradual and linear for most conditions tested. Toughness comparisons between conditions are therefore about the same for any of the temperatures of test.

For example, the as received steel CTOD values were 0.7mm - 2.6mm over the range of temperatures tested. For the 3.0% strained and aged material, the range was 0.5mm - 0.9mm, a reduction of about 35%. For the 7.5% strained and aged material it was 0.3mm - 0.6mm, a further reduction of about 25%. Material strained 7.5% and aged had an eventual toughness of about 40% of its original value

The simulated heat treatments also provided interesting information. The subcritically treated heat affected zone (SC HAZ) was much better in toughness than the as-received steel while the intercritically reheated coarse grained heat affected zone (IRCG HAZ) was much worse. This was not an entirely unexpected result since the investigators expected the IRCG HAZ to be degraded in toughness, however the very good performance of the SC HAZ was not predicted. The IRCG HAZ CTOD was generally less than half that of the as-received steel while the SC HAZ was 2-4 times greater.

It has long been known that the IRCG HAZ forms a small but measurable “local brittle zone” in many steels and that the SC HAZ is reheated close to but below the critical transformation temperature. It is postulated by the investigators that the SC HAZ treatment close to the critical temperature produces a “tempering” effect that leads to the high toughness. Examination of microstructures shown of the two heat affected zone conditions confirms hard and brittle components in the IRCG HAZ but does not provide a ready explanation for the high toughness of the SC HAZ.

Table 9 shows data for both SC HAZ and IRCG HAZ material strained either 3.0% or 7.5 % and aged at 480°F. The SC HAZ toughness falls to a level below that of the as-received material when strained 3.0% and to well below the as-received material when strained 7.5%. The IRCG HAZ strained toughness falls below that of the SC HAZ and is the lowest in the study, between 15% and 25% of the as received material. CTOD values at this level suggest that the a structure having weldments containing with this kind of microstructure could be very susceptible to brittle fracture

Low level CTOD toughnesses such as these have been seen in heat affected zones in steels for offshore structures in the past and have been a source of controversy. One view is that they must be eliminated and a rigorous and extensive screening process should be used to exclude steels and welding processes that create them. Another viewpoint, one which this reviewer subscribes, is that such small zones have existed for many years in multipass welds but were undetected because there was no attempt to find them or reproduce what is an otherwise microscopic zone on a large enough scale to permit CTOD tests on them. Although, brittle fractures have been attributed to them, the reviewer has not encountered any. A probable reason for this is that they only exist as a small interior part of a complex microstructure surrounded by zones of tougher material. As such they have a low probability of initiating or propagating brittle fractures. Therefore, the low toughness regions simulated in the reported strain aging study are real but not relevant to most structures.

G. Dawes and Frances-Scrutton (1995)

Another paper addressing the issue of potential strain aging in weld areas was authored by M. G. Dawes and N. Frances-Scrutton in the Proceedings of the 14th International Conference on Offshore Mechanics and Arctic Engineering, pp. 471-477 (1995)[15]. In this research study, the authors identify and trace the history of locally intensified strain aging embrittlement (LISAE) in steels, welds and weld heat affected zones. The cause of the embrittlement is the plastic strain accompanying shrinkage of welds which can spread to surrounding base plate and heat affected zones. Since the shrinkage strain occurs simultaneously with cooling from welding, it induces "dynamic" strain aging and resultant loss of toughness. The effects of this type of strain aging are greatly increased when weld discontinuities are present since they provide strain concentrators in the weld or heat affected zone that can exacerbate the strain aging effect. These discontinuities can be weld cracks or lack of fusion in weld areas or welds placed over poor joint fit-up.

The authors estimate that discontinuity induced strains can reach 30% and cite literature, such as the work of Sorsa and Verros reviewed above[10], to demonstrate that strain aging in steel at this strain level can be most deleterious. The authors identify this phenomenon as the cause of some structural fractures and urge alternate designs of weld joints.
Better inspection and the use of high toughness steels and weld metals could also used to reduce the effects of this potential problem. They propose adoption of a CTOD test incorporating weld cracks or other discontinuities notches to detect and quantify LISAE. The paper reports the results of initial CTOD tests incorporating cracks and show LISAE can cause a shift in the 0.25 mm CTOD transition temperature for a susceptible steel of 145°F.

While the effects that the authors cite and demonstrate are undoubtedly real, it does not appear that LISAE testing has been adopted yet; indeed, it is not cited in U.S. literature. Moreover, the kind of transition temperature shift they report for LISAE in one susceptible steel, 145^{o}F, is about the same as reported for some susceptible steels in the more conventional CVN tests used by other investigators. This suggests that the same information could be obtained by conventional tests if the appropriate strain levels are used in the experimental design.

