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Management of Residual Stress: An Emerging Technology for Oil Industry Tubular Products

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Abstract

The role of residual stress in the performance properties of tubular products is increasingly coming under renewed interest. A historical review shows how tubular manufacturing standards have added straightening and stress relief requirements to minimize residual stress. International technical reports focusing on performance equations have included a residual stress term for tubular collapse performance. Research summaries concerning full size testing of casing in saturated H_2S liquid environment have reported the significant impact of tensile residual stress in the propagation of surface notches.

Recent technology advancements in the aviation, medical and nuclear industries have resulted in effective ways to strategically place deep, stable residual stress fields into metal structures to greatly improve damage tolerance and to mitigate fatigue cracking and environmental-assisted cracking. Engineered placement of residual stress fields in oil country tubular products, drill pipe, and line pipe has reached the research and testing phase.

This paper also presents a review of residual stress formation during manufacture and as a factor in tubular performance, a review of advanced processing techniques in managing residual stress, and a review of recent performance testing on tubular components incorporating near yield strength compressive residual stress fields.

Introduction

The combination of deeper drilling programs, horizontal drilling, cyclical hydraulic fracturing, and recent increases in well design safety by government regulators has pushed the needed performance of oil country tubular products to their natural limits. In order to enhance tubular performance and consistency, a renewed interest in understanding and managing residual stress is stirring within the industry. This paper reviews the complexities of the various manufacturing processes that add components of residual stress as the tubes are being manufactured so that the reader has an appreciation for the many heating and cooling and plastic deformation processes that are required to produce a finished tube. Also, a historical review of how tubular standards activity has brought about manufacturing requirements that result in a level of control over residual stress is provided. Appendix 1 further provides the user with some key historical excerpts of standardization work related to residual stress beginning in 1938 and links residual stress to pipe performance. To improve management of residual stress will require the use of management tools that can either minimize these stresses or engineer specific beneficial orientations of residual stress that will enhance performance. One new residual stress controlling technology, Low Plasticity Burnishing or LPB, has entered the research and testing phase for tubular products and the 6,376 hours of preliminary test results related to mitigating sulfide stress cracking in a high strength P-110 coupling material are provided.

Complex Manufacturing Processes Related to Residual Stress

Residual stress present in the walls of tubular products intended for use in down-hole applications has generally been looked upon as a negative influence on performance. Yet industry standardization efforts were slow in developing manufacturing requirements that would establish appropriate measures of residual stress control. This is because the orientation and profile of residual stress varies along the length of each pipe and may vary greatly from pipe to pipe. As identified by J. Brison Greer in 1981, “Cold work is the plastic deformation of metal at a temperature below its re-crystallization temperature. Residual stresses are increased by plastic deformation and it is difficult to predict the magnitude and direction of these internal stresses."[1] The manufacturing processes influencing the final retained residual stress for a specific section of a tube's length is varied and complex.

Differential cooling due to wall eccentricity (see Figure 1 a.) results in non-homogeneous plastic hoop deformation, which results in a residual stress distribution through the tube wall. The heavier wall portion of the circumference cools more slowly than the thinner portion and can impart a residual stress component.

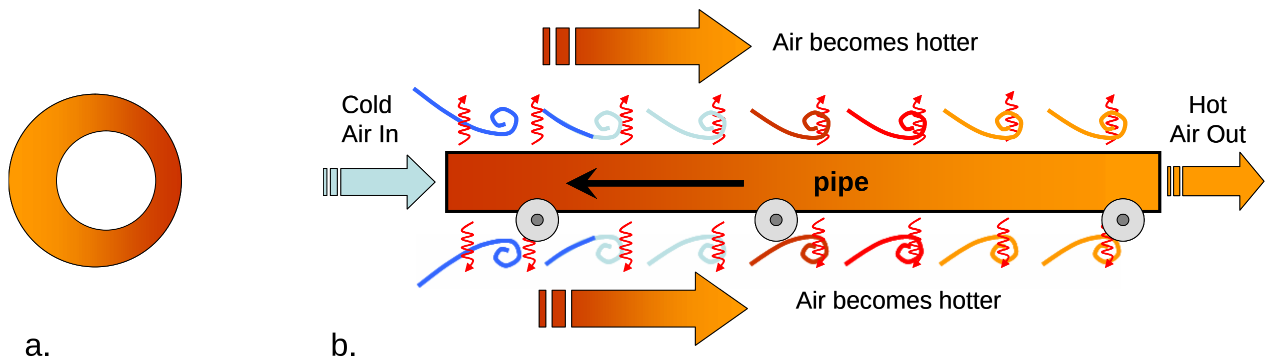

Figure 1 : a. Cooling cross section b. Cooling during longitudinal transportation

The longitudinal cooling rate of a tube is continuously changing along the length of a hot tube that is being transported down roller lines during manufacture (see Figure 1 b.). The leading edge of the tube is exposed to ambient air on both its inside and outside surfaces. However, as the ambient air contacts the leading edge of the tube, it is heated up, and each subsequent length of the pipe is being cooled by an air temperature that is ever increasing. This is most pronounced on the inside diameter of the pipe, where there is no possibility of mixing the heated air with ambient air, as happens on the outside of the pipe. Thus, the leading edge of such a pipe moving horizontally down a roller line contacts cool air on both the outside and inside tube surfaces, whereas the trailing length of the same tube contacts air that has a higher temperature (approaching the temperature of the trailing length of the tube) on the inside diameter (ID) and air that is rather warm air on the outside diameter (OD) surface. Thus, the retained residual stress due to differential cooling is constantly changing from the leading end of the pipe to the trailing end of as-rolled grades H-40, J-55, K-55, and N-80 Type 1.

Outside diameter dimensions are a manufacturing requirement. However, permanent rounding of pipe by sizing can only occur by plastic deformation of portions of the tube wall. Differential deformation produces the desirable attribute of enhanced pipe roundness, but also results in retained residual stress. The temperature of the pipe at the time of the sizing operation weighs heavily on the amount of residual stress being retained by the tube. With as-rolled products, the temperature is typically much higher than stress relieving temperatures and the residual stress component due to sizing is small. On quench and tempered products, sizing temperature after the final tempering operation is dependent on the grade. The higher the yield strength of the grade, the lower the tempering temperature is for the same steel composition. However, since the tempering temperatures are moderately above stress relieve temperature, the retained residual stress component due to hot sizing is small but not necessarily zero.

