Final Interim Report – Task 4.2

Time-Trending and Like-Similar Analysis for ERW-Seam Failures

By

B. N. Leis
B N Leis, Consultant, Inc
Worthington, OH
43085

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U.S. Department of Transportation
Pipeline and Hazardous Materials
Safety Administration
1200 New Jersey Ave., SE
Washington DC 20590

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Executive Summary

The objectives of this report were to assess the nature of changes that have occurred in 1) the electric resistance weld (ERW) seam making process from the early days through the present, and in 2) the related quality practices and the skelp in regard to the in-service performance of ERW seams. This has been done in the context of time-trending, and through the use of Like-Similar and Compare-Contrast Analysis.

Time-trending the in-service ERW seam failure database compiled between Battelle, Kiefner and Associates (KAI), and Det Norske Veritas (Columbus) (DNVC) indicated that there has been little change over time in the in-service failure frequency for such pipe for the period from the 1950s through the present. While the overall failure rate for ERW seamed pipe remained more or less constant, the in-service failure incidence for high frequency (HF) ERW seamed pipe within the database of Battelle, KAI, and DNVC, was found to be sporadic, with failures for HF ERW seams within that database occurring at a rate roughly one-tenth that for low frequency (LF) ERW seamed pipe. Based on that database, it follows that the in-service performance of pipe made by HF processes is much improved as compared to pipe made using LF processes – although failures continue to occur. This observation of reduced failure frequency relative to the vintage LF seams reflects improvements in process control and skelp supply, and the fact that the modern process results in a tougher seam, which facilitates integrity management.

Trending the patent and related literature on LF and HF processes makes clear that both the LF and the HF seam processes are inherently similar, as both create an upset forged weld. Since the 1920s, the literature shows that such processes require pressure between the abutted edges, which are brought to a locally molten or near molten state instantaneously before the abutted faces meet to expel any oxide and other impurities to create the upset over the HAZ for the seam. The upset force to close the seam as well as temperature and speed control are essential aspects of the local response at the V where the abutted facets meet under the effects of the pressure due to the upset force, as are control of the width, alignment, and edge quality for the inbound skelp. Finally, trending the patent and related literature in view of the failure mechanisms for both LF and HF processes makes clear that absent setup and process upsets and with quality skelp available both processes are capable of producing a viable fit-for-service seam.

Because temperature, speed, upset pressure, and the skelp all can benefit from modern developments in allied technologies, one can conclude that the HF processes should create an inherently higher quality seam as compared to the now long abandoned LF processes. From an integrity-management perspective, a well made ERW seam can have properties comparable to the pipe body, and be fit for the service intended. It follows that potential issues with such seams that could lead to in-service failures trace to setup and process upsets and/or lower quality skelp. Critical in this context is the observation that when upsets do occur the HF seam remains tougher (more ductile) in contrast to the LF seam.

Tracing the history of the LF processes and then HF seam processes through the patent literature indicated three aspects that contribute to possible upsets, whose effects could differ significantly given comparable skelp supply. These aspects involved 1) the method of heating, 2) the production sequence as can-by-can versus continuous production, and 3) the benefits available over time through technology developments, which accrued to process and quality control. Through the use of Like-Similar and Compare-Contrast Analysis it was determined that two major factors can conspire against the benefits of the HF processes in regard to these aspects.

First, techniques used during production to detect upsets were not always reliable, and second, the best detection methods do not always identify bondline/seam anomalies that could lead to in-service failures. In this context it is noteworthy that the inability to detect bondline/seam anomalies can be compounded for pipe produced by LF processes when the bondline toughness is reduced as compared to that for the HF processes.

Many conclusions have been drawn over the course of this task, which have been presented throughout this report, and summarized in detail in the last section of the report. The most important of these conclusions follow here:

- Because the LF and HF processes are inherently similar and so can develop many of the same types of anomalies that trace to setup and process upsets or the use of lower-quality skelp, the shift from LF to HF processes can be expected to improve the in-service performance of pipe made via the HF processes only to the extent that specifications and inspections preclude the use of inadequate skelp, and upsets can be avoided, or their deleterious effects reliably detected;
- The HF processes affects more focused heat input that in turn leads to a more refined seam microstructure. This reduces the fracture appearance transition temperature and can lead to increased toughness and critical defect size as compared to the LF processes, all of which facilitate integrity management;
- Time-trending the in-service incidence of failures in HF ERW seams showed that the improvements in the skelp, in process control and detecting upsets affect roughly a factor of ten reduction in the failure rate as compared to that for the LF processes;
- Targeting the industry goal of zero incidents in regard to HF ERW production will require the consistent use of technology to better manage the upsets across the worldwide supply of HF pipe, to reduce the frequency of potentially problematic seam anomalies in entering the US pipeline system; and finally
- Inspection technologies were discussed to detect and size anomalies both during line-pipe production and in-service, all of which target the industry goal of zero incidents through improvements to further reduce the probability of non-detection of potentially problematic seam anomalies.

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List of Acronyms and Symbols

AC	alternating current
API	American Petroleum Institute
AOS	A O Smith (Corporation)
DC	direct current
DCWC	Direct Current Welding Company
DNV	Det Norske Veritas
DSAW	double submerged-arc weld
EI&SC	Elyria Iron and Steel Company
EMAT	electromagnetic acoustic transducer
EMI	electromagnetic inspection
ERW	electric resistance weld
FATT	fracture appearance transition temperature
FW	flash weld
HAZ	heat affected zone
HF (ERW)	high frequency (electric resistance weld)
HFI	high frequency induction
ILI	in-line inspection
ID	inside diameter
ITD	in-the-ditch (methods, technologies, …)
KAI	Kiefner and Associates
LF (ERW)	low frequency (electric resistance weld)
MAOP	maximum allowable operating pressure
MFL	magnetic flux leakage
NDI	nondestructive inspection
NDT	nondestructive testing
OD	outside diameter
PAUT	phased array ultrasonic testing
PHMSA	Pipeline and Hazardous Materials Safety Administration
QA	quality assurance
QC	quality control
RSC	Republic Steel Corporation
SAW	submerged-arc weld
SSC	selective seam corrosion (not to be confused with sulfide stress cracking, which often goes by the same acronym)
S & T	Steel and Tube, Inc.
TOFD	time of flight diffraction
UT	ultrasonic testing
UTS	ultimate tensile stress
YS&T	Youngstown Sheet and Tube Company

Time-Trending and Like-Similar Analysis for ERW-Seamed Line Pipe

Introduction

Welds that are made without filler metal, as is the case for an electric-resistance welded (ERW) seam, are in general termed autogenous welds[(e.g.,1)*]. Line pipe has been made with autogenous longitudinal (long) seams by joining the adjacent skelp faces to make a lap weld, or by upsetting the adjacent edges of the skelp to make a butt weld, which is the case for what today is termed ERW pipe. It is also the case for other similar weld types that are made with variations on the ERW seam process, like flash welded (FW) or high-frequency induction (HFI) welded pipe. All such butt welds are formed under the coupled effects of heat and pressure that is applied in the circumferential plane of the pipe, which upsets the area local to the weld seam. It follows that, at a minimum, making a quality upset autogenous weld requires the consistent application of adequate pressure and heat. But, as for any other welding process, it also requires suitable quality steel and appropriate preparation and fit-up between the abutting edges, and a well-controlled process.

As evident in prior reporting for this project[(e.g.,2)], many changes have occurred in ERW pipe making over the years. Recognizing that such changes can affect the in-service performance of ERW seams, this task as proposed was to assess the nature of the changes in 1) the ERW process, and 2) the quality control (QC) and quality assurance (QA) practices that have evolved for the seam process, and to consider their effects on integrity and to comment on relevant changes in the steel skelp. This is done in the context of time-trending and through the use of Like-Similar and Compare-Contrast Analysis.

First, the incidence of in-service ERW seam failure is time-trended based on failure analysis reports archived by Battelle[(2)], and in reporting[(3)] of the combined archives of Kiefner and Associates (KAI) and Det Norske Veritas Columbus (DNV). This is done to establish patterns (if any) as the basis for subsequent time-trending of the development of the upset autogenous weld process, and to set a benchmark to quantify important changes in the longitudinal (long) seam process over time and to comment on steel making as relevant. Next, trends evident over time and the reasons for the changes are used to establish similarities and differences over time, which in turn is used along with the in-service experience to identify the implications for ERW seam failure relative to current seam-making practices. Conclusions are then identified relative to improved integrity management for ERW-seamed pipe.

Background and Related Terminology

The early ERW seam processes involved progressively closing the seam using current supplied by contact with rolling electrodes, either as alternating current (AC), or as direct current (DC). The underlying technology was developed and evolved in the early years to produce small diameter tubes, for use in decorative and a range of applications other than the transport of petroleum products. Based on language in some early patents, the frequency for processes using AC sources ranged from 60 Hz up through values the order of 900 Hz, all of which relied on wheel (rotating) electrodes.

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[*] Numbers in superscript parenthesis refer to the list of references at the close of this report.

As time passed, and the need developed to transport petroleum products from supply reservoirs to meet the demand in urban centers, attention turned to making larger-diameter and heavier-wall pipe. As noted in the first of a series of three 1950s articles on pipe production(4), which among other topics considers the evolution of pipe-making capacity, before 1927 the total production capacity for 'large diameter pipe' in the United States was about three miles per day. That is, if all the pipe made in the US on a given day, regardless of its long-seam, was laid end to end, it would support just three miles of pipeline construction per day. The article indicates that the A. O. Smith Corporation (AOS) determined that the demand was growing, and recognized the opportunity if they could supply large diameter line pipe to a market that then was starved for such pipe.

In response to this opportunity, in 1927 AOS began construction of a mill that was in production later that year, with a capacity of four miles per day. According to those AOS authors, that 1927 mill was designed to make pipe from plate segments 30 feet long, which were formed into a tubular shape. Thereafter, the seam closed using a shielded-metal-arc weld (SMAW). They state that within a year, and more improvements, the capacity of that SMAW production was increased to 9 miles a day – "but this was not enough". Accordingly, they state that a new mill was built in 1928 designed to make large diameter pipe in 40-foot lengths, but this mill was designed to close the seam using an electric resistance FW. This FW and other early ERW practices are today referred to as low-frequency (LF) ERW production, to distinguish them from the high-frequency (HF) ERW processes that found practical success beginning in the early 1960s. According to present-day API Specifications for line pipe(5), the HF welding processes can be implemented either by using sliding contact, which generally relies on rectangular shoes, or without contact by using a HFI process.

In-Service Failures in ERW Long-Seams

According to the Research Announcement issued by the Pipeline and Hazardous Materials Safety Administration (PHMSA), which was the genesis for this project, the scope of this work responds to the National Transportation Safety Board (NTSB) Recommendation (P-09-1). That recommendation was focused on the Safety and Performance of ERW Pipe. Safety can be measured in terms of in-service incidents initiated by ERW seam failure. In contrast to safety, performance can be more broadly measured in terms of seam failures associated with ERW pipe production, the response of the pipe to increasing pressure, and the ability of inspection and integrity analysis tools to detect, size, and assess the severity of anomalies that could pose a threat in service.

Prior interim reports for Task 1 (Gather and Trend Data), Task 2 (Model and Full-Scale Testing), and Task 3 (Selective Seam (Grooving) Corrosion, SSC) that were completed under this project have considered 1) ERW seam failure experience, 2) the response of the pipe to increasing pressure, and 3) the ability of inspection and integrity analysis tools to detect, size, and assess the severity of anomalies that could pose a threat in service. These interim reports are now posted on the PHMSA website.[1] In reference to NTSB Recommendation P-09-1 concerning the Safety and Performance of ERW Pipe, these first three tasks have focused on ERW Pipe Performance. The reporting for Task 1 has trended the historical databases at Battelle, DNV, and KAI in regard to both failure experience, and the viability of hydrotesting and in-line inspection (ILI), with five

[1] For copies of this reporting, see http://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=390. That site provides downloads of each of the published reports associated with this project.

related Interim Reports now posted. The viability of predictive tools considered and the supporting data has been evaluated in five related Interim Reports developed as part of Task 2, which also are posted on the website. Finally, the work of Task 3 led to four Interim Reports that now are posted regarding aspects unique to SSC, which included developing a field tool to assess susceptibility.

With the performance aspects addressed as just noted, the last task, Task 4: Inspection Technology for Long-Seam Defects, was focused on the Safety of ERW Pipe relative to the NTSB Recommendation P-09-1, through integration and trending, and the analysis of the results of the first three tasks. The reporting for Subtask 4.1 used the full-scale and model-scale testing of Task 2: Identify Samples and Test to Quantify Seam Properties and Full-Scale Response to reassess the viability of more recent technologies to detect and size anomalies in contrast to the historic trends considered in Task 1. It also reassessed the viability of failure pressure predictions for cases where the sizes of the features in the ERW seam were better characterized and the local properties were known. In this way the reporting for Subtask 4.1 developed a bridge between the past and present. Clear improvements were evident in regard to ability to detect and size defects, and to predict their failure response as compared to the practices used a decade ago, or more. The reporting for Subtask 4.1 also discussed recent and ongoing developments, with clear opportunities evident for further improvements in regard to anomaly sizing and detection, with the benefit of improved safety for such pipelines.