The primary contribution of this work is to identify a potential strain-aging related problem that can occur in welded structures even though no external "aging" heat treatments are applied. Since the discontinuities mentioned are exactly the ones which mandated weld inspections are intended to screen out of bridge structure weldments, it is not clear that discontinuities of the size used in their tests (not reported) would be missed in these inspections and would be present to trigger the fractures due to LISAE in bridge structures. It is the reviewer's opinion that the significance of LISAE to bridge integrity is yet to be established.

H. Avent, Mukai and Robinson (2000)

A final paper related to potential strain aging as a result of local heating processes similar to welding is one authored by R. R. Avent, D. J. Mukai and P.F. Robinson and published in the Journal of Materials in Civil Engineering, v.12, no. 3, August, 2000[16] . The focus of this paper is the effect of heart straightening on the mechanical properties of steels. The heat straightening process relies on the controlled differential heating of specific areas of damaged structures to induce contractions that result in dimensional changes restore areas distorted by external (usually mechanical) damage altering their original geometry. The classical example is a bridge girder distorted by being struck by a vehicle being restored to its original shape by a pattern of repeated heating to 1000^{o}F to 1200^{o}F for brief periods followed by cooling to close to room temperature. The effectiveness of the process depends on plastic contraction of the steel on cooling from the heating cycle which can induce dynamic strain aging in or around the heated area. The authors report not only the data from their own research but also that in the literature.

Two types of structural products were tested, ASTM A36 plates and A36 W6X9 beams. Both were damaged by bending about their weak axis, the plates to end of plate rotation angles varying between 6^{o} to 24^{o} and the beams to a more uniform end rotation angle of 6^{o} to 8^{o}. The plates were put through multiple heat straightening (heating to 1200^{o}F followed by cooling to about 100^{o}F) to produce the resulting straightening. For the plates, angles of 5^{o} to 6^{o} would take 20 or more heating cycles while distortions of 24^{o} take hundreds. For the beams, about 20 heating cycles were required to repair the distortion. The plates were repaired only once while the beams were damaged and repaired up to 8 times.

After damage and repair the mechanical properties in four regions of the reheated areas were measured. The region where the heat was first applied generally received the longest heating and thus had the greatest property changes. This review in will focus on the changes in these most sensitive regions.

The results of heat straightening tests on A36 steel plates for various heating cycles did not show much apparent sensitivity to dynamic-strain-induced changes in tensile properties. The increases in yield strength as a result heat straightening ranged from 19% to 31%, small compared to increases in other strain-aging studies. Tensile strength increases were, on average, about 10% and elongation decreases were, with one exception, less then 20%. The strain aging sensitivity did not appear to correlate with the level of angular distortion, and thus number of heat cycles, in the repair. Since the region reported above is the most sensitive, this is the worst case scenario for strain aging due to single repairs using multiple heating cycles.

The multiple repairs in the beam specimens show an increasing sensitivity to strain aging with each damage-and-repair cycle. By the third damage and repair cycle the yield strength in the most sensitive region has increased by 57% and the tensile strength by 22%. After the fourth cycle, the yield strength has increased by 87% and the tensile strength by 67%. After the third cycle the elongation has decreased by 49% and by the fourth cycle by 67%. From this result it is clear that successive repairs in the same area can result in a significant increase in strength and loss in toughness. However, since the area repaired was repeatedly mechanically damaged as well as repaired, it is unclear that this result is due to the heat-straightening-repair or plastic strains from the mechanical damage process.

Although the authors did not do any toughness tests, they report results of CVN toughness tests before and after heat straightening on eight low-carbon structural, ship, and pressure vessel steels. The results were mixed with typical ship and structural steels having increases in transition temperature between 7^{o}F and 17^{o}F while the quenched and tempered steels had transition temperature decreases of about the same magnitude. These transition temperature shifts are, in any case, small compared to those in other strain-aging studies. The decreases in transition temperature for the quenched and tempered steels are probably due to the fact that the maximum temperature typically used for heat straightening these steels is 1050^{o}Fe rather that the 1200^{o}F used for the ship and structural ones, making the heat-straightening process a lower temperature tempering process than the one the steels received in their initial processing.

Based on the results in this report, it does not appear that strain aging of structural steels by heat straightening is of much concern unless excessive repairs of repeated damage to the same area is undertaken.

2.4 Current Lehigh University research on strain aging.

In the last two years, the Lehigh ATLSS Center has conducted two additional research programs pertinent to strain aging in structural steels, one of which was specifically focused on HPS 70W.

A. Kaufmann, Metrovich and Pense (2001)

The first of these investigations was performed by E.J. Kaufmann, B Metrovich and A.W. Pense and the results recorded in ATLSS Report No. 01-13 dated 2001[17]. The study was primarily intended to provide information relevant to toughness loss observed near the web-to-flange region, the so-called “K” region, in rolled beams.