Straightness is a manufacturing requirement. However, the straightening of pipe can only occur by plastic deformation of portions of the tube wall. Differential deformation produces the desirable attribute of straight pipe, but also results in retained residual stress. In most cases, these stresses are oriented in a way that diminishes pipe collapse performance. Also, full straightening forces do not occur until the pipe has been gripped by the front end rolls, traversed over the middle deflecting roll/rolls and finally gripped by the back end straightener rolls. Thus, the ends of the pipe representing half the gripping length of the straightener do not see the full straightener forces and may have dramatically less residual stress than the mid-section remainder. The temperature of a tube during the straightening process has a dramatic effect. If the temperature is too high, the tube may distort after straightening due to differential cooling, losing its optimum straightness quality and gaining back some residual stress. If the temperature is too low, there may not be enough temperature for natural stress relieving, thus the effect of hot straightening is lost. Cold straightened product that is not stress relieved is allowed in the manufacturing standards for grades H-40, J-55, K-55, M-65, L-80, N-80 Q&T, N-80 Type 1, R-95, and P-110 unless PSL-2 or PSL-3 is specified. These products can have elevated levels of residual stress in the finished product.

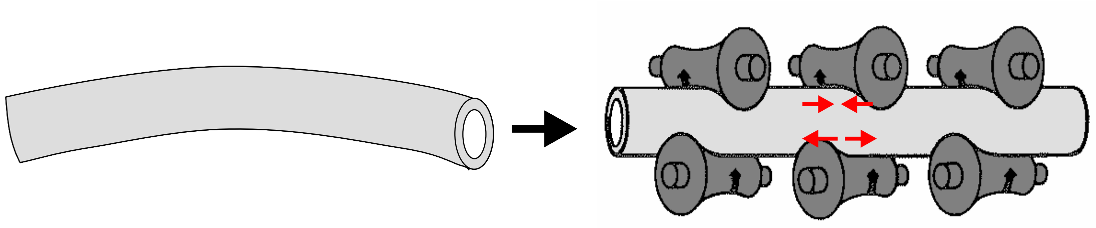

Figure 2 : Rotary Straightening produces plastic deformation

Due to the above complexities, the final residual stress for a finished tube can vary significantly from pipe to pipe and along the length of each pipe from front end to trailing end. The effect on ductile rupture performance in benign environments is not very noticeable since the first yielding causes a reorientation of the residual stress profile without any mechanical instability. However, this is not the case with collapse performance where the elasto-plastic collapse mode can be significantly affected by the magnitude of retained residual stress, resulting in premature yielding of portions of the tube wall followed by mechanical instability (circumferential wall buckling). For brittle fracture initiated by crack propagation of surface imperfections, tensile residual stress can increase the stress intensity at the imperfections root tip and thereby lower the overall performance.

Tubular Standards Historical Development Related to Residual Stress

The earliest American Petroleum Institute (API) standardization committee interest in residual stress began in 1938, yet the first manufacturing requirements that impacted the amount of residual stress retained in finished tubular product were not established until 1970. This 32-year period underscores the difficulty the industry had in trying to bring some form of residual stress management into the manufacturing process. Appendix 1 documents standardization activity related primarily to the issue of residual hoop stress as found in standards committee work from 1938 through 2011. A review of these historical archives shows that residual stress is primarily linked to five technical subjects: Collapse Performance, Internal Yield Pressure, Connection Yielding, Sulfide Stress Cracking (SSC), and Straightening Process. The standardization activity by year for each of these is summarized in Table 1.

Standardization: Residual Stress Related to Performance	
Technical Subjects	Year Discussed or Requirement Published
Collapse Performance	1938, 1939, 1957, 1974, 1975, 1981
Internal Yield Pressure	1955
Connection Yielding	1957, 1962
Sulfide Stress Cracking (SSC)	1991, 2011
Straightening Process	1955, 1970*, 1983, 1984*, 1985*, 1986, 1991, 1998*, 2005*, 2011*

***** New requirement placed into the manufacturing specification

Table 1 : Standardization Activity by Year

Collapse Performance Degradation

The first focus of standards discussions related to residual stress was the noticeable degradation in collapse performance caused by the presence of circumferential residual stress in the tube wall. In 1938 and 1939, a number of technical papers were presented in standards meetings that dealt with tubular collapse performance as affected by residual stress. In the studies by W. M. Frame (The National Supply Company, Spang, Chalfant Division, Ambridge, Pa.), at least 400 collapse tests on oil country casing were conducted, of which 300 were practically free of residual stress.[2] Another interesting study was by P. Mehdizadeh in 1974, which involved approximately 30 collapse tests and included some P-110 data from R.E. Zingham.[3] A brief summary of selected parts of their data is given in Table 2.

Researcher	Yield Strength	Data Points	Residual Stress % SMYS**		% Collapse Reduction
			Low Group	High Group	
W. M. Frame	Mostly less than 80 ksi	400	~0	-1.5 to 55.8	15% to 30%
P. Mehdizadeh	86-95 ksi	12*	-3.3 to -2.1	29.5 to 35.8	25% ave
R.E. Zingham	121-135 ksi	12	-1.8 to 10.2	21.2 to 46.7	12.6% to 20.2%

* 7 5/8 26.40 N-80 ** Residual Stress on the ID Surface (negative = tensile, positive = compressive)

Table 2 : Typical Residual Stress Compared to Collapse Reduction

The 1974 report suggested that the changes needed to secure collapse performance improvements include one or a combination of the following:

a. Incorporate heat treatment quality requirements into its tubular goods specifications in the form of hardness, micro-structure, or other heat treatment gradient test limitations to be imposed on some reasonable lot basis.
b. Incorporate residual stress limitations into its tubular goods specifications in the form of split-ring or other test limitations to be imposed on some reasonable lot basis.
c. Inclusion of heat treatment gradient and/or residual stress measurement data as part of the data essential to the API collapse testing procedure.[4]

Eventually hardness, microstructure, and other heat treatment gradient test limitations were added to the API 5CT/ISO 11960 manufacturing specifications. In 2007 and 2008, technical reports ISO TR10400 and API TR 5C3 were issued, which contained a collapse test procedure (Annex I) that included a section on residual stress measurement and calculation as part of the data essential to the API collapse testing procedure. The same technical reports included the best overall consensus limit state equation for predicting collapse failure, which is a slightly simplified form of the Klever and Tamano 2004 KT equation[5]. In addition to yield strength, average diameter, average wall, wall eccentricity and ovality, a term representing residual stress was also included.[6,7] Specific residual stress limitation requirements have never been proposed for inclusion in the manufacturing specifications.