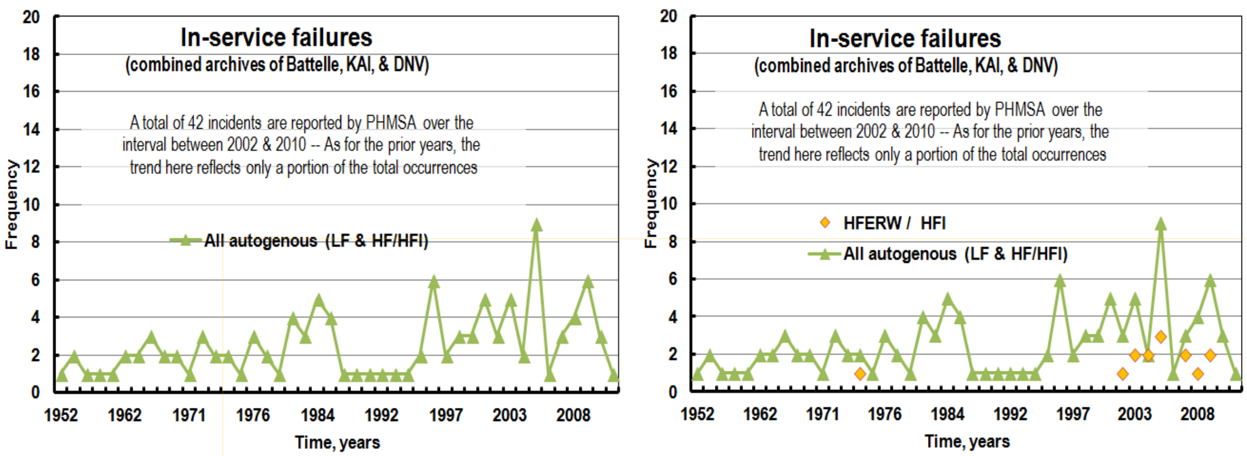
The present report presents the outcomes of Subtask 4.2 which involved compare-contrast and other analysis of the data developed to better quantify the Safety of ERW Pipe, where safety is quantified in terms of in-service incidents initiated by ERW seam failure. Thus, the reporting for Subtask 4.2 is a prelude to the final report, which presents the recommendations in regard to NTSB P-09-1 and summarizes the responses in regard to the NTSB's comments. Recognizing that the scope of incidents considered herein is limited to in-service results whereas Task 1 considered all failures (i.e., included pre-service hydrotesting and in-service hydrotesting), differences in the trends developed should be anticipated.

Against this background, the historical in-service behavior has been trended and the transition from LF to HF seam processes discussed as a basis to understand the trends. This trending makes use of the combined archives of Battelle(2) and KAI-DNV(3), which runs from the 1950s into the post-millennial era. The almost 600 ERW seam failures in that combined archive open to well over 100 in-service incidents as the basis for such trending. In concept, the PHMSA incident database is potentially more comprehensive, because it covers in-service incidents for all interstate pipelines. However, it is only since 2002 that the parameters necessary to support such trending, which involve seam type, year of construction, and details of the location and type of seam defect, have been sought for inclusion by PHMSA. Accordingly, this database is constrained to just post- millennial incidents, which precludes the "historical perspective" sought in time-trending.

Consideration was given to combining the data in the PHMSA and archival databases. While the archival reporting comprises a significant resource, its scope reflects only a fraction of the ERW line pipe in interstate service, whereas the PHMSA database reflects the much broader system. This and other differences preclude "pooling" the data, such that the time-trending herein has been done using the archival database.

Figure 1 presents the incident trends over time for the well more than 100 in-service failures that comprise the data evaluated. The y-axis in Figure 1 presents occurrences while the x-axis bins the occurrences within five-year intervals – starting in 1952 when the first in-service failure is reported in these archives. The trend in Figure 1a includes all upset autonomous seam processes, and so covers failures in both LF ERW and HF ERW / HFI seams. That trend is presented as line segments that join data points representing the total number of failures in each five-year bin. As Figure 1a notes, the results presented are but a portion of the total number of in-service incidents. Figure 1b shows the trend from part a) along with data points that represent failures in each five-year bin that occurred in seams identified as HF ERW / HFI processes, which are represented as diamond symbols. Note in this context that it is generally accepted that the LF process began to be phased out in the US production beginning about 1961, with that transition largely completed by 1970. As such, no HF-ERW failures are anticipated prior to 1961.

Figure 1 indicates that the total number of in-service failures has been increasing slightly over time, although the relative occurrence if quantified per mile[2] is anticipated to be roughly the same given the increase in system mileage over this timeframe. While the trend in Figure 1 does not indicate a decline in the incidence of in-service failures, References 2 and 3 both showed that when hydrotest failures were included in this failure population the total number of ERW seam failures shows a sharp decline after 1970. Reference 2 also alluded to an apparent upswing in ERW failures post 2000 – which is evident in Figure 1.



a) All upset autogenous seam welds **b) With the HF-process failures quantified**

Figure 1. Trends over time for in-service failures in ERW seams

The aggregated archives that underlie Figure 1 represent 36 in-service failures over the period from 2002 to 2010, which corresponds to about 87% of the 42 total ERW incidents tabulated by the PHMSA over the same period. Thus, while the approach adopted falls slightly short of full coverage of the incidents tabulated by the PHMSA, the archival database is rather complete[3].

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[2] The incident rate per-year per-mile is a viable metric in such applications, because it normalizes both time and the relative mileage in use for a given type of pipe. Unfortunately, the specific mileage in use for the database being evaluated is not know, nor could it be reliably estimated because it is only recently that statistics regarding pipe type installed per year or in service for a given company are being gathered. Because these quantities change as construction occurs and time passes, it is impractical to back-estimate such mileage for the circumstances that under lie the combined archives of Battelle, KAI, and DNV.

[3] Figure 1 presents results for "in-service failures" tabulated in the archives by Battelle, DNV, and KAI, while the PHMSA database tabulates "incidents". Depending on the circumstances that motivated the failure analysis, an

The results in Figure 1 represent the absolute number of incidents aggregated over differing amounts of LF and HF pipe mileage, which can bias the outcome of incident frequency for each of LF and HF pipe. While comparison in terms of incident rate per-mile is a better basis for comparison, statistics to quantify the amount of pipe laid by seam type and construction year are not openly available.[2]

Perspective for the relative significance of the aggregated incident rate in Figure 1 can be estimated from mileage data published on the PHMSA website[4]. That data along with industry sources indicate that roughly one-half of the US onshore natural gas and hazardous liquid transmission pipeline infrastructure (which totaled ~480,000 miles circa 2011) was in the ground prior to completing the transition to HF-ERW production. Further, it can be inferred from construction trends and experience that ERW pipe accounts for about one-third of this pipeline infrastructure. On that basis, and considering the worst yearly in-service failure rate in Figure 1, the worst-case ERW seam incident rate is about 6.4×10^{-5} per mile per year for the US Pipeline System.[2,5] In comparison to the overall incident rate, occurrences associated with the ERW long seam represent just 2.2% of the total number of significant incidents.[6] While their occurrence is a concern from a safety perspective, for both the public and environment, the management of this threat must develop in balance with the threats that underlie the other almost 98% of the incidents.

Figure 1b indicates that the first of the HF ERW / HFI in-service failures occurred circa 1974. This was a unique failure that occurred shortly after this products pipeline went into service, with cracking initiating at a hook-origin in a badly ovalized pipe that caused tension local to the seam origin. No further failures are indicated in the aggregate archival database until decades later, with a few sporadic failures occurring since then. While the trends in Figure 1 indicate that in-service failures in LF pipe have continued to occur more or less continuously, the in-service failure incidence for HF ERW / HFI seamed pipe is sporadic, and at a rate much less than that for LF ERW seamed pipe. For example, using the data for the period from 2002 to 2010 the in-service failure rate for pipe made by HF processes is just 12% of that for pipe made by the LF processes. For the period prior to 2002, the in-service failure rate for pipe made by HF processes is an order of magnitude less at just 1.3% of that for pipe made by the LF processes. It follows

incident and an in-service failure can involve the same failure. An incident is defined by the PHMSA as an unintentional releases that involve one or more of the following: fatality or injury requiring in-patient hospitalization; $50,000 or more in total costs (measured in 1984 dollars); highly volatile liquid releases of 5 barrels or more, or other liquid releases of 50 barrels or more, and liquid releases leading to an unintentional fire or explosion. Over that period, the year 2005 had the highest yearly number of incidents. As such, while the spike evident in Figure 1 could reflect a quirk in the archival database, it is not inconsistent with the trends for the broader database.

[4] http://www.phmsa.dot.gov/portal/site/PHMSA/menuitem.7c371785a639f2e55cf2031050248a0c/?vgnextoid=3b6c03347e4d8210VgnVCM1000001ecb7898RCRD&vgnextchannel=3b6c03347e4d8210VgnVCM1000001ecb7898RCRD&vgnextfmt=print

[5] The worst number of ERW incidents per year in Figure 1 is 9. The ERW mileage is one-third of the 480,000 total gas and liquid transmission mileage. Thus, the worst-case rate can be estimated as $9/(480{,}000/3) = 5.6 \times 10^{-5}$ incidents/year. Even after this is factored up by 1/0.87 or 1.15 to account for failures noted by PHMSA but not covered in the archival cases leading to a rate of 6.4×10^{-5}, the resulting failure rate is quite low in comparison to the average incident rate for the US transmission system.

[6] The website http://primis.phmsa.dot.gov/comm/reports/safety/SigPSIDet_1993_2012_US.html?nocache=2966 that presents PHMSA incident statistics indicates that seam and seam related incidents account for 2.2% of the total number of significant incidents.

that the failure response of pipe made by HF processes is much improved over that for pipe made using LF processes.

In summary, trending outlined in the above paragraph indicates that HF ERW / HFI pipe is a factor of about ten less likely to fail in-service than is LF ERW pipe, which is consistent with theoretical expectation that the fracture properties of HF seams are improved as compared to that of seams made using the LF processes. This follows from the observation that the data for the period from 2002 to 2010 show the in-service failure rate for pipe made by HF processes is just 12% of that for pipe made by the LF processes. This apparently traces to the more localized and controllable heat input associated for HF processes, which are apparent in practice in a narrower heat affected zone (HAZ), and a more refined grain size in the seam. As discussed in some detail later, more refined microstructures should decrease the ductile to brittle fracture appearance transition temperature (FATT)[7]. In turn, this should make a larger fraction of the HF seams produced more ductile at typical service temperatures as compared to the LF processes, which should make the HF processes relatively less prone to failure. These and other aspects of these seam processes and the steels used are considered in the ensuing sections, along with the QA/QC practices employed, with a view to better understand the time-trends evident in Figure 1.

Development of Early ERW Seam Processes for Line Pipe

Regardless of the specific autogenous process used to make pipe as implied above, all electric-resistance long-seam butt welds are made under the coupled effects of heat and pressure applied across the seam of the pipe, the results of which depend on the speed of production. The coupled effects of heat and pressure produce an upset local to the HAZ of the weld that is trimmed (scarf'd off), as has been discussed in detail in References 2 and 3.

While the coupled effects of heat and pressure, and welding speed, are broadly understood today as keys to a successful ERW seam, it is generally not recognized that their coupled significance has been recognized and written about for almost 90 years. Their coupled effects are elaborated in the patents[(6,7)] that underlay the first successful production of an ERW-seamed product, which was short-length small diameter tubes. It is more clearly evident in the written record of the early patent infringement litigation, which occurred between then competing ERW tube-making processes, with those three factors becoming the benchmark for such decisions[(e.g.,8)]. In this specific context, there appears to be little practical difference between the success factors for producing small diameter decorative tubes in the early 1920s versus those for large diameter pressure pipe production over the period of what is now almost a century.

Over the years, the various applicable API Specifications for line pipes[8] have termed long 'seams joined electrically welded without the addition of extraneous metal' – which by definition is an autogenous weld – as 'electric weld' pipe. The API usage of this 'electric weld' terminology since the 1940s is perhaps a consequence of a search then of the history of the ERW process,

[7] The FATT is the temperature associated with the transition from brittle to ductile behavior, which is evident in an increasing percentage of ductile response. Ductile response is evident on a fracture surface as shear versus brittle response that is evident as cleavage. The FATT is typically associated with a high percentage of shear area (% SA): often 85 %SA is adopted, with of 50 %SA being the onset of this shift to ductile behavior.