It had been observed that attachment welds in rolled beams in or near the K region sometimes resulted in toe cracking or fractures. Investigation into the causes indicated that in some beams the K region had low toughness, apparently induced by roller straightening. When the beams are manufactured, flanges that are out of plumb with the web are passed through straightening rollers that apply alternately positive and negative plastic bending strains on the flange until it is at right angles to the web. This leads to strain hardening in the K region and a resulting loss in toughness. The investigation was to assess how much loss of toughness could occur by cyclic plastic strain similar to that which would occur in roller straightening. In addition to the cyclic strain effects, however, there was an investigation of monotonic strain and the effect of aging following the strain. The other elements of the study are not reviewed here but the strain and aging work is relevant to this review and is reported here.

The materials in the investigation included rolled beams from two heats of ASTM A572 grade 50 (Steels A and C), one heat of ASTM A913 Grade 50 (Steel B) and one heat of ASTM A36 (Steel D). The steels were monotonically strained 2%, 8%, and 12%. One heat of A572 grade 50 (Steel A) was also tested after straining 8% and aging at 200^{o}F or 400^{o}F for 10 hr. Material from the webs of the beams was used for the tests.

One of the issues to be addressed in the research was a comparison of modern steels made primarily from scrap and older steels normally made in an integrated mill using hot blast furnace metal and a smaller proportion of scrap. It was postulated that steels made primarily from hot metal would be lower in residual elements, particularly nitrogen and therefore less susceptible to strain aging. The two beams of A572 Grade 50 and the beam of A913 Grade 50 were believed to be modern while the beam of A 36 (steel D) was believed to be made in an integrated mill prior to 1984. The chemical analysis of steels D indicates that it does indeed have lower levels of residual elements, particularly nitrogen, however, it is also much higher in carbon than the modern steels.

The data from the strain aging part of the study are seen in Table 10.

Table 10. Results of Research of Kaufmann, Metrovich and Pense

A.Chemical Compositions of the Steels (%)

Steel	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	V	N	Al
A572	0.067	1.57	0.022	0.005	0.28	0.23	-	0.06	0.31	0.15	0.003	0.032
A913	0.085	1.20	0.023	0.020	0.18	0.11	0.11	0.07	0.22	-	0.003	0.002
A572	0.072	1.48	0.014	0.016	0.21	0.13	0.06	0.09	0.29	0.05	0.004	0.002
A36	0.17	0.75	0.020	0.024	0.05	0.03	0.04	0.04	0.021	-	-	0.002

B. Tensile properties of A572, A913, A572, and A36 steels strained 2%, 8%, 12% and aged at 200°F and 400°F.

Yield Strength (ksi)

Steel & Treatment	Base	2% Strain	8% Strain	12% Strain	8% Strain + 200°F	8% Strain + 400°F
A572 As Rolled	58	70	82	90	83	84
A913 As Rolled	51	66	80	85	-	-
A572 As Rolled	54	65	79	82	-	-
A36 As Rolled	36	49	69	76	-	-

Tensile Strength (ksi)

Steel & Treatment	Base	2% Strain	8% Strain	12% Strain	8% Strain + 200°F	8% Strain + 200°F
A572 As Rolled	76	80	83	90	82	85
A913 As Rolled	70	76	83	84	-	-
A572 As Rolled	72	76	88	82	-	-
A36 As Rolled	63	71	71	77	-	-

Elongation (%)

Steel & Treatment	Base	2% Strain	8% Strain	12% Strain	8% Strain + 200°F	12% Strain + 400°F
A572 As Rolled	34	30	21	16	21	22
A913 As Rolled	38	25	25	22	-	-
A572 As Rolled	31	20	20	18	-	-
A36 As Rolled	45	32	32	22	-	-

C. Charpy impact toughness of A572, A913, A572 and A36 steels strained 2%, 5%, and 12% and aged 200oF and 400oF. 15 ft-lb transition temperature.

Steel & Treatment	Base	2% Strain	8% Strain	12% Strain	8% Strain + 200oF	12% Strain + 400oF
A572 As Rolled	-25	-4	15	0	25	35
A913 As Rolled	-60	-45	-4	5	25	35
A572 As Rolled	-22	-10	20	38	-	-
A36 As Rolled	-42	67	88	75	-	-

The results follow the same trends as previous ones. All of the steels show some sensitivity strain aging, both the relatively modern structural steels and the older one. The yield points of the steels increase from 20% to 40% with 2% strain and increase by 50% to over 100% at 12% strain.

The tensile strength increases are from 10% to about 20%, while the elongation decreases are close to 50%. The strain sensitivity of the older Steel D is generally greater then of the other steels. Aging at either 200^{o}F 0r 400^{o}F after straining does not significantly increase the yield or tensile strength of Steel A, the only one given this treatment, nor did the elongation continue to decline.