The US federal government's recent regulatory tightening of offshore well design safety requirements has sparked renewed interest in improving casing collapse performance. Because residual stress is a significant contributor to collapse performance, management of residual stress and development of the tools to achieve it may very well result in a new level of collapse resistance performance.

Internal Yield Pressure Degradation

F. A. Prange and G. G. Hebard (Phillips Petroleum Co., Bartlesville, OK) presented a paper in March 1955 at the Thirty-fifth Annual Meeting of the American Petroleum Institute in which they consider the negative effect of residual stress when internal pressure is applied. They stated, "A somewhat more obscure source of plastic deformation is caused by residual stresses. If the outside of the tubing were in compression (perhaps because of working in the straightening rolls), the inside would be in tension. Application of pressure to the tubing would aid the tension stresses and thus allow yielding before the tubing reaches its nominal yield point calculated purely on the pressure, dimensions of the tubing, and the yield strength of the steel."[8]

Initial tensile yielding of the inside tube fibers in a benign environment may hardly be noticeable because there is no accompanying mechanical instability. Also, initial yielding will of necessity re-orient the residual stress profile. However, in an H_2S environment, crack propagation could be a significant problem long before internal yielding can occur due to the embrittlement of the steel.

Connection Yielding

P. D. Thomas (Asiatic Petroleum Corp., New York, N.Y.) presented a paper in June 1957 and identified residual stress as one of the properties of the round thread joint that needs to be known in order to take full advantage of the connection and set up its true limitations.[9]

Edwin Joyce (retired, former Assistant Director in charge of Standardization, American Petroleum Institute, Division of Production) in a 1962 paper titled "Joint Strengths of API Casing and Tubing" commented on the mechanics of tension failure for pipe subjected to coupling make-up stresses, stating, "The resistance of the pipe to deformation is influenced by its wall thickness (the wall thickness for the coupling in a given size is constant) and by the presence of residual stresses if the yield point of the material is exceeded."[10]

FEA connection modeling with various profiles of residual stress present may eventually enable engineers to establish connection designs with enhanced performance. Advanced residual stress modeling applied to connection design is another area for technology development and new research.

Sulfide Stress Cracking (Brittle Fracture)

In 1991, a report was made to the Task Group on Oil Country Tubular Goods which referenced a paper titled "Planning for High H_2S Concentrations" by Charles J. Levesque (Hydril Company) in which he stated, "The final microstructure and the SSC resistance in oil country steels can be improved by: (. . .) tempering at a high temperature for maximum removal of residual stresses." He went on to say, "Cold work causes an increase in residual stress that reduces the steel's resistance to SSC. Residual stresses from cold work can be removed by properly stress-relieving the affected area. Both the concern drilling engineers feel about the effect of stress relieving on resistance to SSC and the need for tight controls on the stress relieving temperature derives from the need to remove as much residual stress as possible without re-tempering the steel and thus reducing its strength."[11]

Higher-strength products such as C-90 and T-95, which are used heavily in sour applications, have some of the highest tempering temperatures of oil country tubular products. The high tempering temperatures of these grades are a direct result of the higher molybdenum and chromium chemistries specified by the manufacturing requirements. Any cold rotary straightening of these products requires stress-relieving at a minimum temperature of 480 ºC (900 ºF). All of this is aimed at removal of tensile residual stress, which promotes cracking.

In January 2011, an API Production Research Advisory Committee (PRAC) presented a report to the Resource Group on Sour Service Products in which a full size test sample of C110 in a full NACE Solution A test environment failed after 1.5 days at 2,000 psi, compared to Failure Analysis Diagram (FAD) critical pressure prediction of 3,162 psi. An FEA sub-workgroup was evaluating why an over-prediction of 58% may have occurred.[12] One possibility that was suspected was the -17.9 ksi residual stress (compression at the inner surface and in tension at the outer surface) measured in the test sample by split ring method. This residual stress is not accounted for in the FAD equation found in API TR 5C3 since it does not contain a residual stress term. Using FEA modeling of the test pipe sample and the known depth of the OD surface imperfection, the crack tip stress intensity factor K_I ,without residual hoop stress, for the full-size casing was calculated as 7.9 ksi $in^{0.5}$. Thus, without residual stress accounted for, the pipe's 15.6 ksi $in^{0.5}$ K_I material property should have been adequate to prevent crack propagation and failure at such a low pressure. Yet, it did fail. Simulating a residual stress profile of -18 ksi, the FEA program recalculated K_I. With residual stress accounted for, the K_I was now found to be 15.2 ksi $in^{0.5}$, which is very close to the 15.6 ksi $in^{0.5}$ measured material property. If the pipe had no residual stress, it would not have failed by brittle fracture. Yet, even with low levels of residual stress typical of hot straightened product (-16% SMYS), the test sample was very near its capability limit at the time of failure. In severe service environments where the product is pushed to its material limit, residual stress needs to be considered.

Straightening Process

The last process that has a significant, if not the largest, effect on the magnitude of a product's final residual stress is the rotary straightening process. In the case of cold straightening, compressive residual stress on the inner surface of the tube can exceed 50% of the product's minimum yield strength and produce significantly reduced collapse resistance or less than optimum SSC resistance.