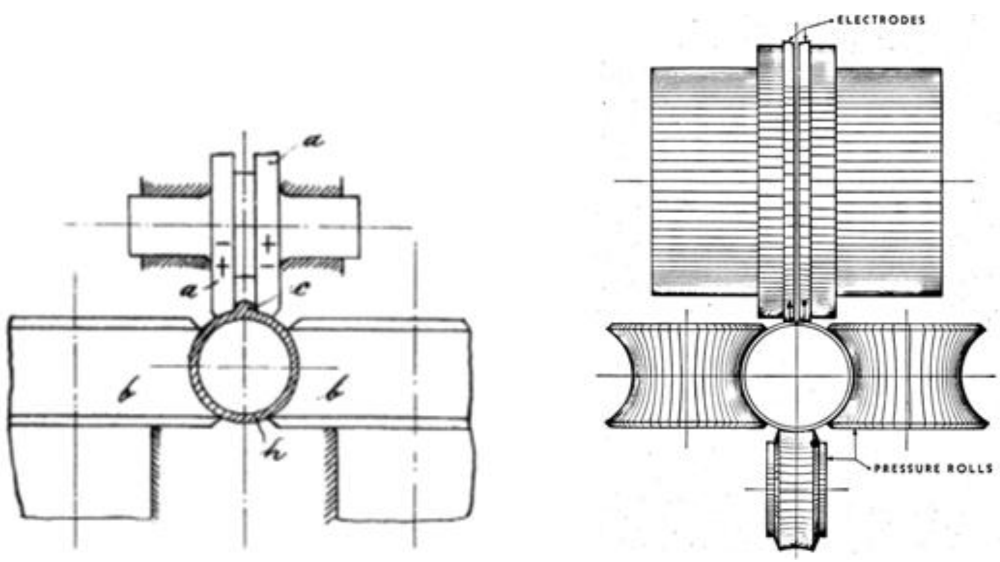
[8] The API 5L Specification[(5)], which has existed since 1928, makes reference to 'electric welding' as it was called then first in the 5th edition, with that process defined later in the 8th edition (by supplement in late 1942). API 5LX Specification, which came into use 1948 and remained in use through 1982, also addressed 'electric welded pipe' and 'flash-welded' pipe beginning in 1948, as did API 5LS.

which then as now leads to a patent granted to Thomson in 1886[9]. The apparatus and claims of that patent define a method involving an autogenous upset butt weld between the ends of two pieces of wire. The text of the introductory paragraphs to that 1886 patent describes the process that over time has become known as electric (resistance) welding, which Thomson initially coined ‘electric welding’.

Rotating Electrode (LF) ERW Processes

Subsequent patents adapted that early electric upset welding practice to close the long seam in tubes, and later in pipes – for which the term tube as used in the 1920s represented a small-diameter circular cross-section of the order of a few inches or so. The first of the patents to adapt the electric weld concept (and today’s ERW process) appears in 1889, which also was granted to Thomson for an electric lap weld[10]. Little of consequence in making tube and/or pipe emerged until 1898[11], when what appears to be the first patent to close a butt-welded long-seam in a tube using electric welding was granted. Apparently impractical based on consideration of its method[e.g., see 12], that patent was followed just two years later by the patent referred to in the subsequent extensive infringement litigation as the Parpart Process.[13]

A comparable patent of consequence to making tube and/or pipe was granted in Europe in 1912[14], whose claims also reflect a method for closing of the longitudinal seam of tubes by electric resistance welding. The figures and loosely translated claims of that Austrian Patent, as amended in its filing in Germany, indicate that two rolling electrodes are coupled with two lateral ‘pressure’ rollers to close the seam along a previously formed cylindrical can. Figure 1 of that 1912 patent shows the position and arrangement of the roller electrodes, and the shape and confinement provided by the lateral pressure rollers, all of which are comparable to the related aspects shown in the many figures in the two above-noted Johnston Patents[6,7], which were



granted much later in the US (in 1921 and 1922, respectively). The similarity between these method patents is evident in Figure 2.

a) From the 1912 European rotating electrode patent[14]

b) Concept for the 1922 Johnston patent[7] (The image is from Reference 15)

Figure 2. Similarities in concept between early patents filed in Europe and the US

The view shown in Figure 2a is reproduced from the afore-noted 1912 German patent(14), while the view in Figure2b shows the setup later presented(15) of the Johnston patents, which is reproduced from a 1934 Handbook(15) on tube production published by Steel and Tube, Inc., (S&T) to document their process and apparently also market their products. At the time that handbook was published, S&T was held by the Elyria Iron and Steel Company (EI&SC), which was assigned the rights to the second of the Johnston Patents(7). In turn, EI&SC became part of the Republic Steel Corporation (RSC), as it was formed circa 1930. While the level of detail that exists between the renderings shown in Figure 2 differs slightly, this difference is consistent with trends in the patent literature over the decade that has passed between the images shown. While the components were not identified in the original patent drawing, the view in Figure 2a includes the centerlines of the pressure rollers, which are shown there only in part. It is apparent from Figure 2a that a pair of rotary electrodes lie above the pipe, which from their shape and position in this elevation also serve to confine the tube's shape. Comparison of Figure 2b with that in Figure 2a indicates that little difference exists in concept: the only essential difference lies in is the addition of a lower support roll for the early 1920s concept.

Both Johnston patents(e.g.,6,7) are broadly referred to in US infringement litigation associated with early ERW production. Litigation(8) that involved S&T as the infringed party, which makes clear that the Johnston patents underlie the first successful ERW long seam process in the US, begins in the mid-1920s and continues well into the 1930s(e.g.,8,12,16,17). Such litigation is important in the present context because it establishes the timeline for the capability to make a functionally sound ERW seam using a rotating electrode process as being the early to mid 1920s. According to claims in Reference 15, at the time of its publication tube was being commercially produced in accordance with the Johnston patents in diameters up to 4 inches, and in wall thicknesses up to 0.238 inch. Tables in Reference 15 cite pressure capacities in excess of 4000 pounds, while other aspects note the use of flattening, cross-seam tensile testing, and pressure testing as part of the product's functional qualification. While it is clear that the initial production involved smaller diameter thinner-walled products, it is equally clear that products made circa the early 1930s involved high pressure applications in diameters up to 4 inches. The image of the through-seam cross-section reproduced from Reference 15 here in Figure 3 is not inconsistent with such claims. As shown therein, the upset material is not removed in that image – although various approaches to process the 'flash' as it was called were offered. Finally, it is noted that "because scrap increases at a greater proportion in length" they offered the product in a standard length of 16 feet.

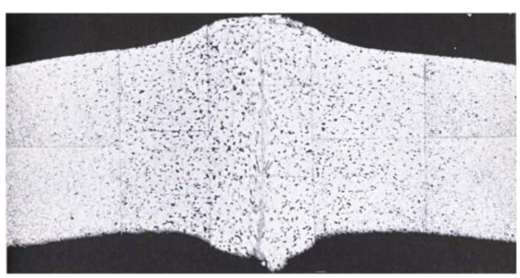


Figure 3. Cross-section montage through an ERW seam produced prior to 1934(15)

Within a year of filing his initial (process) patent, Johnston applied for a patent on an apparatus to electrically butt weld tubing, which while applied for in 1920, was not granted until 1924(18). While that tube-machine patent was still pending, Johnston applied for the tubular product patent that was cited above as Reference 7. Shortly thereafter, Johnston also recognized the need for and had developed approaches to improve his seam-process patent, with the related application filed in 1923(19). In parallel, EI&SC (who held the rights to the Johnston patents for tubular products and the apparatus) filed a quite comprehensive process and product patent in Great Britain in 1924(20). Two years after the Johnston 'apparatus' patent application and even longer after his initial process application, Axel and Nels Johnson(21) filed a patent that claimed improvements to the Johnston process. While the 1922 application of Axel and Nels Johnson was granted in 1924, as was that for Johnston's apparatus based on 1920 application, the earlier application controlled in the related infringement litigation. Even so, the similarity in names involved opens to the somewhat confusing the history that underlies the rotating electrode ERW long seam process.

In summary, the 1922 Johnston patent establishes the coupled relationship between current (heat), upset pressure, and welding speed, which served as the benchmark to establish those patents as the basis for the first successful ERW seam production. The Johnston patent two years later eventually paved the way to economic production of products with a heavier wall than the tubing of that time, and so opened the door to produce heavier wall ERW line pipe.

The Rotary Electrode Processes is Scaled-Up for Line Pipe Production

The first process patent located that included the terms 'electric welding' and 'pipe' in its title was granted in 1934 to Blevins(22)[9], and assigned to RSC. This patent made use of the rotating electrode concept, possibly because this was the basis for the Johnston tube process held by S&T (which then also was part of the RSC).

The Blevins patent is a key benchmark in the timeline for the rotating electrode process because it establishes the size heretofore produced commercially at a maximum thickness of ~0.125 inches and a maximum diameter of ~four inches. That Blevins assigned his patent to the RSC suggests that he would be aware of the scale of the S&T production, such that it is not a surprise that the diameter he cites is consistent with the maximum size claimed by S&T. While this serves to benchmark the maximum diameter produced circa 1934, the maximum thickness cited in this patent is much less than that claimed by S&T in their 1934 handbook(15), which leaves the maximum thickness produced uncertain. However, this difference could also reflect a change due to recent S&T developments that had not yet been conveyed to Blevins.

Figure 4 illustrates the key features of the Blevins patent, with this view being cut from a much more complex view of the apparatus. Specifically, the view shown is cut from near the shaft centerline of the rotary electrodes down through near the shaft centerline of the lower support roller, which encompasses the essential features of the method. When compared to the image for the Johnston patent of about a decade prior, or the German patent more than two decades earlier, it is clear that the level of detail evident between these renderings differs greatly. This is not an indication of differences in process complexity, but simply rather reflects the trend to present more detail, which is apparent in the patent literature over that period.

Although a decade had passed, the position and arrangement of the pressure rollers and the rotary electrodes for Blevins' patent are comparable to those shown in Figure 2b. Figure 4 indicates a pair of rotary electrodes lies above the pipe, identified as item 18, which from their disposition in this elevation and the related text also serve to confine the pipe shape. They act together with a

[9] Given that AOS had produced large diameter ERW pipe in 1928 via the FW process(4), whether for commercial or other reasons apparently Blevins and the RSC did not consider the FW process to be an ERW process.

pair of lateral 'pressure' rollers, identified as item 105 and its unnoted partner, and a lower support roller, just as in Figure 2b. As such, the major aspects of the process are similar in concept over the decade that falls between these patents, with similar circumstances being the case in the vicinity of the welding station throughout LF ERW production using rotary electrodes.

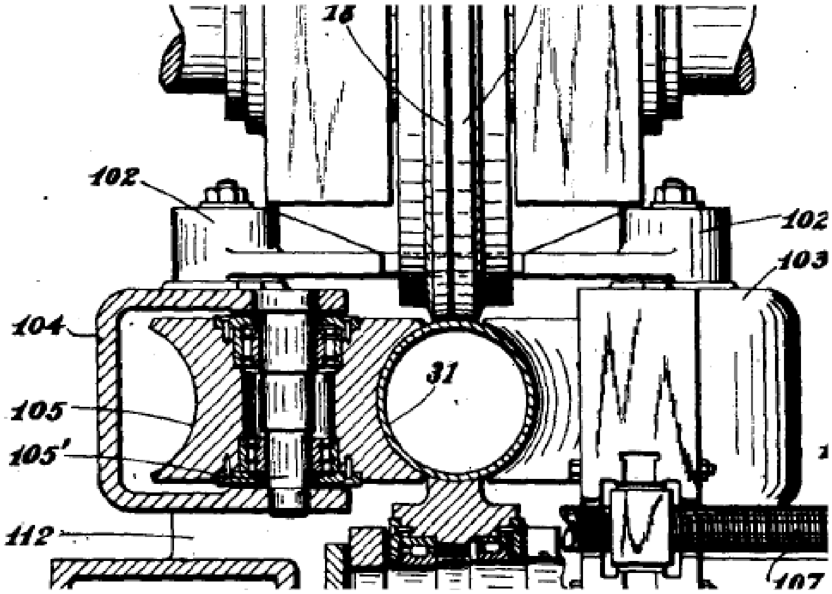


Figure 4. Pressure rollers and rotating electrodes circa 1935[22]

In summary, key aspects of the welding practice for LF ERW production using rotary electrodes have changed little since the concept was first practiced at a smaller scale to make tube since the mid-1920s, and the process as elaborated in Europe circa 1912 also being similar.

A co-pending application to that of Blevins (also assigned to RSC) was filed in 1931 by Neckerman, for the 'continuous production' of electrically welded pipe of large diameters and heavy gauge material. That patent, granted in 1935[23], also is an important benchmark in time for the rotating electrode process, because it makes clear the so-called 'continuous production' was can-by-can: the reference to 'continuous' apparently was specific to provision of a system that involved a sequence of steps that carried from inbound skelp to outbound pipe.

While patents are seldom in hand prior to the first production, it is usual to apply for patent protection at a point in time that the process is reduced to practice and the product is in hand. On that basis, it is unlikely that larger diameter or heavier wall pipe was being produced on a commercial basis using a rotating electrode process before 1931. Finally, while no constraints on pipe size are indicated, reference is made to current demand[23], among other factors, that led to noting a thickness of 9/16 inch and a diameter of 16 inches. On that basis one could infer that at least over the near term circa 1931 that sizes larger than that were not commercially produced.

The Flash Weld Process

At the same time that the rotary electrode process was being developed to make tubing and pipe, AOS was contemplating a 'flash' weld type of ERW process to make tubing. In co-pending applications for process patents in 1928[24,25], AOS set out to make tubing and pipe by making the long seam weld over the full length of a preformed can ‘substantially immediately’ in a simple and efficient apparatus. Direct current was supplied to the edges to be joined in that apparatus, with the patents granted in 1932(24,25). Figure 5 provides one view of the FW process as it was characterized in the early 1930s. This figure shows just the portion of the pipe-making machine that held the pre-formed can, and closed and welded the seam. In this view, items 58 and 41 are linear electrodes that ran the length of the pipe. The pipe is centered in this view, from which it is apparent that the pipe is supported on its exterior, but also supported on the interior local to the loading due to the linear electrodes.