The CVN 30ft-lb transition temperatures show the normal shifts with strain and aging, the upward shift with 2% strain is about 15^{o}F to 30^{o}F and with 12% strain they are between 25^{o}F and 55^{o}F with several showing anomalous larger increases at 8% strain than at 12% strain. For Steel A, aging at 200^{o}F and 400^{o}F after 8% strain increased the 30 ft-lb transition temperature by 10^{o}F to 20^{o}F, for as total of 50^{o}F to 60^{o}F. From this study, it does not appear that a clear conclusion concerning the sensitivity of the modern compared to older practice steels can be made. Steel D did not have smaller transition temperature increases than some of the modern steels and, on the basis of yield strength increases, it had the greatest. The effects of aging at either 200^{o}F or 400^{o}F for Steel A were, however, much smaller than in other aging studies reviewed.

B. Wilson and Gallagher (2001)

The final paper reviewed contained results of strain studies performed on HPS 70 W material tested in conjunction with its use in corrugated web girders. This research was performed in at the ATLSS Center and is found in "The Effect of Cold Deformation on the Mechanical Properties of HPS-70W Steel", an ATLSS Internal Report by A.J. Wilson and J. Gallagher, 2001[18]. The specimens employed were strained 3%, 6%, 10% and 12%, levels intended to duplicate or exceed those that might occur when bending the corrugated web plates to be used in girders. Since it was not anticipated that heat treatment would be applied subsequent to bending, no aging treatments were used. Tensile and CVN impact toughness properties of the steel before and after strain were measured. The results of the research are found in Table 11.

Table 11. Results of Research of Wilson and Gallagher

A. Type Composition of the ASTM A709 HPS 70W, (%)

C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Ti	V	Al	N
0.011 Max.	1.10-1.35	0.20 Max	0.006 Max	0.30-0.50	0.25-0.40	0.45-0.70	0.02-0.08	0.25-0.40	-	0.04-0.08	0.010-0.040	0.015 Max

B. Mechanical properties of HPS 70W steel strained 3%, 6%, 10% and 12%. 40 ft-lb transition temperature.

Property	Base	3% Strain	6% Strain	10% Strain	12% Strain
Yield Strength (ksi)	73	90	103	111	112
Tensile Strength (ksi)	98	99	106	111	112
Elongation (%)	26	31	20	17	15
Trans.Temperature (^{o}F)	-55	-41	-25	-20	4
CVN at -10^{o}F (ft-lb)	71	63	51	53	33

The increases in yield and tensile strength with strain for the HPS 70W are essentially the same as for other modern steels, an increase of about 20% in yield strength for low levels of strain rising to 50% for strains at the 10% and 12% level. Smaller increases in tensile strength occur over the same strain range. The elongation gradually decreases to about 60% of its initial value at 12% strain. The 40 ft-lb CVN transition temperature increases are also similar to those previously measured in other modern steels, 14^{o}F for 3% strain increasing to 59^{o}F at 12% strain. However, as Table 11 indicates, in spite of any loss, the toughness of the HPS 70W was still well above required for service; 25ft-lb at -10^{o}F.

There are several important outcomes from this investigation; (1) the HPS 70W steel is about as susceptible to changes in strength and toughness with plastic strain as other modern steels and (2) the way to avoid significant toughness problems when plastic strains are expected to occur is to select a material with a high initial toughness so that any deterioration in toughness does not compromise service temperature performance. The latter outcome is a reinforcement of the conclusions of earlier investigators.

3. ANALYSIS OF THE LITERATURE REVIEW

When trying to analyze, or even summarize, the results of diverse investigations done over a fifty year period and in many different laboratories, a significant disparity of results might well be expected. Surprisingly, this does not seem to be the case. The trends observed in most of the investigations are in relatively good agreement and, taken together, delineate the practical parameters relating to the effects of strain aging on the mechanical properties of low carbon steels. The investigations reviewed in this survey did not focus on the theory of strain aging even though they often referred to it in their introductions. Apparently, the investigators concluded, as this reviewer has from his own reading, that while modest details have been filled in with respect to dislocation locking by interstitial atoms or compounds, no really significant additions to the ***theory*** of strain aging have been made over the last 50 years and it stands much as first articulated.. Since this is the case, and neither the current (2001) investigations nor most of the intervening ones over the last 50 years resulted in any really new information about the ***effects*** of strain aging, it raises the question why some much time and effort was repeatedly expended on this topic only to produce essentially the same results.

It is the reviewer's opinion that most of the investigations surveyed here were for one of three reasons; (1) to determine if newer steels that were being developed would be less susceptible to losses in toughness from this phenomenon (it was hoped that they would be), and (2) to determine the extent of the toughness loss that could be expected for a particular fabrication operation or (3) to determine if there were heat treatments that would erase or mitigate any toughness losses that were known to occur. It should be noted that, while increases in yield and tensile strength and decreases in tensile elongation were identified in most of the investigations, the main concern was always toughness loss. Perhaps this is not surprising since concern for, and code requirements for, adequate toughness in all large structures such as ships, pressure vessels, bridges, off-shore platforms and some building components have become continuously more stringent over the last 50 years. Whatever the intent that led to the investigations, as will be shown below, while some details were elucidated, few really new conclusions were reached.