It is not surprising that much of the standardization activity on residual stress is linked to discussions concerning the straightening process. For the most part, manufacturing requirements to improve or minimize residual stress, have been associated with straightening requirements or stress relieving procedures following the straightening operation:

- In 1985, the first ever hot straightening requirement was published as part of the Q-125 manufacturing requirements.[13]
- In 1998, restrictions were placed on the roll marks on M65 and L80 pipe rotary straightened at temperatures less than 900^{o} F.[14]
- In 2004-2005, two product specification levels (PSL-2 and PSL-3) were added to the manufacturing specification. For PSL-2 C90 and T95 grades, stress relief (after cold straightening) minimum temperature and hot straightening minimum temperature would be calculated based on the final specified tempering temperature. For PSL-2 C-95 and P-110, the same hot straightening and stress relief requirements for Q-125, namely 400^{o} C (750^{o} F) and 510^{o} C (950^{o} F), respectively, were now required.[15,16]
- In 2011, stress relief and hot straightening minimum temperatures for the new C-110 grade would be calculated on the basis of the final specified tempering temperature.[17]

The key focus for straightness improvement as a means to minimize product residual stress will be on equipment, processes, and procedures that can produce consistently superior as-quenched straightness. The straighter that a pipe is as it exits out of the quench, means that less straightening force has to be applied. This results in a reduced the level of residual stress retained by the product.

Management of Residual Stress

With residual stress affecting tubular performance in the areas of collapse, initial yielding in the pipe body, initial yielding in the made-up connection, sulfide stress corrosion, and fatigue, it is imperative that management of residual stress be improved. Effective management of complex issues depends on the development of management tools. Indeed, the standardization activities of the last 73 years have depended on and developed three primary tools that have been employed in the battle to manage residual stress. The first is the stress relief process. After all major plastic deformation processes have been completed, the tube can be heated to stress relieving temperatures and air cooled. For heated treated products like quench and temper C90, this may mean a second trip through the heat treat facility, which nearly doubles the cost of heat treatment. However, the second management tool that gets the job done without a second trip to the heat treat facility is that of hot straightening. Since 1985, this process has increasingly been employed as a very cost effective method to minimize residual stress. Standardization work has further refined the minimum stress relief and hot straightening temperature by making the tempering temperature the basis upon which the minimums are calculated. The benefit here is that if the chemistry of the product provides for very high tempering temperature, then the minimum stress relief and hot straightening temperatures can also be elevated. The third tool developed by standardization activity is the actual measurement of residual stress. Here the minimum length of the sample (2 x diameter), the test procedure (ASTM E1928), the calculation based on the sample dimensions before and after the ring is split, and a procedure for creating a product-specific calibration curve if samples less than 2 x diameter are to be used. This calculation will help the residual stress data generated throughout the world to be more consistent and higher quality.

One of the oldest tools that was developed in the 1930s to improve collapse resistance was the A.O. Smith radial compressor. A pipe is advanced through the machine a few feet at a time, and forming jaws surround the pipe circumference and radially compress the pipe to a slightly smaller diameter. This subjects the pipe to high hoop compression and plastically deforms/compresses the wall. This cold working increases the yield strength, but also it results in a hoop tensile residual stress at the ID surface that further improves collapse performance. With government regulators pressing for higher offshore safety standards, there is a need for manufacturers to increase the collapse resistance efficiency of application-specific products. The radial compressor as a residual stress management tool may need to be re-evaluated for use in the production of a new class of ultra-high collapse resistant product.

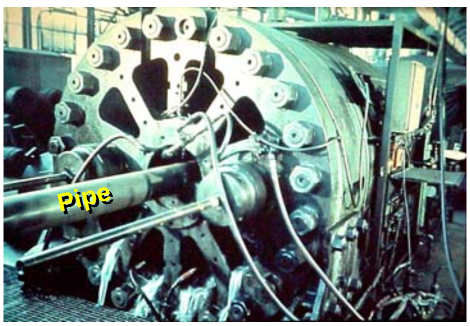

Figure 3: A. O. Smith radial compressor, Lone Star, Texas

Other residual stress management tools will be in the area of new or improved equipment, new procedures with the existing facilities or completely new processes. New equipment might be as simple as next-generation fuel-to-air-ratio controllers on the heat treat furnaces, or improved water jets or flow controls on the quench line. With all of the integrated electronic controls of modern facilities, sequence timing procedures may be another area that improves straightness and lowers residual stress. For quench and temper products, the best method of establishing a new class of ultra-low residual stress product is to consistently produce superior straightness of the as-quenched pipe. If this can be achieved, straighteners might only be needed for cosmetic purposes.

Possibly the most effective management tool would be the application of new processes that are being used in other industries. Emerging technology has repeatedly made profound changes in the tube making industry. One of the newest residual stress technologies on the horizon for the tubular industry is a technology that was developed in the aerospace industry, and now has applications in the biomedical and nuclear industries. Low Plasticity Burnishing (LPB), developed initially with the aid of NASA research grants, provides a computer-controlled process that can induce into the steel surface a near yield strength compressive residual stress field. Residual stress that is not managed has a wide scatter of magnitudes and orientations that are hard to predict. Orientations that are in the wrong direction can dramatically reduce collapse resistance, increase fatigue cracking or accelerate brittle fracture. However, near yield strength residual stress fields that are managed and precisely oriented in the right direction can produce dramatic crack mitigation results. Crack propagation in a steel tube requires tensile stress in order to generate a stress intensity at the radial imperfection tip that exceeds the steels K_I material property for a specified environment. If a deep surface layer of near yield strength compression can be introduced into the steel, then propagation of radial imperfections can be greatly mitigated.

There are a number of surface treatment techniques, such as shot peening, gravity peening, cold rolling, and laser shock peening, that can change the orientation of residual stress at the work piece surface. Those methods have long been recognized to increase fatigue strength and mitigate stress cracking.[18,19,20] Low Plasticity Burnishing (LPB), however, is a unique surface treatment process that produces a deeper and more stable layer of compressive residual stress at the surface of the work piece than the older conventional methods.[21,22] Figure 4 schematically shows the principle of the LPB application process. A high hardness ball rolls over the work piece surface under precise hydraulic pressure control and leaves in its wake a near yield strength compressive residual stress layer at the work piece surface. Figure 5 shows a comparison of residual stress distributions generated by shot peening, gravity peening and LPB. It can be seen that LPB generates much deeper compressive residual stress layer at the work piece surface and yet accomplishes this with the lowest consistent level of cold work that has been shown to produce residual stress that is remarkably stable under mechanical testing up to 2.75% plastic strain and thermal loading up to 380° C.[23]