Apparently also concerned for issues related to the control and other aspects of the rotary electrode process, AOS was granted a patent in 1930 for this apparatus, which included the claim that it was ‘simple and efficient’ to operate that would create the long seam simultaneously over its length based on a process patent applied for in 1930(26).

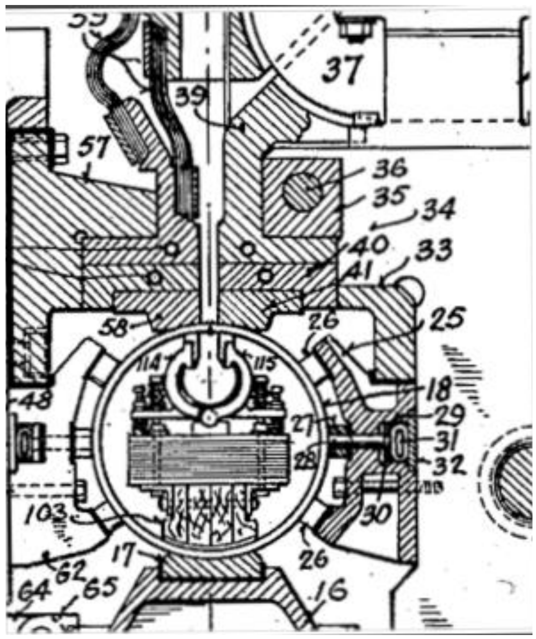


Figure 5. Patent-based view of a cross-section through an AOS machine circa 1932(25)

Consistent with the earlier assertion that patents are applied for as a process is reduced to practice, the AOS website(27) notes that in 1927 it perfected a method to economically form and weld and so mass produce large-diameter steel line pipe. While it cannot be confirmed from the patents or other literature, it appears that the processes referred to in reference to 1927 involved the 1928 patent applications. In spite of the initial patent applications being made circa 1928, a 1928 newspaper(28) notes that production of 400 miles (of unstated diameter pipe) was underway by AOS, and also indicated that they then could produce pipe in diameters up to 26 inches in segments 30 feet in length.

It follows in view of the above discussion that large diameter FW pipe was produced and likely went into service prior to pipe produced using the rotary electrode concept.[10]

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[10] According to the AOS authors that wrote Reference 4, the 1928 FW mill was producing pipe that was 40-foot in length, while the 1927 SMAW mill was not converted to produce FW pipe in 30-foot lengths until 1930. As such it appears that the pipe referred to in Reference 28 was not ERW pipe. Nevertheless, it is clear from Reference 4 that AOS was making large diameter FW pipe in 1928, such that this conclusion remains valid.

Evolution of the Early ERW Processes

The FW process just discussed relied on a DC source, and created the seam 'simultaneously' over the length of the pipe, with a suite of patents to cover that simultaneous process[e.g.,24-26]. In contrast, the rotary electrode process adopted by the RSC closed the seam 'progressively' from one end of the pipe to the other using alternating current[e.g.,6,7,18,19,29]. Because both of these two much different schemes had established process patents, either alternative schemes had to evolve as a 'design around' the concepts and claims of the existing rotary electrode and simultaneous FW patents, or the user had to pay to make use of these patented processes. Accordingly, it is not a surprise that the 1930s gave rise to alternative pipe making practices that either changed or broadened the utility of the existing schemes. The new schemes had to differ in some important way to avoid the infringement litigation, which had been initiated in the mid-1920s in regard to the Johnston patents and remained active for over a decade. Key among those early developments included the DC welding scheme developed by the Direct Current Welding Company (DCWC), and by the Youngstown Sheet and Tube Company (YS&T)[e.g.,30,31], which also closed the seam 'progressively' from one end of the pipe but used direct current.

Key considerations for all such patents included the power level required, the efficiency, the type and disposition of the transformer, and the approach used to supply the current to limit the losses.

The above-cited documentation establishes the RSC as the first successful rotary electrode pipe maker, circa the early 1930s[22], and establishes AOS as the first large-diameter pipe maker, circa 1928[4], with Reference 27 inferring the possibility it was made as early as 1927. The RSC practice is termed today LF ERW, whereas the AOS practice is today termed flash welding, as it was in the 1920s. While the process names differ, both create the long seam using an ERW process. Without reference to such documented history, the National Institute of Standards and Technology (NIST) states in their 1989 report on ERW seam failures[32] that ERW "pipe" was first produced 1929. Kiefner and Clark[33] also note a timeline for the first ERW production with reference to a 1957 paper[34] that considered this history. Reference 34 states that in "1933 production of ERW pipe was begun ….." – which is close to the date of the Republic patent for large-diameter pipe production[22], but well after 1929. Kiefner and Kolovitch[3] (without citation) subsequently noted the first production occurred in 1929, and indicate (without citation) that the RSC was the first to produce pipe with an ERW long seam.

Pipe Making Began Joint-by-Joint, and Continued So Apparently for Decades

Regardless of the specific date or the first producer, suffice it here to note that ERW pipe was commercially available circa 1930. Review of the early tube-scale production patents indicates that a major change occurred in the process sequence circa the late 1920s. Up until then, tube was made from precut lengths of skelp that were preformed into a tube shape and then welded. Starting in the late 1920s, production on a tube-by-tube basis shifted to a truly continuous process, with the tubes cut to length after welding.[e.g.,35,36]. Study of the patents for early pipe production[e.g.,22,37,38] makes clear that this production process closed the long seam in preformed cylinders, termed a 'blank' or a 'shell', as had been the case early on for tubes. Figure 6 reproduces a view of one of the early joint-by-joint production sequences, circa the mid 1930s.

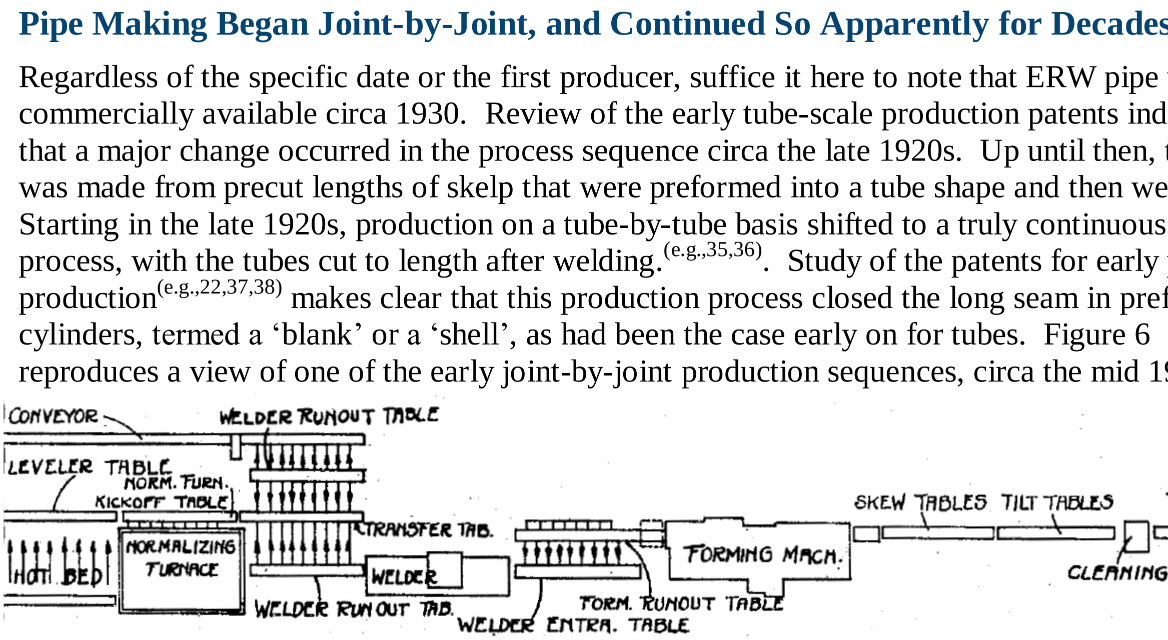

Figure 6. View of one early (circa 1934) joint-by-joint production sequence[(23)]

In some cases, the patents for the early processes also indicate that preheating was used apparently to assist in the forming process, as well as to facilitate the welding process – even though this would form an oxide skin that in extreme cases might compromise the weld quality.

Joint-by-joint production opens to setup and process variations, in contrast to what might be achieved using a steady-state process that made pipe from a continuous supply of skelp, which would separate the completed pipe from the process after the long seam was closed. In spite of the benefits that could accrue to a continuous process, apparently due to complications in that approach and other factors, patent applications for joint-by-joint pipe production continued in the 1940s, and on into the 1950s[11]. Patents for such processes were filed in that timeframe[(e.g.,39,40)], with some as late as 1956[(e.g.,41)]. That said, patents for truly continuous ‘progressive’ electric resistance seam welding processes[(e.g.,42)] also were being filed, such that by the 1950s pipe was being made with ERW seams joint-by-joint, as well as by continuous processes. Of significance in regard to the continuous processes is that some patents[(e.g.,43)] sought to limit the temperature of the preheat step. While advantageous as a cost saving and to minimize bondline oxides, eliminating the preheat also opened to the possibility of more rapid cooling of the seam, and the potential for untempered martensite in some cases. Such a transition in process could explain in part the relatively high incidence of failures in LF ERW pipe produced in the 1950s timeframe[12].

It follows from the above discussion that the LF ERW processes have changed little in concept since the late 1920s, with the essential differences over time being driven by the need to scale up in size and/or improve efficiency. It also is clear from the discussion in the 1934 S&T Handbook[(15)] that the process as it was practiced in that era could produce a ‘quality’ seam. That Handbook makes clear that seams of that era survived a range of testing, including flattening, cross-weld tensile tests, and burst tests, all of which showed failure remote to the seam. While the steels of the 1930s era have since been much improved in terms of cleanliness/chemistry and processing, some grades were listed in the Handbook with values of the ultimate tensile stress (UTS) up to 80 ksi. Given that those steels failed in burst testing remote to the seam, the LF process of the early 1930s could produce a very strong viable seam that was fit-for-purpose, which remained the case up through the transition to the HF processes.

Thus, it also follows that the issues evident in the context of Figure 1 for LF processes do not indicate that those processes were inherently problematic, but rather suggest that upsets in those processes underlie the in-service and hydrotest failures. Realizing that bondline defects such as cold welds and stitched welds reflect process upsets whereas hook cracks and selective seam (or grooving) corrosion reflect issues with skelp quality[(2,3)][13], the continued use of a LF seam process that has its roots in the late 1920s was not the primary cause of the trend evident in Figure 1.

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[11] Given 1) the capital sunk in equipment to produce joint by joint, and 2) the benefits by the transition to use of the emerging HF technology, it is reasonable to assume that companies that had a major investment in joint by joint production would persist in its use until HF processes were being perfected in the 1950s.

[12] Reference 43 summarizes ERW seam failures tabulated from various sources including Reference 33, with the data therein and the related analysis indicating the clustering of incidents in the 1950s, which could trace in part to the reduced use of preheating and/or a reduced preheat temperature.

[13] Process upset is used here generically, covering not only current-supply issues but also issues with the skelp such as leveling, edge preparation, alignment, and follow-up processes like scarfing, etc.

Finally, it follows that until upsets in such processes are managed (i.e., avoided or detected online), such in-service failures can be anticipated to persist.

Practical HF ERW and HFI Processes Emerge Circa the Late 1950s

As the processes collectively termed LF ERW evolved, it became evident that much more efficient production could be achieved via HF processes. This was because the HF processes could focus the energy to create the bondline between and local to the interfaces to be joined. This process efficiency and other potential benefits due to the use of a HF in lieu of a LF ERW process were recognized quite early. For example, a 1931 patent was filed that while granted much later in 1937[(44)] targeted 'improvements in the electrical methods of heating plates or tubes'. The introduction to that patent states "my invention is a method of confining or concentrating the heating current to the portions in which the heating is desired." It continues noting that the benefit "is to lessen the cost and improve the quality and uniformity of the welding by reason of superior control." While the introduction to that patent only vaguely notes "using an alternating current of the necessary frequency," later in that patent reference is made to a frequency the order of 30 KHz. It was, however, until the 1950s that the vision of a contact-based HF ERW concept from the 1930s found practical utility through a series of patents due to Rudd, and coworkers[(e.g., 45-47)]. Likewise, it was about the 1950s that non-contact HF ERW – so called HFI – began the transition from concept into practice[(e.g.,48)]. Rudd and his colleagues were likewise engaged in this aspect[(e.g.,49)], along with others early during its development[(e.g.,50)]. These early HF patents laid the foundation for the developments that continue to evolve today, with current production based on this concept using what could be viewed as third-generation technology relative to that at the close of the 1960s.

As for the LF processes, little has changed conceptually following the early developments that ran into the later 1970s, with the essential differences over time being driven by the desire for better control and improved efficiency. Research has targeted theoretical modeling and understanding of the physics[(e.g.,51)], and the capability to 'tune' both the process and mechanical setup to produce a given thickness of skelp[(e.g.,52,53)]. In addition, technology has become increasingly available as the years have passed, which has been adapted to sense temperature, and other process variables. References 52 and 53 are good examples of the adaptation of technology to understand the effects of heating, while such adaptation in the late 1970s capitalized on advanced image processing and related aspects.