A synthesis and summary of all the relevant data extracted from Tables 1-11 are shown in Figures 1 to 4. The process of creating the synthesis in Figures 1-3 was to normalize all of the property changes from all the relevant tables by percentage increase or decrease compared to the base value for the steel and to calculate an adjusted average of the resulting changes for each category of strain and aging temperature. The synthesis in Figure 4 followed the same procedure as for Figures 1-3 except that the adjusted average of the actual transition temperature shifts from their base values were used.

In order to combine the data, strains and aging temperature ranges on the figures are grouped in increments. Strains are in increments of 1% - 3%, 5% - 6%, 8% - 10%, 12% - 14%, 15% - 19% and 20% - 29%. Aging temperatures are in increments of 400^{o}F-600^{o}F, 650^{o}F - 800^{o}F, 900^{o}F - 1000^{o}F, 1100^{o}F - 1200^{o}F.

For example, for the first category in the yield strength change table, Figure 1, for all the steels for which strains of 1% - 3% were applied without aging treatment, an adjusted average percentage increase in yield strength for each strain increment was calculated by discarding the highest and lowest value and averaging the remaining data. For the 1% - 3% strain category there were 9 data points drawn from 5 tables and the percentage increases were 0, 8, 35, 10, 21, 29, 20, 36, and 23. The 0% and 36% data points were discarded and the average of the remaining was 21% (the simple average was 20%). The reason for the decision to discard the highest and lowest points was concern that, with the wide variation in testing procedures, there would be some data at wide variance with the rest for a random rather than any fundamental reason. This use of an adjusted average was to eliminate these potentially spurious data.

The number of data points in each category varied from 16 to 1. When the number of data points did not exceed 5, however, the "adjusted average" was the simple average. When the number of data points was less than 4, this is indicated on the figures. If there was only one data point available in a category, it was not reported. The majority of the reported categories had 4 or more data points. Even in the limited data categories the values were not widely dispersed. As a result, in spite of the wide range of steels reviewed in this study and the variety of straining and aging cycles used, the mechanical property changes in low carbon steels with strain aging can be well characterized in the four property summary figures.

An examination of Figure 1, below, indicates that the largest increases in yield strength due to strain aging occur during the strain process and aging in all but a few cases reduces the yield strengths from the cold strain levels. The increases in yield strength are proportional to the applied cold strain up to about 12% - 14% but some modest increase occurs at 28%. Where data are available, the same trend of increasing yield strength with increased strain continues at each temperature but, as indicated above, the maximum levels are lower for each successively higher temperature. Aging at 1000^{o}F - 1200^{o}F has about the same effect as aging at 900^{o}F - 1000^{o}F and neither restores yield strength to its initial value.

As Figure 2, below, indicates, the effect of strain aging on tensile strength is identical to its effect on yield strength, but the increase levels are much lower. Once again, the increases in strength are greatest for cold strain without aging.