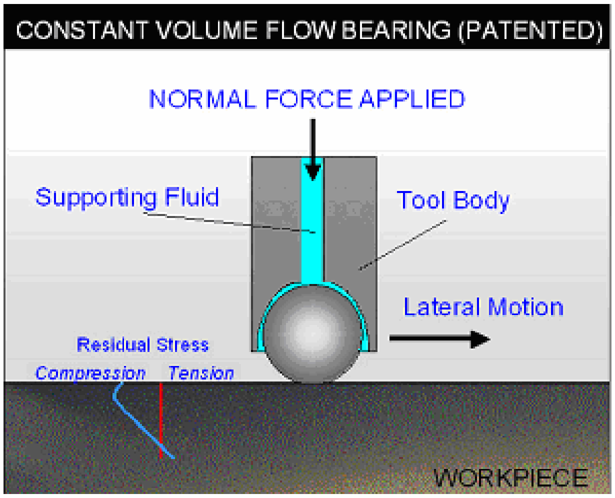

Figure 4 : LPB Application to the Metal Surface

Figure 5 : Residual Stress and Cold Work Distributions

Considering that LPB technology has shown great improvement for mitigating stress corrosion cracking (SCC) in the aerospace and nuclear industry, it was proposed that a study be carried out to determine if LPB surface enhancement could also mitigate sulfide stress cracking (SSC) in high strength oil and gas industry tubular products.[24] The material used in the study was API grade P-110 quench and temper coupling stock with 5.000 inch OD and a measured yield strength of 132 ksi. Coupling blanks were LPB processed to induce a near yield strength compressive residual stress field approximately 0.040 inch deep and covering the entire OD surface. NACE C-ring tests and full-size coupling blank internal pressure tests in 100% saturated NACE Solution A environment were conducted on both LPB treated and as-received, non-treated samples.

X-ray diffraction residual stress measurement was conducted on the LPB treated and untreated coupling surfaces. Material was removed electrolytically for subsurface measurement. The measurements were corrected for both the penetration of radiation and stress relaxation caused by layer removal. The measured results are shown in Figure 6. It can be seen that LPB introduces a compressive residual stress close to the material's yield strength and with a depth of about 0.04 inch, compared to a minor compressive residual stress layer at the original coupling surface.

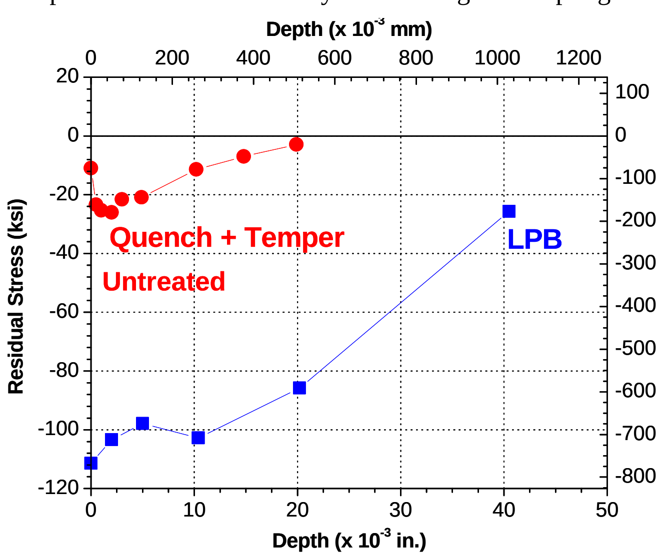

Figure 6 : Residual Stress Comparison for LPB Processed and Untreated Coupling

C-ring testing was performed on LPB treated and untreated C-ring specimens (see Figure 7) per NACE TM0177-Method C. All testing was performed in a 100% saturated NACE Solution A environment at 1 bara H_2S at room temperature. The pH was monitored continuously throughout testing to ensure conformance to NACE TM0177. Specimens were loaded initially to 45% of SMYS. LPB treated test specimens were also loaded to 80%, 85%, and 90% SMYS. Table 3 shows the C-ring test results. LPB treatment dramatically increased the SCC resistance of P-110 coupling stock in the C-ring test configuration. The untreated specimen loaded to 45% SMYS surface stress failed in 10 hours. There were no failures on LPB treated samples up to 90% SMYS with no test conducted less than 740 hours. Testing of LPB treated test samples totaled 4,202 hours.

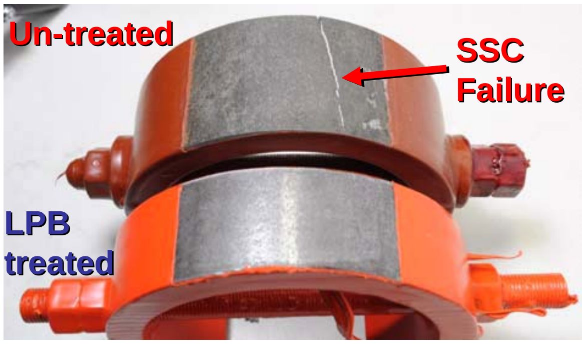

Figure 7 : Results of C-ring Testing of P-110 Coupling Blanks

Stress Loading	Sample Treatment	One-sided OD Exposure (Hours) 100% Saturated NACE Solution A	
% SMYS	None or LPB	C-ring	Full size Coupling Blank
45	None	10 - Failure	37.5 - Failure
45	LPB	1,719 - No Failure	720 - No Failure
80	LPB	822 - No Failure	720.25 - No Failure
85	LPB	820 - No Failure	734.5 - No Failure
90	LPB	841 - No Failure	-

Table 3 : SSC Testing of 132 ksi Yield Strength P-110 Coupling Stock

Full-size Coupling Blank Internal Pressure Test

Internal pressure testing of full size couplings was performed using a custom-made holding fixture connected to a pressurizing control station. The devise was designed to impart no axial load stress during the entire pressure test. Specimens loaded onto the holding fixture were placed into an acrylic vessel. The vessel with sample was nitrogen purged to eliminate all traces of oxygen. The vessel was then control filled with 100% saturated NACE TM0177 Solution A at 1 bara H_2S at room temperature until the test sample's surface was completely immersed. The pH of the solution was continuously monitored and refreshed as needed to conform to NACE TM0177. The specimens were internally pressurized hydraulically with water to apply the desired amount of hoop stress. LPB treated and untreated specimens were loaded initially to 45% of SMYS hoop stress. LPB treated test specimens were also loaded to 80% and 85% SMYS. Testing was conducted until specimen failure or at least 720 hours (30 days). Table 3 shows the internal pressure test results. LPB dramatically increased the SCC resistance of P-110 coupling stock configured as a one-sided sour environment OD exposure test. The untreated specimen loaded to 45% SMYS hoop stress failed in 37.5 hours, yet the LPB treated samples performed successfully up to 85% SMYS with no test conducted less than 720 hours. Testing of LPB treated full-size coupling blanks totaled 2,174 hours.