Both contact and noncontact HF processes have benefited from technology development or adaptation, in regard to process control[(e.g.,54,55)] and online inspection[(e.g.,54-56)]. Each has also benefited from the availability of skelp that has been designed specifically for such applications[(e.g.,57)], although this and the other benefits begin to become evident primarily for the post-1980s production. The related literature indicates that aspects of the technologies involved to date capitalize on adaptation from parallel fields, as well as make use of developments specific to ERW production.

As for the LF processes, work done to evaluate the strength and other aspects of the quality of HF seams indicates that when the seam is produced under control it has properties that are comparable to the pipe body, and otherwise is free of integrity issues[(58-60)]. Thus, the few HF failures evident in the context of Figure 1 do not indicate that the HF processes are problematic. Rather, as noted for the LF processes, the failures evident for the HF processes in Figure 1 reflect upsets in the setup and/or production of the seam. Likewise, as for the LF processes, such failures can be due to issues with skelp quality – whether made in the early 1960s or post 2000.

It follows that until upsets in the HF processes that have the potential to fail in-service are uniformly managed (i.e., avoided or detected online), failures can be anticipated to occur. Because both the contact and noncontact HF processes have benefited from technology development or adaptation in regard to process control[(e.g.,54,55)] and on-line inspection[(e.g.,54-56)], it is reasonable to anticipate that the HF processes will be inherently less prone to failure than the LF processes. The trends evident in Figure 1 bear this out. Such controls must ensure adequate heat supply and cross-seam upset to create the weld, with appropriate inspection available to detect the consequences of upsets when the controls fail across the pipe for all producers sourced by US operators. The implications of these topics are discussed further in the ensuing sections.

Low versus High Frequency Long Seam Processes

Compare – Contrast Analysis

It follows from the review of the above discussed patents for the LF and HF processes that the essential difference between these processes lies in the method or scheme used to heat the abutting faces of the skelp. The patents also provide for positioning and alignment of the abutting edges in ways unique to the method of heating. Although these LF and HF processes differ in such mechanical aspects, because the early patents[(e.g.,5,6)] as well as the modern processes[(e.g.,51,52)] both recognized the need to 'tune' their setup for a specific thickness of skelp, such mechanical aspects can be taken as secondary to the success of a particular method of heating. In addition to the just noted difference in heating method, as just discussed in regard to the HF processes, technology has become increasingly available as the years have passed, which has benefited the contact and noncontact HF processes. As noted above, these benefits affect better process control, online inspection, and the skelp used – with the technology supporting these benefits well developed largely for post-1980s production.

Aside from differences in the method of heating, and the benefits of the passage of time, both the LF and HF processes create a forged weld, both require pressure between the abutted edges that are brought to a molten[14] state instantaneously before the abutted faces meet to expel the oxide and create the upset over the HAZ for the seam. Clearly temperature and speed control are essential facets of that response, as is control of the width and edge quality of the inbound skelp. Because all such aspects benefit from modern developments of allied technologies as noted above, one must conclude that the HF process has the potential for inherently higher quality.

Another benefit that derives from technologies made available as time has passed is that the HF mills have been designed as new mills or were reworked from existing facilities to support continuous production. In contrast to the mix of joint-by-joint and continuous production

[14] High-speed imagery for the HF process shows that well developed droplets[(e.g.,52,61)] form along the very narrow heated zone prior to the V where the edges abut, and indicates a steep thermal gradient along the length of the faying surfaces as they approach the V. This indicates the steel has fluid-like properties as it enters the V, wherein the material is clearly above the solidus temperature for the local alloy content and very near and/or above the liquidus. One recent treatise on welding[(1)] states that 'the presence of liquid is essential' for such processes, such that the steel local to the faying surfaces is molten, albeit for a very short time, and goes on to add that the liquid serves to flux the abutting edges. Research on HF seams[(52)] indicates that the edges of the abutting faces are molten through the thickness prior to contact between them. Whether or not this molten state existed for the LF processes, or exists for other HF processes is unclear, but it does exist at least in the context of the cases just cited.

processes in use with the LF seam processes that existed as the transition to HF processes began in the mid to late 1950w, all HF mills known to the author currently make use of a continuous production scheme, and so generally run under steady-state conditions.

In parallel, and more critically, in the 1960s the API specifications added requirements for the nondestructive inspection (NDI) of seams(62), and the post-weld heat-treatment (PWHT) of seams(63), which have been updated periodically since. This coupled with steel-mill and pipe-mill process controllers and online monitoring and NDI has led to more consistent steel and pipe production. Another major change that began circa the 1960s involved the realization that steel cleanliness and rolling practices contributed significantly to the problems with brittle fracture that became evident in the pipeline industry in the late 1950s(e.g.,64). As the steel cleanliness improved and sulfide shape control became common practice, the threat posed by brittle fracture could be eliminated by appropriate steel specification.(e.g.,65) Likewise, the presence of inclusion stringers or worse yet flattened bands of inclusions was greatly diminished.(e.g.,65) In turn, the threat of hook cracks and also selective seam corrosion diminished – as both are directly tied to steel quality[15]. The presence of impurities such as sulfur and phosphorous also can affect reduced toughness(e.g.,60). But, it was well into the 1980s before sulfur was reduced below the threshold whereby step gains in toughness became evident.(66)

Over this same period, work to improve the properties of steel also was initiated to reduce the grain size of steels, through selective microalloying and thermomechanical rolling practices. In materials where grain size directly controls the mechanical and fracture properties, this reduction in grain size affects increased strength, with the potential also for reduced FATT and increased toughness.(e.g.,67) Because steels generally exhibit this response, the localized heating associated with the HF processes reduces the heat input as compared to the LF processes, so relatively less grain growth occurs for the HF processes. While this opens to the benefits that accrue to more refined microstructures in the HF pipe, it must be recognized in this context that "there is considerable uncertainty regarding the …. appropriate definition of grain size."(67) Thus, while the HF processes do give rise to a refined grain size in contrast to the LF processes, there is some uncertainty in its effect. That being said, studies of the bondline developed using HF processes typically show very high toughness levels and low FATTs,(e.g.,59) whereas the LF processes show arguably much lower toughness values and much higher FATTs. While such dependencies exist, it is also clear that scatter abounds in this dependency(e.g.,59) so its benefit is variable. Such variability could in part explain the significant scatter in local fracture properties measured in ERW seams.

As happens for cases where seam defects form, it appears that cases where low values of FATT have been evident for HF processes are associated with a process upset, as for example in the PWHT. This is evident in work by Groeneveld(68) wherein one end of one of five randomly supplied pipe HF joints[16] showed a FATT of +60°F while the other end had a FATT of -20°F. And while the HF bondline typically shows very high toughness, some work involving burst tests of HF pipe(69) infers toughness values more typical of the LF processes. It follows that upsets in the HF processes can lead to response that is not too different from that apparent for LF seams. This possibly traces to variability in the local microstructure, and the variability of

[15] These aspects are further discussed in References 2 and 3, and in other literature cited therein.

[16] Reported in 1992 as recent US and foreign production using microalloyed controlled-rolled steels made in Grades X-60, X-65, and X-70: all seams reported to be subject to a PWHT (normalized).

the FATT and toughness as a function of the scale of that microstructure. The significant upside for the HF process is as noted above that it is more controllable, and so is much less prone to such upsets as compared to the LF processes. Thus, it is not a surprise that in-service failures in HF pipe evident in the results in Figure 1 tend to reflect pipe made early in the timeline for HF pipe production, prior to the evolution of on-line process sensors and controllers.

Some aspects of the modern process, such as preparing the skelp or plate and its forming into pipe, are comparable for both the LF and HF processes. This can be seen by comparing Figure 6, which shows one early production sequence (circa 1934), with Figure 7, which shows a typical production sequence for modern HF production. Figure 6 is reproduced from an early process patent, while Figure 7, is reproduced in part and adapted from the documentation of a pipe-mill of one modern ERW producer(70). While some similarities exist[17], there are some significant differences evident in the modern production sequence, which involve online NDI and the use of sensors. This is typical of modern pipe mills, in contrast to their absence in Figure 6. Annex A provides further details on such online NDI processes, whose development continues to evolve, as does the scope of their use. This continuing development benefits significantly from parallel developments that are underway in sensor technology and data interpretation and processing algorithms for both in the ditch (ITD) and ILI tools.

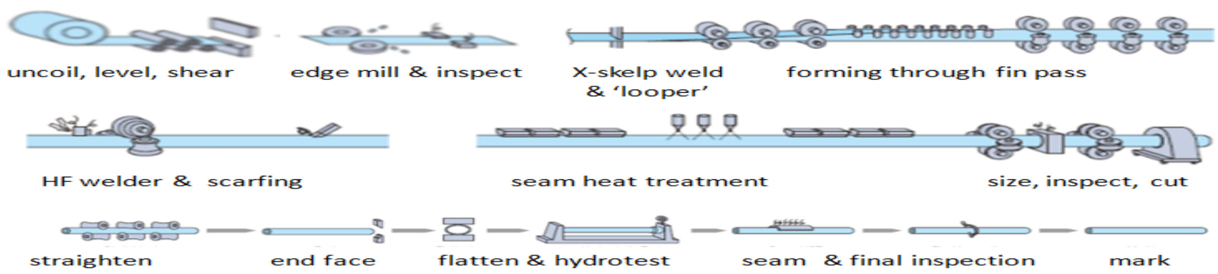

Figure 7. Production sequence for one modern HF pipe mill(adapted in part from Ref. 70)

[17] This is not to infer that all LF production was can-by-can, as prior text notes the shift to continuous production aided by a 'looper' up front and 'traveling cut-off' upon completion was indicated to start in the early 1950s.

Apparent Benefits of the HF Processes

The above compare-contrast process coupled with information presented in select patents(e.g.,48,71) helps identify a number of high-level benefits that accrue to the HF process, which affect both production efficiency and line-pipe seam quality, including:

1. Improved process control, resulting in more consistent melting/bonding along the abutting faces into the apex of the seam and a higher quality seam;
2. Focused current flow into the abutted edges, with shallow penetration, resulting in more efficient production, and the avoidance of grain-coarsening that tended to produce brittle bondlines in LF pipe;
3. Potential for higher production rates as a consequence of 1 and 2 above;
4. Seam quality is less sensitive to process parameters and setup variability, with less concern for electrode trimming and related maintenance; and
5. Arc burns and related aspects can be avoided.

Like-Similar Analysis

It is apparent from the above discussion that the only essential differences between the HF and LF processes involve the method of heating and continuous versus can-by-can production for the early LF processes. Like-Similar Analysis of the in-service history of the LF seam processes follows to assess the extent to which these two process differences indicate the potential for a significant reduction in the in-service failure trends for the HF processes relative to that for the LF processes.

Consider first can-by-can versus continuous production. A steady-state continuous production process avoids the individual setup of each weld, and avoids the differences in end fixity and related HF process variations as the end of the can is reached in a can-by-can process. As such, the weld cracking observed near the ends of a joint with the FW process are avoided, as should other alignment related defects observed for the LF processes. Trending Battelle's database(2) suggests that the majority of those features large enough to be problematic appear to have been exposed early on in the service life of the LF seamed system. As such, it is unlikely that this aspect of can-by-can versus continuous production is a factor in the continued incidence of LF failures evident in Figure 1. In turn, no major difference in the history of in-service failures is indicated relative to the use of a continuous HF process versus a can-by-can LF process.

A steady-state continuous production process likewise avoids the need to restart the seam weld process and so avoids the joint by joint process variations that can occur in a can-by-can seam process[15]. However, trending again suggests that the majority of features due to major process variations that were large enough to be problematic appear to have been exposed early on in the service life of the LF seamed system. Thus, it is unlikely that this aspect of can-by-can versus continuous production is a major factor in the continued incidence of LF failures evident in Figure 1. Thus, again, no significant difference in the history of in-service failures is indicated relative to the use of a continuous HF process versus a can-by-can LF process.

Insight as to the causes for the continued failure of the LF seamed production based on the text of the patents suggests that the majority of the process upsets reflect a dirty or uneven contact interface between the electrode and the surface of the skelp, and in the maintenance of the electrodes. Each of these causes of process upset can occur without bias in can-by-can as well as continuous production. As such, it is unlikely that anomalies formed due to such upsets would vary selectively depending on the production sequence. Again, no significant difference in the history of in-service failures is indicated relative to the use of a continuous HF process versus a can-by-can LF process.

It follows that Like-Similar Analysis does not point to a major shift in in-service failures due to the type of production sequence. This is simply because the major source of historic LF process failures trace to causes of upsets that do not discriminate between a continuous HF process and a LF process that was produced can-by-can.

The second essential difference between the HF and LF processes involves the method of heating. Reality in this context is that – absent upsets – both the LF seam process and the HF seam processes produce a sound weld. Clearly, it can be argued that the HF processes are more easily controlled, and are used in mills that make use of more sophisticated sensors and improved process controllers. Thus, if the upsets that lead to imperfections that could pose a threat can be reliably detected through those sensors or managed/avoided by use of those controls, and if those sites are adequately tracked and excised or repaired using an acceptable practice, then Like-Similar Analysis indicates that modern HF seams should show a reduced incidence of failures as compared to earlier HF or LF seamed pipe. This is the situation evident in Figure 1.