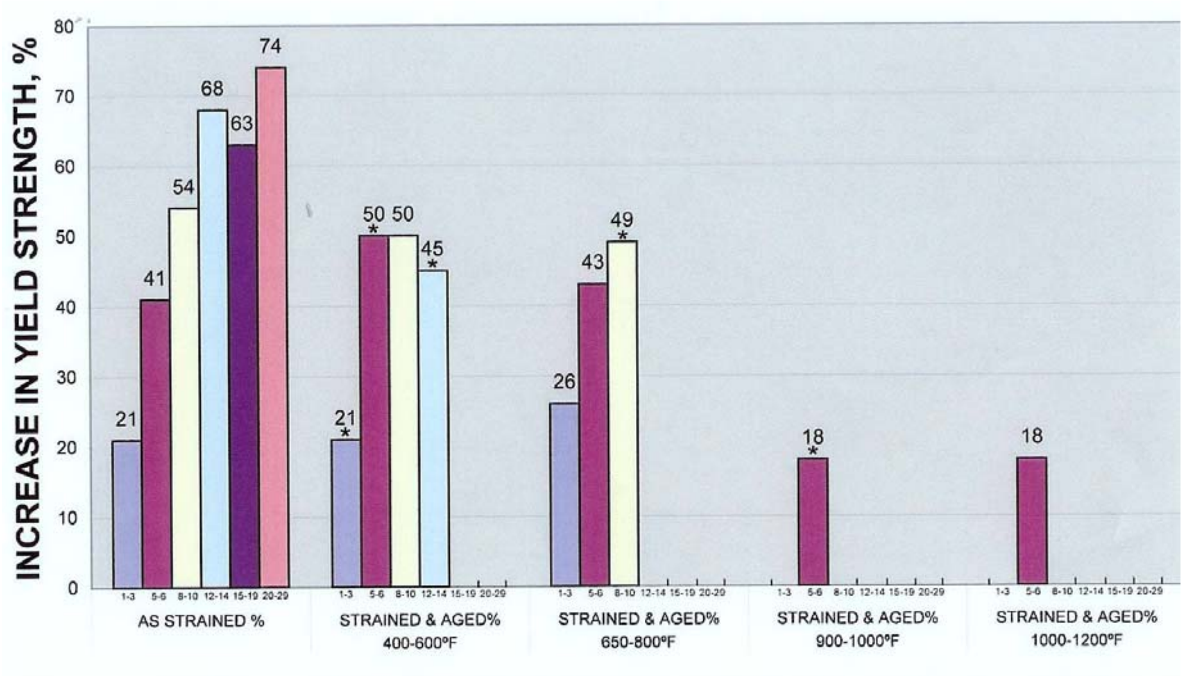

Figure 1. Increase in Yield Strength with Straining and Aging

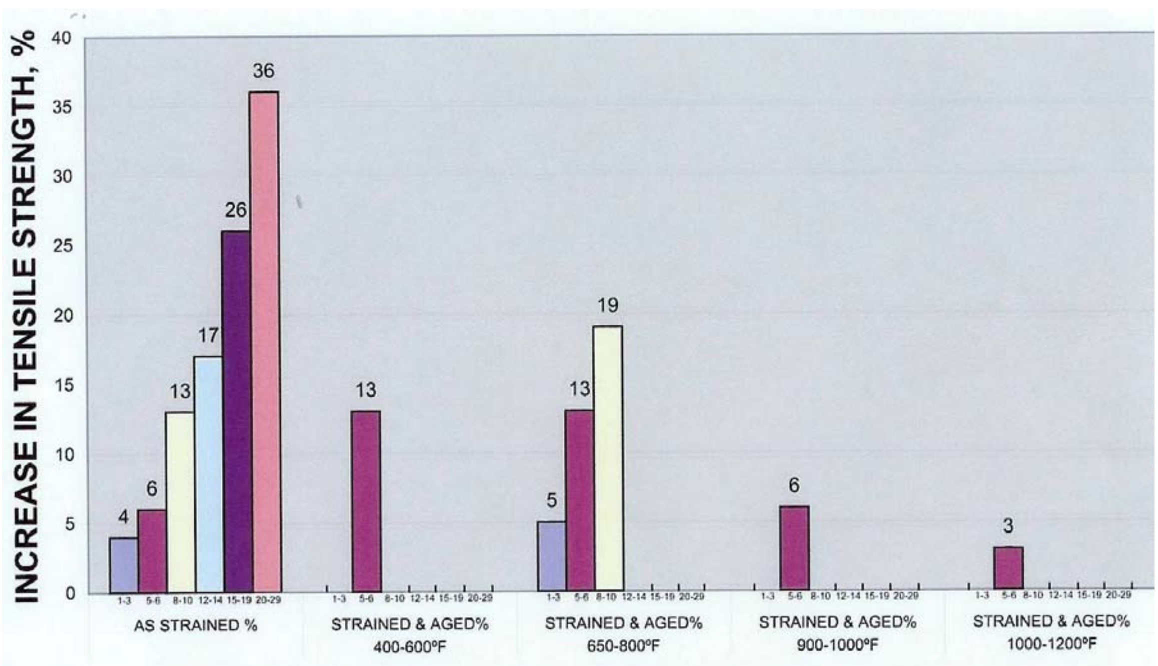

Figure 2. Increase in Tensile Strength with Straining and Aging

Although the tensile strength data are limited for the aged steels, the pattern is for higher strength level for higher levels of strain when followed by aging but with lower maximum values as aging temperature increases. Once again, aging at temperatures as high as 1200^{o}F did not restore the tensile strength to its pre-strain levels.