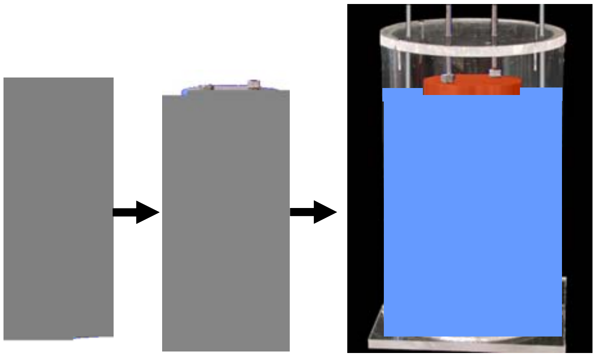

Figure 8 : Holding Fixture, Coupling Blank Assembly, and Sample Emersion within an Acrylic Vessel

Research on the effects of LPB on oil country tubular product fatigue strength, foreign object damage tolerance, brittle fracture in sour environment and other properties are currently under way.

Conclusions

Residual stress has an effect on the performance properties of oil country tubular products because they add to or take away from the applied stresses created by in service internal pressure, external pressure, axial loads, and bending. They affect pipe body performance as well as connection performance. The relative invisibility of residual stress fields and their wide scatter of magnitude and orientations due to the complexities of the manufacturing process have made management control over them difficult. Seventy-three years of standardization efforts have primarily focused on hot straightening requirements for high-strength sour service products and Q-125 high-strength casing as well as stress relief procedures after straightening. These tools of residual stress management have served the industry well.

With the recent events in the Gulf of Mexico, government regulators have added challenging requirements related to safe, acceptable well design. As a result, more attention has been focused on further enhancement of casing products' collapse performance. Here again, improved management control of residual stress for the entire length of each pipe could lead to a new class of ultra-high collapse casing. Management tools such as radial compressors, thermal cooling controls, improved quench line equipment and other processes and procedures must be reconsidered and refined to help facilitate technical advancements that improve residual stress control.

Crack propagation due to fatigue mechanisms, stress corrosion cracking, or sulfide stress cracking can have catastrophic results and can be negatively influenced by even moderate levels of residual stress. However, one new process, Low Plasticity Burnishing (LPB), is a powerful management tool that allows precise placement of near yield strength compressive residual stress to be engineered into specific parts of a tubular product that require crack mitigation enhancement. Some of the earliest products that might benefit from this emerging technology are: high-strength couplings, drill pipe, girth welds, and higher-strength sour service grades like C-110.

Appendix 1
Standards History Related to Residual Stress

1938. The first mention of residual stresses in American Petroleum Institute (API) tubular standards committee work was at the eighth mid-year meeting of the American Petroleum Institute in Wichita, Kansas, where a paper was presented titled "Casing Setting Depths Are Not Assured by Physical Properties of the Steel" was delivered by W. M Frame (The National Supply Company, Spang, Chalfant Division, Ambridge, PA.). He stated, “The results of nearly 400 collapse tests of oil country casing are described in the paper. Parts of these tests were made with various amounts of residual stresses existing in the pipe structure. The results show that unfavorable residual stresses of a magnitude not uncommon in casing can reduce the collapse pressure 15 percent or more, depending on the D/t ratio involved. The results of nearly 300 collapse tests of pipe practically free of residual stresses show that collapse pressures can be obtained that were previously considered impossible except with steel of much higher yield strength.”[25] The entire paper, including comments and rebuttals, was published the following year.[2]

1939. C. A. Dunlop (Humble Oil and Refining Co., Houston, TX) presented a paper in March 1939 which made references to Mr. W. M. Frame’s paper as follows: “The presentation of this paper created considerable interest in the subject of collapse of casing, and at the Institute's mid-year meeting, May 1938, W. M. Frame presented a paper dealing with the collapse problem, in which it was shown that some of the methods used in manufacturing oil-well casing produced high residual stresses which are of an unfavorable nature and which lowered the collapse strength of the pipe considerably. It was pointed out that a residual stress of 20,000 lb. per sq. in. was not uncommon in casing; and, from the test data included in the paper, the residual stress may be as high as 37,000 lb. per sq. in. It is the presence of this high residual stress in some pipe, and the variation in out-of-roundness and possibly wall thickness of the tube, which account for the large variation in the collapse strength of pipe made of the same material and having the same physical properties as determined by strip tests.”[26]

1939. Walter C. Main (Youngstown Sheet and Tube Co., Los Angeles, CA) presented a paper in March 1939 in which he developed collapse equations that incorporate bending and hoop stress. Although his equations did not directly incorporate residual stresses, he nevertheless cautioned the reader that, “it should be kept in mind that any residual stresses either will add to or will detract from our result”. His paper also indicates that there were disagreements concerning the method by which residual stress should be determined but admitted he had no better method to propose. He suggests that if accurate collapse equations incorporate a tube’s proportions and yield strength then it should be possible to estimate the residual stress.[27] In other words, he assumes that if his equation accurately considers everything except residual stress, then any error in its prediction of actual collapse can be attributed to the simple accounting of residual stress.