Two major factors also conspire against the just-noted outcome. First, techniques such as spark detection that are used by some producers to detect upsets during production(72) are not always reliable. Second, as discussed in Annex A, if a seam is produced without a physical separation between the abutting faces, but the bondline lacks adequate strength to transfer load across that interface, the best existing on-line ultrasonic detection methods cannot detect that weakness. On this basis, Like-Similar Analysis relative to experience with LF seam data does not infer any significant change in the failure incidence for pipe produced via HF seam process if such defects develop de to a process upset.

It follows that the only certain way to further improve HF processes and reduce their in-service failure frequency is to manage such upsets, with more certain process controls to avoid them and better detection to preclude such pipes reaching the right of way.

Implications: HF versus LF Processes

The above-listed benefits suggest that there should be a significant difference between the in-service performance of pipe made using the modern HF processes in contrast to that seen for pipe made using the early LF practices. The results in Figure 1 support this expectation, as the rate of in-service failures in HF pipe is less than that for LF pipe by about a factor of about ten. The ensuing paragraphs provide perspective for the trends in failure rate evident in Figure 1 for pipe produced by LF and HF processes, and assess their implications relative to if and when further benefits might accrue that affect the relative incidence of in-service failures for HF versus LF production.

Consider first insight that can be gleaned from recent US experience with the construction of several cross-country larger diameter pipelines during the period from 2007 through 2009. In that interval, operators such as Boardwalk and Kinder Morgan experienced what became known on the PHMSA website as 'low-strength pipe' issues. These issues became apparent following the post-construction ILI that identified excessive deformations, apparently due to the pre-service hydrotesting of that new primarily Grade X70 construction. There also was one unexpected failure that occurred in that hydro testing that was traced to a 'switched slab', which occurred during concurrent rolling of similarly-sized slabs steel for different jobs, and also some issues with girth welds. As time passed, these issues led the PHMSA to issue Advisory Bulletins[73], and gave rise to critical inquiries by stakeholders[e.g.74].

Given that X70 steel had been produced prior to 2007 for about 40 years, and mill-procedures were in place to track slabs, there was no apparent reason to expect such difficulties. It became evident as research into the causes moved forward[e.g.75] that newer steel and pipe producers were involved, with the issues in part traced to concerns with the quality controls in place, and related considerations. In this context, newer or less experienced producers, as well complacency for existing producers, can contribute to in-service failures for the HF pipes, such as those evident in regard to Figure 1.

Another factor that could promote in-service failures is that the introduction of any new product is initially followed by a higher than normal frequency of problems – so called 'infant mortality'. Few new steel or pipe mills have entered production recently in the US, so infant mortality is not a major issue in relative terms for domestic production. However, the US exists in a global economy, and steel and pipe are produced in nonintegrated operations worldwide, so US buyers have the option to source their pipe in a world market – where many new companies have begun to produce both steel and pipe. Mills are qualified by the operators prior to purchasing pipe, which is done in accordance with the requirements of the many consensus Standards and Recommended Practices that are incorporated by reference into the US Regulations and Codes. So it falls on the operators and their mill inspectors and inspection practices to manage this potential concern.

At best, consensus requirements establish minimum expectations. Minimal benchmarks coupled with developing steel and pipe mills in a global pipe market opens to the possibility that 'infant mortality' is continual. Accordingly, it is usual for operators to expand on those minimum requirements as necessary and/or appropriate, and make use of in-mill inspection to ensure that what is specified is delivered. However, experience indicates that even where operators use in-mill inspection, and bolster the minimal consensus requirements with their own purchase standards, issues such as 'low-strength pipe' as noted above still occur. So care must be exercised when pipe and steel are sourced from new suppliers, particularly in a global setting.

While Figure 1 has been developed in reference to archival data, when such trends are developed using the PHMSA incident database[5] the trends that develop over time can be affected by changes in the incident reporting requirements. Several significant changes in what constitutes an 'incident' have occurred over time beginning in 1984, and have occurred since at different times for the gas and hazardous liquid systems, not always in the same year. Such changes can be manifest in time-trending as in Figure 1 in two ways. First, when trending is based on frequency, changes that typically involve more stringent requirements lead to a relatively increased incident frequency. Second, because the HF seam is generally much tougher and more ductile than that made via LF processes, process upsets that cause anomalies large enough to become an issue in service are prone to cause leaks rather than ruptures, and so lead to relatively smaller releases. This benefit of the HF process is evident for when trending in terms of spill volume, for example, but is lost when frequency is used in lieu of product loss, or consequences.

Finally, while process changes affected through the use of HF in lieu of a LF heating can reduce the frequency and extent of bondline anomalies during steady-state production, this alone does not ensure a quality seam, Three additional factors must be addressed: 1) clean quality skelp must be used, 2) online process controls and sensors must be involved to identify setup and process upsets, and 3) the NDI used must be capable of detecting imperfections that might occur during process upsets, whose size is large enough to eventually pose an in-service threat to integrity. As Reference 76 makes clear[18], the HF seam processes can be prone to many of the same types of anomaly that have been experienced with LF ERW seams. As such, the just-noted three factors could affect the trends evident in Figure 1. Upsets in the HF processes thus pose an integrity threat comparable to that for LF process – only at a reduced frequency in what is generally a tougher seam that helps to mitigate their presence.

Much also has been done to research and control the HF process(e.g.52,55,72,81,82) and understand the causes for HF anomalies(e.g.,61,83,84), as the basis to adapt the process to limit their formation. That being said, it is apparent that the list of HF seam producers doing such research is limited in contrast to the number of producers, so ‘caveat emptor’ applies when sourcing ERW pipe or the skelp supply in a global market. When coupled with the gas-industry goal of zero incidents(85), Figure 1 indicates that there is room for improvement in HF seam process control and inspection, particularly in regard to the continued entry of new producers into the global supply chain for the US transmission systems.

Prior analysis and discussion has made clear that the problems that underlie Figure 1 are due to setup and process upsets, with both HF and LF seam processes being viable otherwise. It follows that hitting the industry target of zero incidents in reference to ERW pipe will require improvements to limit or detect such upsets, with a focus on: 1) skelp supply, 2) online process controls and sensors to identify upsets, and 3) NDI to detecting imperfections cold eventually threaten integrity.

While avoiding in-service issues with ERW seamed pipe is dependent on improvements in mill QC and QA, as elaborated in Annex A, the need for effective pre-service high-pressure testing in the mill, and again post-construction also remains. But recognizing that such controls were in place to some extent in regard to Figure 1, there also is a need for periodic ILI supported by verification digs using viable ITD technologies. Related reporting(86,87), reinforced by the discussion in Annexes B and C, makes clear there is room for improvement in this context as well.

[18] Several papers address defect types that have occurred in HF seams(e.g.,76,77), which can include susceptibility to selective attack in the seam(e.g.,78-80). One paper authored by a HF welding equipment producer(76) discusses the “most common (seam) defects” and in that work cites nine defects in total – just in the bondline. Identifying nine bondline defects for the HF processes relative to the five or so anomalies commonly noted for the LF processes suggests the HF processes is more prone to defects. Such is not the case, as many of the nine can be considered subsets of the anomalies known for LF seams.

Summary and Conclusions

Prior reporting for Task One indicated that many changes had occurred over time in the way ERW seams were made. The objectives of this report were to assess the nature of changes that have occurred in 1) the electric resistance weld (ERW) seam making process from the early days through the present, and in 2) the related quality practices and the skelp in regard to the in-service performance of ERW seams. This has been done in the context of time-trending, and through the use of Like-Similar and Compare-Contrast Analysis.

Time-trending the in-service ERW seam failure database compiled between Battelle, Kiefner and Associates, and Det Norske Veritas (Columbus) indicated that there has been little change over time in the in-service failure frequency for such pipe for the period from the 1950s through the present. While the overall failure rate for ERW seamed pipe remained more or less constant, the in-service failure incidence for high frequency (HF) ERW seamed pipe within that database was found to be sporadic, and at a rate roughly one-tenth that for low frequency (LF) ERW seamed pipe. It follows that the in-service performance of pipe made by HF processes is much improved as compared to pipe made using LF processes. This observation reflects improvements in process control and skelp supply, and the fact that the modern process results in a tougher seam, which facilitates integrity management.

Trending the patent and related literature on LF and HF processes makes clear that both the LF and the HF seam processes are inherently similar, as both create an upset forged weld. Since the 1920s, the literature shows that such processes require pressure between the abutted edges, which are brought to a locally molten (or near molten) state instantaneously before the abutted faces meet to expel any oxide and other impurities to create the upset over the HAZ for the seam. The upset force to close the seam as well as temperature and speed control are essential aspects of the local response at the V where the abutted facets meet under the effects of the pressure due to the upset force, as are control of the width, alignment, and edge quality for the inbound skelp. Finally, trending the patent and related literature in view of the failure mechanisms for both LF and HF processes makes clear that absent setup and process upsets and with quality skelp available both processes are capable of producing a viable fit-for-service seam.

Because temperature, speed, upset pressure, and the skelp all can benefit from modern developments in allied technologies, one can conclude that the HF processes should create an inherently higher quality seam as compared to the now long abandoned LF processes. From an integrity-management perspective, a well made ERW seam can have properties comparable to the pipe body, and be fit for the service intended. It follows that potential issues with such seams that could lead to in-service failures trace to setup and process upsets and/or lower quality skelp. Critical in this context is the observation that when upsets do occur the HF seam remains tougher (more ductile) in contrast to the LF seam.

Tracing the history of the LF processes and then HF seam processes through the patent literature indicated three aspects that contribute to possible upsets, whose effects could differ significantly given comparable skelp supply. These aspects involved 1) the method of heating, 2) the production sequence as can-by-can versus continuous production, and 3) the benefits available over time through technology developments, which accrued to process and quality control. Through the use of Like-Similar and Compare-Contrast Analysis it was determined that two major factors can conspire against the benefits of the HF processes in regard to these aspects. First, techniques used during production to detect upsets were not always reliable, and second, the best detection methods do not always identify bondline/seam anomalies that could lead to in-service failures. In this context it is noteworthy that the inability to detect bondline/seam anomalies can be compounded for pipe produced by LF processes when the bondline toughness is reduced as compared to that for the HF processes.

Many conclusions have been drawn over the course of this task, which have been presented throughout this report, and summarized in detail in the last section of the report. The most important of these conclusions follow here:

- The LF ERW processes have changed little in concept since the late 1920s, with the changes over time being driven by the need to scale up in size and improve efficiency;
- The LF ERW processes as practiced in the late 1920s and early 1930s could produce a ‘quality’ seam, which passed a range of testing, including flattening, cross-weld tensile tests, and burst tests that showed failure remote to the seam;
- The issues that underlie the incidence of in-service failures for the LF ERW seamed pipe reflect setup and process upsets and/or issues with skelp quality, with the relative significance of the resulting defect(s) aggravated by the lower toughness and higher FATT generally associated with upsets;
- Until upsets in the LF seam processes are better managed (i.e., detected in-line or via pre-service hydrotesting), in-service failures can be anticipated until the population of near-critical defects is fully exposed;
- The potential benefits of the HF seam processes, such as the capability to focus the energy local to the abutted interfaces to be joined, leading to more efficient production, were recognized as far back as the early 1930s, but did not become practical until the later 1950s;
- The HF processes affects more focused heat input that in turn leads to a more refined seam microstructure, which reduces the fracture appearance transition temperature and can lead to increased toughness and critical defect size as compared to the LF processes, all of which facilitate integrity management;
- Both contact and non-contact HF processes offer the potential for better process control, and have been researched to enhance seam quality;
- Little in concept has changed for the HF processes since the developments of the late 1970s;
- Technology has become increasingly available as the years have passed, which has been adapted to better control the HF processes;
- Techniques such as spark detection are being researched to improve detection of process upsets;
- While online inspection continues to evolve, current technology relies on physical separation of the interface between abutted surfaces, which falls short of detecting weaker bondlines that could fail in-service;
- Skelp has evolved to support ERW production of better quality and higher strength grades of steel;
- In-service failures for the HF seam processes – whether made in the early 1960s or post 2000 – reflect either process upsets or issues with skelp quality, just was the case for the LF seam process;
- Until upsets in such HF processes are managed (i.e., avoided or detected online), in-service failures can be anticipated to persist;

- HF seam processes are prone to the many of the same bondline anomalies experienced with the LF processes, and where lower quality skelp is used can develop selective seam corrosion, and hook cracks;
- Time-trending the in-service incidence of failures in HF ERW seams showed that the improvements in the skelp, and in process control and detecting upsets affect roughly a factor of ten reduction in the in-service failure rate as compared to that for the LF processes;
- Targeting the industry goal of zero incidents in regard to HF ERW production will require the consistent use of technology to better manage the upsets across the worldwide supply of HF pipe, to reduce the frequency of potentially problematic seam anomalies in entering the US pipeline system; and finally
- Inspection technologies have been discussed in the Annexes that have been adapted to detect and size anomalies both during line-pipe production and in-service, all of which target the industry goal of zero incidents through improvements to further reduce the probability of non-detection of potentially problematic seam anomalies.

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ANNEX A: MILL SEAM INSPECTION TECHNOLOGIES

Prepared by Mr. E. B. (Ted) Clark of Battelle's Pipeline Technology Center.