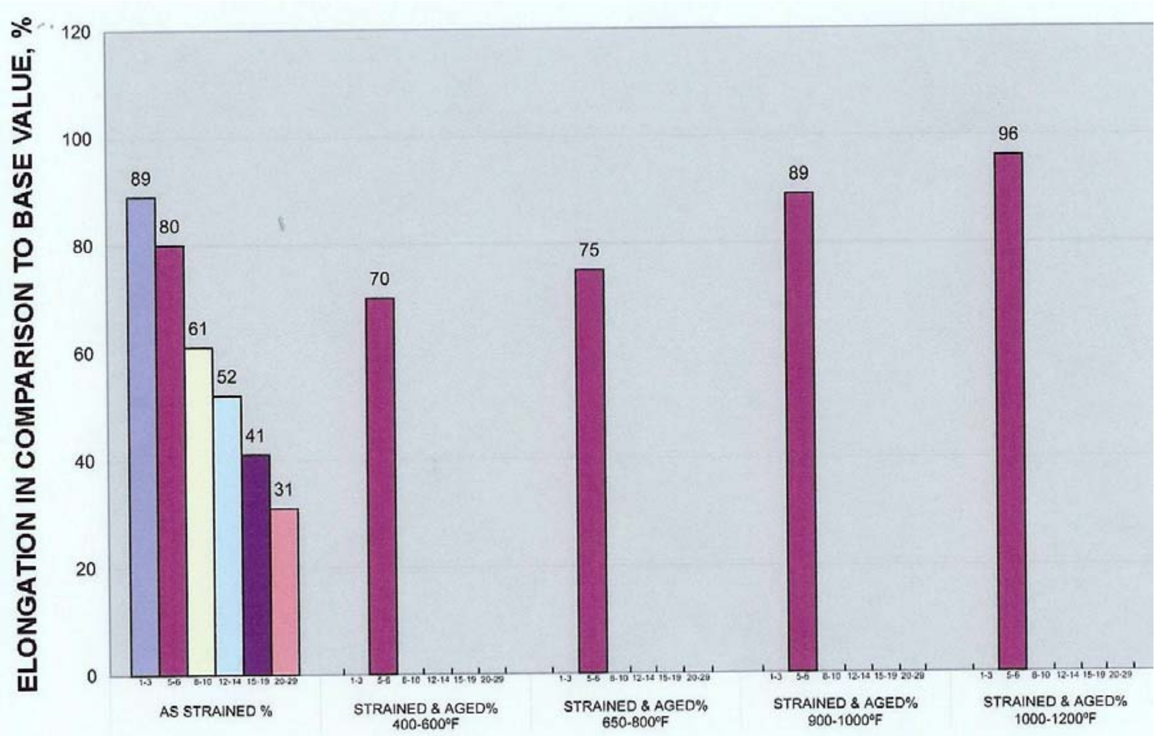

Figure 3. Decrease in Elongation with Straining and Aging

The elongation data seen in Figure 3 follow the trends of yield and tensile strength by exhibiting a decrease in tensile elongation that is proportional to strain when no aging is used. The data for the aged steels is limited to only one strain level, 5% - 6%. At this level, the effect of aging is to gradually restore tensile ductility as aging temperature increases but, as before, aging at as high as 1200^{o}F did not restore the elongation to 100% of its initial level.

The effects of strain and aging on changes in transition temperature, seen in Figure 4, below, are somewhat different than observed for the tensile properties. For steels strained but not aged, transition temperatures increase with strain up to about 12% - 14% strain but remained about constant at higher strain levels. Contrary to the results for the tensile properties, aging at 400^{o}F - 600^{o}F and 650^{o}F - 800^{o}F increases the transition temperatures above their as-strained values, in some cases very substantially. Only when aging is done at temperatures above 900^{o}F are transition temperatures reduced close to their as-strained levels, but they are still well above their pre-strained level. As will be discussed below, from the engineering viewpoint, of all the properties measured in these investigations the toughnesses of the steels are the most adversely affected by strain aging.

A small number of investigations included static fracture toughness tests, either K_{Ic}, J_{Ic} or CTOD, because, in these cases, it was assumed that the service involved was not dynamic and therefore a dynamic test was not appropriate. The results of these tests indicate that strain aging affects static toughness as well as dynamic toughness and must be taken into account in these applications.