1955. F. A. Prange and G. G. Hebard (Phillips Petroleum Co., Bartlesville, OK) presented a paper in March 1955 at the Thirty-fifth Annual Meeting of the American Petroleum Institute, in which they consider the negative effect of residual stress when internal pressure is applied. They state, “A somewhat more obscure source of plastic deformation is caused by residual stresses. If the outside of the tubing were in compression (perhaps because of working in the straightening rolls), the inside would be in tension. Application of pressure to the tubing would aid the tension stresses and thus allow yielding before the tubing reaches its nominal yield point calculated purely on the pressure, dimensions of the tubing, and the yield strength of the steel.”[8]

1955. J. P. Fraser (Shell Development Co., Emeryville, CA) presented a paper in April 1955 to discuss the use of high-strength steel for oil-well casing. He included a short paragraph where he compares the residual stress levels of P-110 casing as being higher than N-80: “In addition to quench cracks, heat-treated casing is prone to residual stresses because of the difficulty of keeping the pipe straight during quenching. These residual stresses will tend to be higher than in API grade N-80 casing because higher forces are necessary to straighten the crooked pipe. Although a stress-relief anneal is commonly used after heat treating, it is difficult to anneal out all of the residual stresses without simultaneously lowering the strength, so that some residual stresses almost certainly remain.”[28] It is interesting that he mentions quench cracks but does not relate such defects to their cause, which are residual stresses exceeding the ultimate strength of the as-quenched casing.

1957. P. D. Thomas (Asiatic Petroleum Corp., New York, NY) presented a paper in June 1957 and identified residual stress as one of the properties of the round thread joint that needs to be known in order to take full advantage of the connection and set up its true limitations. He stated, “There is a dearth of information on the quantitative effects of residual stresses, although in one case at least advantage has been taken of the residual stresses being in a favorable direction for higher joint and collapse strengths. About 20 years ago, W. M. Frame presented a paper to the API, showing that average residual stresses in casing at that time were appreciable and in some instances were as high as 35,000 psi.”[9] Thomas never puts forth any specific method by which knowledge of residual stress and the round thread connection could be used tomaximize its capability.

1962. Edwin Joyce (retired, former Assistant Director in charge of Standardization, American Petroleum Institute, Division of Production) in a paper titled “Joint Strengths of API Casing and Tubing” commented on the mechanics of tension failure for pipe subjected to coupling make-up stresses, stating, “The resistance of the pipe to deformation is influenced by its wall thickness (the wall thickness for the coupling in a given size is constant) and by the presence of residual stresses if the yield point of the material is exceeded.”[10] Thus, he links deformation performance of the connection pin to residual stress if the connection make-up stresses exceed the yield strength of the pin.

1970. After 32 years of standardization discussions and study concerning residual stress, a manufacturing requirement was established that would indirectly affect residual stress by limiting a straightener’s compressive cold working after final heat treatment. The published requirement was “Grade C-95 casing shall be subjected to no tensile or expansion cold working, except for that which is incidental to normal straightening operations, and to no more than 3% compressive cold working, after the final tempering temperature.”[29]

1974. Continental Oil Company distributed a report on a casing collapse failure which reportedly was caused by slack quenched material containing excessive residual stresses. This report suggested that the industry is being penalized from 20%-30% in the collapse property of its casing by insufficient attention to and specification control of residual stresses generated by improper heat treatment (slack quenching) and by insufficient attention being given to straightening practices. The report suggested that the changes needed to secure improvements include one or a combination of the following:

a. Incorporate heat treatment quality requirements into its tubular goods specifications in the form of hardness, micro structure, or other heat treatment gradient test limitations to be imposed on some reasonable lot basis.
b. Incorporate residual stress limitations into its tubular goods specifications in the form of split-ring or other test limitations to be imposed on some reasonable lot basis.
c. Inclusion of heat treatment gradient and/or residual stress measurement data as part of the data essential to the API collapse testing procedure.[4]

The committee referred these suggestions to the Task Group on Performance Properties for study and recommendations. The documented report that prompted the committee recommendation was published the next year as an ASME paper by Parviz Mehdizadeh (Continental Oil Company) titled “Casing Collapse Performance.”[30]

1975. The Task Group on Performance Properties concluded that there was not sufficient information available to implement the 1974 recommendations. The Pipe Committee accepted the Task Group report and agreed to drop this item from the agenda.[31] The impact of the Continental Oil Company 1974 report and the suggestions it generated should not be underestimated. Even though standardization action concerning the recommendations did not go forward in 1975, hardness, micro structure, and other heat treatment gradient test limitations eventually made their way into the API 5CT manufacturing specification as requirements. Direct residual stress limitation requirements were never adopted.

1981. A paper written by Y. Nara , N. Matsuki, M. Furugen, and K. Ohyabu (Sumitomo Metal Industries, LTD.) entitled “Theoretical Study on Casing Collapse” was presented at the January 1981 meeting of the Task Group on Performance Properties. Addressing residual stress, the authors stated, “The decrease of collapse pressure is caused by the decrease of elastic limit due to residual stress. It should be noted that the effect of residual stress conspicuously appears in the transition collapse region.”[32] This importance of this statement is that it links the shape of the stress-strain curve to the effect of residual stress. The difficulty is that in order to machine a tensile test out of a tube, the circumferential residual stress is released. Thus, the only way to directly detect the effect of residual stress on the shape of the stress-strain curve would be to apply circumferential compression testing on ring samples of the pipe.

1983. In User Subcommittee discussions focused on the effect of ovality on collapse performance a paper titled "Analysis and Testing Factors Affecting Collapse Performance of Casing" by J. R. Fowler, Erich Klementich and J. F. Chappell. Concerning residual stress, it states, “The factors of D/t, Y_p, μ *(ovality)*, and residual stresses can be fairly simply accounted for in fundamental mechanics formulas.”[33,34] Interestingly, the simple accounting for residual stress is not incorporated into the derived equations.