Annex A: Inspection Technologies used in ERW Pipe Mills

Various methods have been used in pipe mills over the years to determine the seam quality of ERW and FW line pipe. Prior to the introduction of electromagnetic and ultrasonic seam inspection methods, seam inspection and weld quality were essentially implied from the results of destructive tests and other nondestructive tests (NDT) that were part of the pipe manufacturing process. Over time, seam NDT was phased into the production process. Some of the NDT methods were captured in pipe specifications and others were specific to pipeline companies.

API 5L and 5LX Related Long Seam Inspection Timeline

The first edition of API 5L was published in 1928. Inclusion of a general term "electric welded pipe" occurred in 1931(4th ed.). Weld seam NDT was not required at that time but the pipe was hydrotested, subjected to flattening tests, and a weld tensile test had been added. It wasn't until the 9th edition (1944) that the term "electric welded pipe" was defined to specifically include ERW, and mentioned the FW pipe manufacturing process. In early 1955, the 14th edition of API 5L contained a reference to "non-expanded" electric welded pipe with respect to the frequency of required flattening tests. Cold expansion would have provided another long seam integrity evaluation prior the introduction of long seam NDT. From about 1948 to 1963, unless additional inspection (that may have included early UT and/or eddy current methods) was required by the purchaser, the primary FW or ERW seam inspection involved the mechanical testing noted above. Based on the UT and eddy current development timelines considered in the following sections, it is unlikely that only a very rudimentary seam NDI could have been performed prior to 1948. In 1963 (20th edition), specific methods of long seam NDT were required for any "electric welded" pipe that included ultrasonic, electromagnetic (eddy-current), or continuous magnetic particle methods.(1)

The 1st edition of API 5LX was published in early 1948. Both FW and ERW pipe were allowed. No long seam inspection was specified but transverse weld tensile tests, cold flattening, and hydrostatic testing were required. Cold expansion was not mentioned initially. In late 1954 (5th ed.), cold expanded FW and ERW were added to the process of manufacture. In the 11th edition of 5LX (1963), it was required that ERW and FW pipe seam must be inspected by ultrasonic, eddy-current, or continuous MP. From the results of numerous mill inspection reports reviewed from this period, later ERW mill inspections, and API specifications, it can be stated that cold expansion of ERW pipe was only done on a limited basis, whereas FW pipe was cold expanded. Thus, from 1948 through 1963, unless additional inspection was required by the purchaser, the results of the just-noted mill inspection methods served as the primary criteria to qualify ERW seams.(2)

Ultrasonic and Eddy Current Inspection Background

In the US, numerous eddy current methods for comparing similar products were patented between 1925 and 1945. Many of these early material comparator systems were not well accepted by industry. Some of the early applications were continued through associations with large companies (i.e., Republic Steel, General Electric, etc.) with one developing large-scale, automated eddy current devices for inspection of tubes, bars, etc. The development of commercially viable eddy current inspection equipment was hampered by the lack of significant long term support. Military requirements during WW II accelerated the development and demand for NDT equipment. Additional industrial eddy current development was facilitated by more advanced electronic circuitry and instrumentation developed for wartime use. Aerospace and nuclear NDT requirements for improved, more sensitive methods further stimulated research. However, the industries involved (and related government agencies) in this development were more focused on UT methods than on eddy current methods. It wasn't until the arrival of Forster from Germany that eddy current testing began to achieve industrial acceptance in the US. Based on work conducted earlier, Forster developed the basis for many types of eddy current equipment. From 1950-1965, primarily based on Förster's work, improved eddy current methods were developed and achieved industry acceptance. His methods were transferred to NDT equipment companies starting in 1952. Forster formed an alliance with Magnaflux that lasted about 10 years, and later he worked with Krautkramer Branson.(3,4)

Although the principles of ultrasonic testing (UT) were known in the late 1800's, its initial development was slow. During WW I, a pulse echo UT system was developed to locate submarines and was used for hydrographic surveys between WW I and WW II. In Russia, Sokolov was the first to use through transmission transducers with continuous waves to locate defects in metals circa 1935. Working with continuous, through transmission waves in metals proved to be difficult due to the effects of reflected waves. A second issue that stymied development was also in play. Available electronics and instrumentation was inadequate. Such instrumentation was very complicated and required operators that were technically trained even for laboratory functions. During WW II, like eddy current testing, the advanced electronic circuitry derived from wartime sonar and radar development was adapted for UT applications. Improved electronics plus the adaption of pulse echo UT methods were developed in Europe and in the US. At this point in time, only straight beam UT defect detection methods were being used, because UT wave mode conversion in metals could not be easily interpreted. In the US, a patent was issued to Firestone in 1942. His investigation included straight beam UT inspection of welds that had been ground flush which was not a practical application. Finally, in 1947, a shear wave transducer was developed that allowed rapid adaptation to metals and other purposes. Earlier UT defect detection systems relied on vacuum tubes, needed clean power, and were bulky. Also signal amplitude and resolution were poor. By the mid 1970's, more advanced electronics were incorporated that improved UT defect detection performance. Following WW II due to increasing demand for NDT, UT became generally accepted as a practical methodology.(5,6,7)

Eddy Current versus UT Inspection

As eddy current and UT equipment became practical, tools for long seam pipe inspection, UT was more accepted and became the preferred method. UT was capable of detecting smaller defects and could potentially determine defect size. Eddy current was more suited for detection of defects close to the inspection surface while shear wave UT had the potential to detect defects throughout the weld seam.

A survey conducted by the API provided some insight regarding pipe manufacturer's weld seam NDT preferences. In addition to basic long seam inspection in ERW pipe mills, so called "end effects" were a manufacturer and user concern (especially those that used pre-cut skelp). The pipe ends were often not inspected or incompletely covered during the seam inspection process due to equipment limitations. In order to evaluate this issue, a questionnaire was distributed by API Committee 5 to pipe manufacturers and users. In response to NDT methods the manufacturer's response indicated that their seam NDT systems consisted of 40% UT, 27% electromagnetic inspection (EMI), and 25% UT+EMI. The remainder used other combinations of these including MPI and even radiographic testing in two cases. In 71% of the responses, such inspections were performed automatically or semi-automatically. More than half of the responders (55%) reported that 100% coverage of each weld end inspected was not achieved.[8]

Even with this early knowledge concerning comparative capabilities of UT and eddy current as applied to FW and ERW seams, some ERW manufacturers still continued to use only eddy current long seam inspection. This was practice primarily evident in smaller diameter pipe mills and continued into the well into 1980's.

Pipe Production Long Seam Inspection

FW pipe was produced primarily by AOS in Milwaukee and Houston (the Page-Hersey pipe mill in Canada also produced FW for a short time). Hydraulic cold expansion was done between 1930 and early 1950. In 1950, a mechanical expander was installed in the Houston plant and at the Milwaukee plant in 1951. As a result of competition from the double submerged-arc welding (DSAW) pipe manufacturers who were providing full length weld seam radiographic inspection, AOS installed an early model Sperry UT system at both mills in 1957. UT was selected instead of eddy current because it was considered to be more capable of detecting defects associated with the FW process, such as hook cracks, which could initiate at either the ID or OD whereas external eddy current methods were only sensitive to OD cracks. The Houston facility was converted to DSAW production in 1969 which effectively ended FW pipe production for line pipe applications, although the Milwaukee mill continued pipe production for about two more years.[9,10,11]

Some 1937 FW pipe production inspection reports reviewed mentioned the additional pipe hydrostatic burst tests that were conducted to provide an additional demonstration of FW integrity. Such tests were conducted in the 1930's and 1940's until pipe users began to more widely accept the FW process. Also, a submerged-arc welded (SAW) cap pass was made on the OD surface trimmed weld flash to improve seam integrity which was an early production issue. The SAW cap weld was used in the 1930's and into the 1940's. Since FW pipe was primarily produced by one pipe manufacturer, the weld seam inspection process documentation is more comprehensive as compared to ERW pipe.[12]

With respect to ERW pipe seam mill inspection, documentation of the methods throughout the industry has not been well documented. It is known that many variations existed since beginning production in the late 1920's. It is not clear when weld seam inspection by eddy current and or UT methods were first introduced into ERW mills but the NDT development timeline previously discussed indicated it probably occurred in the late 1950's and into the 1960's.

ERW seam inspection in the various pipe mills was far from a standard practice, especially during the earlier period of production and even into the 1980's. Initially, the only seam inspection was conducted just after seam welding by first generation single frequency eddy current methods and/or simple ultrasonic inspection systems. Also, the API pipe specifications did not stipulate the location of weld seam NDT in the pipe production process.

Later on, probably in part due to user demands, a second NDT site was typically located after hydrostatic testing (and cold expansion, if used). The initial NDT site was then considered as serving a "mill control" function while the second was the basis for "final weld seam inspection" prior to mill/customer final pipe inspection. Weld seam NDT after stress application (hydrostatic test and cold expansion) was preferred since the detectability of smaller seam defects was improved, particularly for UT systems. This included improved inspection systems, especially improved shear wave ultrasonic transducers. However, pipe mill literature from the 1970's and 1980's still indicated that the application of early inspection methods persisted. In one case from the 1980's, a manufacturer stated that a first generation eddy current device (Farrow Tester) was being used in conjunction with ultrasonic inspection after the welder. This was followed with a post hydrotest UT inspection. In the same time period, another ERW manufacturer continued the use of eddy current equipment alone for mill control weld seam testing.

In addition to production long seam weld, other applications, primarily ultrasonic were also used at various mills. This include edge inspection on the incoming steel skelp prior to pipe forming and an attempt at overall steel quality inspection by a single, automated ultrasonic probe that move across the skelp body. Also, offline, secondary manual UT inspection was used to confirm the results on online inspection indications as a basis for determining pipe disposition.(13,14)

A look at the state of ERW pipe mill NDT in the early 1970's is provided by a Battelle project progress report to the API dated December, 1972. In 1970, the API sponsored a project aimed at development of improved tests and procedures for evaluation of ERW pipe long seams. Problems during field hydrostatic testing were occurring from small leaks or ruptures originating in the weld seam due to "cold welds". With respect to ERW long seam inspection, this program focused on existing UT and eddy current technology along with the latest versions of these methods that were not being used in pipe mills. UT variations included pulse-echo evaluation of unstressed and stressed (pressurized) pipe along with acoustic emission and other techniques. Multifrequency eddy current was considered to be a viable improvement compared to the single frequency methods currently in use was not initially evaluated since new inspection systems, trained operators, and new procedures would have been required. One result from the work conducted to this point was that pulse-echo UT sensitivity improved when the stressed pipe was tested.(15) Due to the complexities associated with multifrequency eddy current inspection applications, there is no evidence to suggest that this technology has ever been used in a pipe mill.

Another ERW production issue consistently encountered especially in mills that welded coiled skelp is camber. This condition resulted in a weld seam that was not completely straight but assumed a long arc as it proceeded through the welder and into the initial NDT station and through post weld heat treatment. If such a condition existed and it was not closely monitored, the weld NDT would likely not be centered on the weld seam and similarly for the weld heat treatment equipment. The result was a incomplete or non-existent weld seam inspection, particularly where no other seam inspection was used later in the production practice. Adjustment of initial online weld seam inspection and heat treatment equipment was typically accomplished manually although seam tracking methods were being developed.

Additional insight into ERW seam camber issue in the 1970's is provided in Reference 13. It was stated that final weld seam ultrasonic inspection was conducted on individual cut pipe lengths at one ERW mill and was performed with a manual shear wave device. At this point in time, weld seam tracking and UT transducer positioning equipment had not been sufficiently developed to allow an automated system.

Yet another issue in ERW mills that existed even into the 1980's involved the NDT calibration methods. Some pipe mills, particularly smaller diameter producers, preferred to perform static calibrations and then operate the mill at high speeds approaching 200 feet/minute. In some cases, no other weld seam inspection was conducted. Since defect detectability was effectively reduced by the high speeds, some customers objected to this method. This led to third-party weld seam inspection of the finished pipe prior to final acceptance or additional inspection provided by the manufacturer using available offline inspection equipment. Calibration usually included full pipe sections or smaller "saddles" made from pipe material which contained notches and/or drilled holes.

Summary

To meet the need for higher quality pipe, inspection was added to the manufacturing process and improved as technology advance driven by other industries and seam welding processes developed. The key findings include:

- Weld seam inspection of ERW and FW pipe was not required by API 5L and 5LX until 1963 although earlier inspection systems were most likely in use since the late 1950's.
- Since FW pipe was primarily produced by one manufacturer, the weld seam inspection timeline is comparatively well established. For ERW pipe, however, the timeline is less clear. Only ultrasonic and eddy current seam inspections have been used but in various combinations and equipment vintages that were not standard throughout the industry. Older eddy current devices have been used in some ERW pipe mills into 1980's and possibly later.
- In ERW pipe mills, UT applications after hydrotesting was brought in (circa 1970's) due to customer requests and probably as a result of industry projects indicating the benefit of testing after the pipe had been subjected to stress. Cold expansion was infrequently used in ERW pipe mills.
- Prior to the introduction of seam weld NDT, FW and ERW quality could only be inferred from other destructive and nondestructive tests required by API standards. This included flattening tests, cross seam tensile tests, and hydrostatic testing. FW pipe was periodically subjected to full scale hydrostatic burst tests during the 1930's and 1940's.