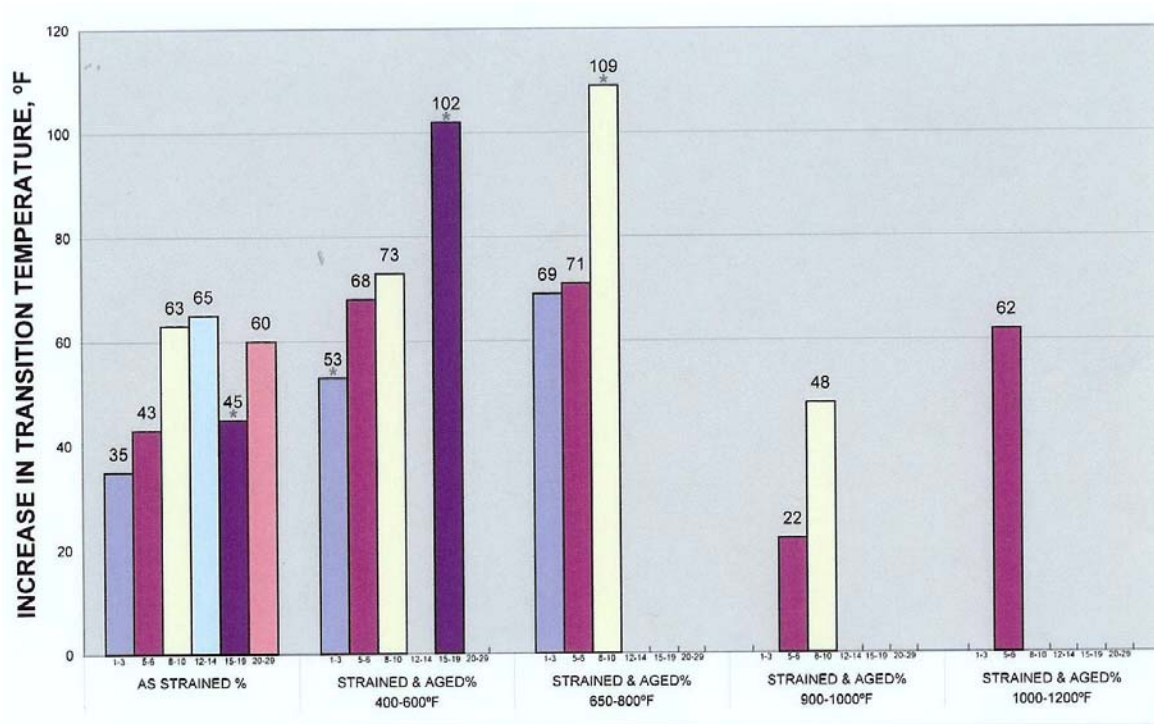

Figure 4. Increase in Transition Temperature with Straining and Aging

It may be noted that one of the variables that was quite different in the various research investigations was the time at aging temperature. This varied from 0.5 hr to 1000 hr and yet did not seem to have as much effect as might be expected. This is due to the fact that most metallurgical reactions respond directly to temperature but exponentially to time. That is to say, for a metallurgical reaction, the first 1 minute has about the same effect as the next 10 minutes, which has about the same effect as the next 100 minutes. From the practical standpoint, this reduces, although it does not eliminate, the influence of time on the aging cycle. Only in the case of the 1000 hr treatments (Table 3) would time at aging temperature be expected to have much of an effect and even in this case, although the data are limited, it did not seem to do so.

As noted above, based on the multitude of tests undertaken, some by the same sponsors, over a 50 year period indicates that most of the investigators anticipated one or two outcomes from their research that might be of practical use for them. The first was to identify a steel, probably a new steel, that would be more strain-aging resistant. The second was to better define the conditions of strain and temperature of aging that could lead to a loss in toughness large enough to be of concern for a specific application.

The first outcome was never achieved, While there was some variation in behavior between different steels over the 50 year period, all of the responses to strain aging were pretty consistent; there are no resistant steels. Changes in alloy composition, heat treatment, deoxidation practice and processing have only minor a minor effect on this metallurgical phenomenon.

The second was somewhat more successful. Lower levels of strain, 1% - 3%, are damaging but the greatest damage occurs for higher strain levels. This is useful when considering normal bridge service since current codes limit the cold strain levels that steels can undergo. In this reviewer's experience, these strains are typically well under 5% and any toughness losses will be limited. The "K" region problem in rolled girders, which is usually associated with members for buildings but might apply also to bridges, could be an exception as strain in this region can be very high.

Additional damage that may occur through aging is not a significant concern for most bridge applications. This is not to say that there are not locations in certain bridge members that are heated during fabrication, i.e., by preheating, welding or heat curving, but the combination of such treatments with strain in critical locations is unlikely and, if present, isolated. Since current the AASHTO provides mandated toughness requirements for steels to be used in critical applications, these provisions should also provide adequate toughness to mitigate losses due to strain aging.

For manufacturers of other products, for example pressure vessels which are cold strained during fabrication by rolling into cylinders or in proof testing, precautions need to be taken to mitigate the potential effects of strain aging. For cases like the "K" region problem in building girders, the solution may require careful design of weld locations. There is always the option of offsetting losses through strain aging by using steels of high initial toughness level. This option, as represented by the high toughness levels of the HPS steels at all bridge service temperatures regardless of location obviates, in the practical sense, concern for strain aging in bridge service.

4. SUMMARY

The literature review of strain aging in low carbon structural steels can be summarized as follows.

1. All of the structural steels in this review, over 30, were susceptible to significant changes in tensile properties with strain. All had increases in yield and tensile strength and decreases in elongation. Strains as low as 1.25% produced measurable property change and this increased up to about 18% cold strain. The typical maximum increase in yield strength was about 70% above its initial value and the typical maximum increase in tensile strength was to about 35% above its initial value. The typical maximum decrease in elongation to about 30% of the initial value.

2. Aging at temperatures up to 1200^{o}F tended to decrease the yield and tensile strength and increase the elongation from the levels reached by straining but did not return to them to their original values.

3. Toughness as measured by CVN transition temperature and other criteria deteriorated as a result of strain starting with strains as low as 2.5% and continued to deteriorate the transition temperature with strain up to strains of 12% - 14%. The typical maximum upward shift in transition temperature was about 65^{o}F.

4. Aging at temperatures up to 800°F further deteriorated toughness, resulting in a typical maximum upward total transition temperature shift of about 100°F. Aging at temperatures between 900°F and 1200°F restored some of the toughness loss but did not return the transition temperatures to their initial values.

5. Because of the modest cold strain levels typically used in fabrication of bridge members and the general absence of aging treatments, it is not considered a significant problem in bridge fabrication or service. When cold strain is used in bridge fabrication, steels with high initial toughness can be selected to offset toughness losses from strain or strain aging.

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