1983. The Task Group on New Casing Items considered the opinion that for Q-125 grade, the 950°F minimum temperature at the end of the hot rotary straightening operation is too high. Experimental work was under way to show that a lower temperature is both more practical and fully adequate to prevent undesirable residual stresses. The Task Group was willing to consider the results of experimental work that would help to determine the minimum acceptable rotary straightening temperature and help minimize the Bauschinger effect and residual stresses. Several manufacturers were assigned to provide data to show that 750°F at the end of hot rotary straightening provides a suitable product, and to additionally submit data on transverse and longitudinal tensile tests.[35]

1983. The Manufacturer Subcommittee expressed the opinion that the 950°F minimum temperature at the end of the hot rotary straightening operation was too high and noted that experimental work was under way to show that a lower temperature was both more practical and fully adequate to prevent undesirable residual stresses.[36,37,38]

1984. After another 14 years of standardization discussions concerning residual stress, a manufacturing requirement was established to ensure residual stress after straightening would be minimized on product intended for sour service with hardness greater than 23 HRC. The published requirement was, "Grade C90 pipe may be subjected to cold rotary straightening if, subsequent to the cold rotary straightening operation, the pipe is heated to a minimum temperature of 900^o F (482 C) for stress relieving."[39]

1985. When API standardized the highest strength casing grade, Q-125, the manufacturing requirements included provisions for the employment of hot straightening technology for the first time. The published requirement was "Gag press straightening or hot rotary straightening (750^o F minimum at the end of rotary straightening unless otherwise specified on purchase order) is acceptable. If hot rotary straightening is not possible, the pipe may be cold rotary straightened provided it is then stress relieved at 950^o F or higher. Pipe may be cold rotary straightened without subsequent stress relieving only when agreed on the purchase order."[13]

1986. The International Association of Drilling Contractors' Permian Basin Chapter hosted a drill pipe symposium in Midland, Texas, October 28-29. Contractors compared drill pipe performance and agreed on group action to improve that performance. The Task Group on OCTG reviewed a magazine article that summarized the symposium details as follows: Drill pipe failures were transverse fatigue cracks in the tube body, 4 to 5 inches from the internal upset transition, in 4-1/2 inch grade E pipe. Seminar attendees volunteered the following possible causes, recognizing that more than one of them might play a part: corrosion; faulty heat treatment; high residual stresses; inadequate lengths of upset transitions; and operation near the drill strings' critical rotary speeds. They indicated that residual stresses will be superimposed on the cyclic stresses generated by drill string rotation and that tensile residual stresses will reduce the metal's ability to withstand the cyclic stresses, effectively reducing the metal's endurance limit. They reported that large residual stresses might be imposed during heat treating, leaving tensile stresses in the pipe's outer skin, and alternatively, residual stresses might result from cold straightening the pipe during manufacturing or during drilling operations. Seminar participants concluded that, although residual stresses might contribute to the recent problem, they were most likely not the primary cause.[40] As a side note, in 1987 the Task Group on Upsets recommended to specify a length of 2" for dimension m_{iu} for 4-1/2" 16.60# internal external upset Drill Pipe,[41] thus reducing the stress of the drill pipe run-out area and improving the ability to effectively apply coatings.

1991. In the development of straightening requirements for L-80, residual stress was a repeated topic as follows by page number :
A4-6 - "Cold work is the plastic deformation of metal at a temperature below its re-crystallization temperature. Residual stresses are increased by plastic deformation and it is difficult to predict the magnitude and direction of these internal stresses (Greer 1981)."
A4-4 - "Tempering after cold deformation decreases the probability of failure in H_2S, by relieving residual stresses. The microstructure most resistant to SSC is a fully tempered martensitic steel."
A4-7 - "SSC can result from strains arising from the additive effects of operating loads, pressure fluctuations, thermal stresses, and residual stresses during normal operation, start-up or shut down."
A6-2 - "Tubing Failure. Although not typical, this failure occurred as a result of sulfide stress cracking (SSC). Cracking initiated at the OD; 1-2 ft. from the upset and was promoted by high residual stresses in the tubing. Residual stresses were caused by severe cold rotary straightening in the mill."
A6-2 - "The failed L-80 tubing joint was unusual in that the yield strength and hardness were slightly higher than specified, and, more significantly, high residual stresses were imparted by cold rotary straightening."
A7-1 - "The final microstructure and the SSC resistance in oil country steels can be improved by: (. . .) tempering at a high temperature for maximum removal of residual stresses."
A7-3 - "Cold work causes an increase in residual stress that reduces the steel's resistance to SSC. Residual stresses from cold work can be removed by properly stress-relieving the affected area. Both the concern drilling engineers feel about the effect of stress relieving on resistance to SSC, and the need for tight controls on the stress relieving temperature derives from the need to remove as much residual stress as possible without re-tempering the steel and thus reducing its strength. To accomplish this, process control engineers must allow enough time for the dislocations within the steel to move around and reduce the internal residual stresses, yet limit the time enough to prevent diffusion and segregation of carbides, tramp elements or inclusions which might reduce the steel's resistance to SSC."[11]

1998. After several of years of discussions concerning L80 straightening requirements, the manufacturing specifications were modified in such a way that residual stress would be minimized. Grades M65 and L80 pipe rotary straightened at temperatures less than 900^o F could no longer contain roll marks that exceed hardness levels of 23 HRC, and roll marks detectible by feel must not exceed 23 HRC and could not be more severe than that established by the manufacturers document procedure. Otherwise, the material would have to be stress relieved at 900^o F or higher.[14]

2005. Two product service levels (PSL-2 and PSL-3) were added to the casing and tubing manufacturing specification that would allow users a convenient path of ordering tubular product with more stringent manufacturing requirements. PSL-2 for C90 and T95 grades included a much more sophisticated method of setting stress relief and hot straightening minimum temperatures, which would be calculated based on the final specified temper temperature. For grades C-95 and P-110, PSL-2 applies the same minimum hot straightening and stress relieve requirements of Q-125, namely 400^{o} C (750^{o} F) and 510^{o} C (950^{o} F), respectively.[15,16]

2011. A full-size test sample of C-110 in a full NACE Solution A test environment failed after 1.5 days at 2,000 psi, compared to Failure Analysis Diagram (FAD) prediction of a critical pressure of 3,162 psi. An FEA sub-workgroup is evaluating why this over-prediction of 58% may have occurred. One possibility is the -17.9 ksi residual stress in the sample pipe. This is being evaluated via FEA analysis.[12]

2011. New grade C110 stress relieve and hot straightening minimum temperatures must be calculated based on the final specified tempering temperature.[17]

Nomenclature

API	American Petroleum Institute
FEA	Finite Element Analysis
ISO	International Organization for Standardization
ID	Inside Diameter
K_I	Stress Intensity Factor at the tip of a notch or imperfection
LPB	Low Plasticity Burnishing
NACE	As meeting NACE International standard TM0177
NASA	National Aeronautics and Space Administration (USA)
OD	Outside Diameter
SCC	Stress Corrosion Cracking
SSC	Sulfide Stress Cracking

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