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ANNEX B: IN-LINE SEAM INSPECTION TECHNOLOGIES

Prepared by Dr. J. B. Nestleroth of Kiefner and Associates.

Annex B: In-line Inspection Technologies for Weld Seams

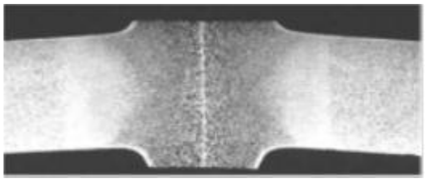
In-line inspection methods for pipelines have been used for assessing pipeline anomalies since the 1960s. Each implementation of an inspection technology typically focuses on a subset of the pipeline anomalies that affect pipeline serviceability. Because corrosion was the first anomaly considered, many methods to detect and size corrosion are mature and broadly used by the pipeline industry. In contrast, the ILI methods for seam weld anomalies that are commercially available came into development much later, and so have been evolving as they are used. As in all such developments, new technology and methods are introduced to overcome the limitations that have been identified, such as the incorrect identification of anomalies when none are present (false calls), failure to detect anomalies, and sizing discrepancies. This annex evaluates the outcomes noted to this point and their implications for potential inspection technologies in applications to seam weld anomalies.

Anomaly Implications

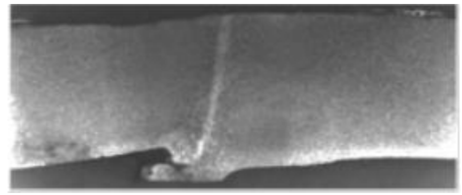
Various weld anomalies can be found in or along the bondline and heat affected zones. Anomalies at the interface/bondline are the most challenging for nondestructive testing. Since these anomalies can be as thin as an oxide layer, not all inspection modalities are appropriate. The properties of the interface can affect the reflection and the transmission factors for the sound waves impinging the interface, thus affecting the signals used to detect and size these anomalies. A subset of the interface anomalies is selective seam weld corrosion. This can be considered a separate class of anomalies for the bond line anomalies because of the loss of metal. In addition to ultrasonic methods, because of this loss of metal, magnetic flux leakage techniques can be added to the list of potentially appropriate technologies.

For cracks in the HAZ, ultrasonic methods can be appropriate technologies, although the through-thickness angle of anomalies in skewed seams, as evident for example in Figure B1, can be an important factor, as discussed later. If the crack is open, as the case for many hook cracks, magnetic flux leakage methods can again be an appropriate technology. In the ditch inspection method procedures typically use magnetic particle inspection methods as a first pass to detect bond line anomalies such as cold welds and stitching. Thus, any magnetic flux leakage (MFL) method that has the magnetic field oriented across the weld has the potential to detect seam weld anomalies. Detection is best when the anomaly is open to the ID surface. Sizing is a function of depth, length, and width of the opening, which makes precise quantification difficult.

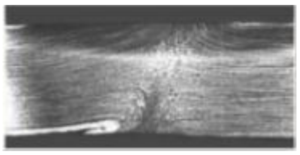
The upset and trim associated with the fabrication of the weld is an important variable, because these typically produce what are spurious signals. Signals from weld defects combine with the spurious signals from the upset and trim to produce a signal pattern that is complicated and thus must be carefully analyzed. For welds with a consistent trim, the signal processing methods can be tuned and used to extract the signals from the anomalies. A typical weld signal can be generated by averaging recorded data from several axial measurement positions. To detect defects, the average weld signal is subtracted from the measured signals. This difference should reveal the anomaly signal only, but also shows natural variations in the welding process and potential defects. If there is a local variation in the trim, the change produced by this factory condition can be misconstrued as an injurious defect to some technologies The quality of the weld and the trim define the false alarm and false dismissal rate of the inspection technology, the former being an economic issue and the later a safety issue.



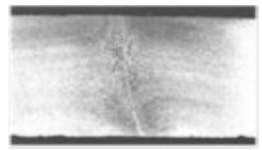
a) near perpendicular FW: t = 0.250”



b) poorly matched YS&T: t = 0.312”



c) strongly skewed YS&T: t = 0.250”



d) slightly skewed Republic: t = 0.250”

Figure B1. Views of Cross-Sections Through Intact Seams, after the Flash Was Trimmed.

The inspection tools are developed for ideal weld geometries with the interface between the two edges of the pipe essentially planar and vertical. While this is nominally the case, non-uniform heating and upset can cause a deviation in the interface. Based on the images for some of the examples shown earlier in Figure B1, worst-case interface angles of 20 degrees or more can develop. This variation is likely to adversely influence the ultrasonic methods that rely on the return of reflected energy. The deviation of the weld interface can direct the reflected sound in unexpected directions while mode conversion can, in addition to sending the wave in an unexpected direction, cause the wave to arrive at unexpected times. Either case may cause signals from weld anomalies to go undetected.

When developing an inspection technology, knowing the dimensions and characteristics of a critical anomaly early in the development process can influence engineering decisions such as resolution and aperture. The size must be defined in terms of length along the axis of the pipe and depth or percentage of the wall thickness. One issue is the length relative to the aperture of the inspection technology. If the length of the anomaly is large compared the aperture of the sensor, then the depth of the anomaly is typically a simpler function than if the anomaly is shorter than the aperture. Unfortunately, the critical length of anomaly is a function of mechanical properties such as fracture toughness, one of the topics being addressed in the current research program. Therefore, certain technologies being deployed are based on parameters derived from pipe operators’ intuition or rules of thumb. The converse implies that new definitions of critical anomaly dimensions may require modifications to existing tools.

Implications for Existing Inspection Technologies

Implementations of inspection technologies typically focus on a subset of the pipeline anomalies that affect pipeline serviceability. For the seam weld problem, three technologies are viable:

- Magnetic flux leakage inspection with the magnetization in the circumferential directions, transverse to the more typical axial field;
- Angle beam ultrasonic inspection with the energy generated by piezoelectric transducers; and
- Plate wave ultrasonic inspection with the energy generated by electromagnetic acoustic transducers (EMATs).

Each technology is discussed in turn below.

Magnetic Flux Leakage

MFL systems, regardless of configuration, can be designed to remain functional in an abusive pipeline environment for long distances at product flow speeds. The source of inspection energy (permanent magnets) requires no energy during an inspection and the sensors and data recorders require reasonably low power to operate. The magnetic flux naturally enters the pipe and distributes evenly to produce a full volumetric inspection. While the deficiencies of MFL systems are often highlighted, these attributes keep MFL at the forefront of pipeline inspection technologies.

MFL systems can detect cracks, as evidenced by magnetic particle inspection that is a MFL-based method that has been used for over a century. The strongest signals come from cracks that have broken to surface where the sensor is located. Also, the width of the crack opening plays an important role in detecting these anomalies(1). To be effective in detecting axially aligned features, the magnetization direction must be such that the magnetic field crosses the seam weld. The most common approach is circumferential MFL, which is transverse to the more typical axial field used in the earlier MFL systems. A new implementation of MFL uses an oblique magnetization direction; the output is a combination of the axial and circumferential response(2). For the seam weld anomalies considered earlier, the non-axial MFL configurations are the most appropriate to detect selective seam corrosion at the interface and hook cracks in the heat affected zone. Sizing these anomalies can be challenging since the amplitude of the MFL signal used to perform this task is a function of three variables (axial length, radial depth and the circumferential opening width). Besides amplitude, the only other independent measure is the length for the three variables. Depth is more difficult to accurately assess because of the potential variation in crack opening. To overcome this limitation, calibration methods for the cracks on the specific pipeline are used to provide better estimates. A patented method for detection of cracks and performing such a depth assessment is available(3). Variation in trim of the seam weld can produce signals that are affected by other implementation issues, and thus affect performance of these ILI tools(4).

Some early research on circumferential MFL shows the potential of the technique for selective seam weld corrosion(5). Figure B2 shows strong signals are possible from selective seam corrosion in ERW pipe. In addition, nearby metal-loss corrosion is also visible. When both selective seam corrosion and metal-loss corrosion occur, the signals superimpose which confuses their interpretation. Based on these results, circumferential MFL has the potential for detecting selective seam weld and metal loss corrosion; however, many implementation and signal interpretation problems remained.

Angle Beam Ultrasonic Testing

Angle beam ultrasonic inspection methods with the energy generated by piezoelectric transducers are commonly used in many industries for detecting cracks in metals. Implementations for ILI became commercial in the mid 1990s[6]. These systems require the pipeline to contain liquid media for coupling the ultrasound from the transducer into the pipe; this complicates the utilization of this technology for natural gas pipelines.

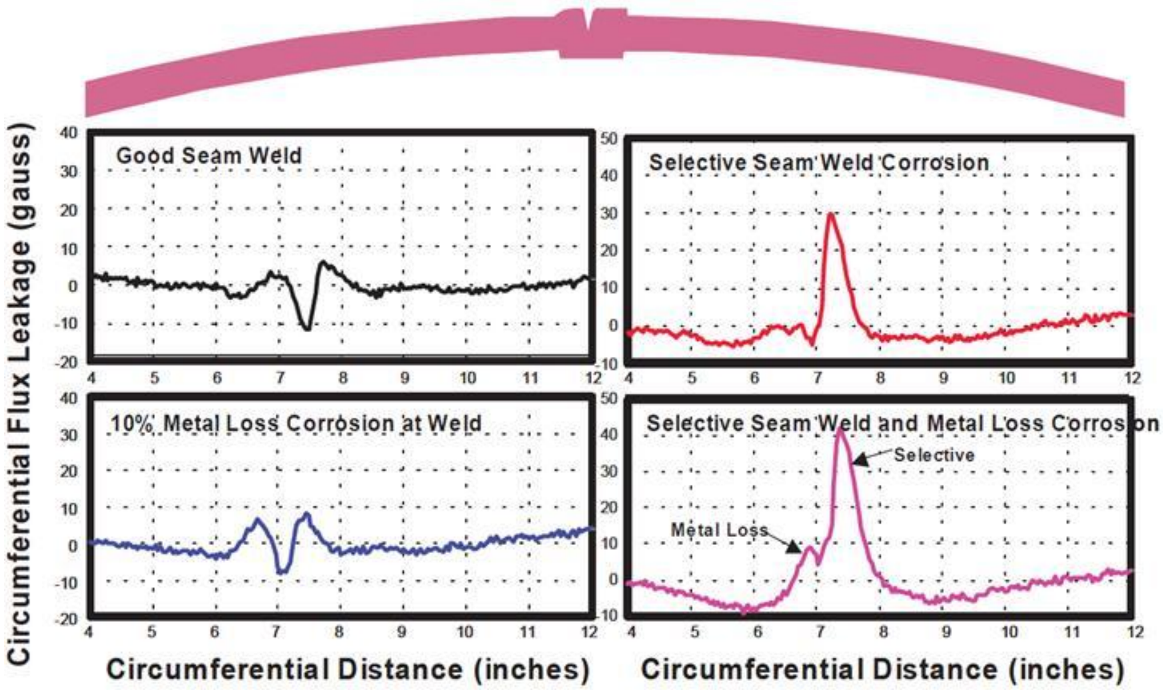


Figure B2. The Potential of Circumferential MFL to Detect Selective Seam Weld Corrosion in Flask Welded Pipe.

Common seam weld anomalies have the potential to be detected using ultrasonic methods. This includes interface anomalies such a cold welds, selective seam corrosion, and hook cracks in the heat affected zone. Unlike MFL, ultrasonic methods are not significantly influenced by the crack opening as long as anomaly does not transfer stress. The UT systems are sensitive to upset and trim associated with the fabrication of the weld, as well as inclusions and laminations that are considered benign anomalies. Some of the same steel plate issues such as impurity segregation that lead to hook crack also complicate the detection and sizing analysis. Distinguishing the fabrication and material variation from potentially significant weld seam anomalies requires examination of signals from multiple pairs of sensors and detailed analysis.

Figure B3 illustrates the detection and sizing aspects of UT systems. The depth of crack-like features is provided in bins that typically reach a quarter or eighth of the wall thickness[7]. In the illustration, a quarter thickness sizing system is illustrated; two sensors respond to the crack while two do no indicating that the crack is in 50% deep bin. Increasing the number of sensors would enable finer sizing bins. This is a simplified illustration of the sizing concept as ultrasonic beams have width and spread as they propagate. Detecting and sizing axial length and radial depth involves examining images of sensor output in both pulse echo and thru-transmission mode, from both sides of the weld; this is also illustrated in Figure B3. The sizing method can work well for planar radial cracks; however, misaligned skelp and the complex shapes of some hook cracks can make sizing less accurate because the angle and curvatures can cause mode conversions that redirect ultrasonic energy. This technology has an excellent potential for detecting significant seam anomalies, but pipeline variables including steel quality, mill acceptable pipe fabrication upsets, and line cleanliness can impact inspection tool performance; identification of false calls due to fabrication and materials variation can make this approach less desirable. For natural gas pipelines, the technology is limited by the process of filling the pipeline with liquid. For many pipelines, the extent of the modifications that must be made to run liquid coupled ILI tool can make a hydrotest a cost-competitive option. The major advantage of inspection is the overall knowledge of all the anomalies in the pipeline.

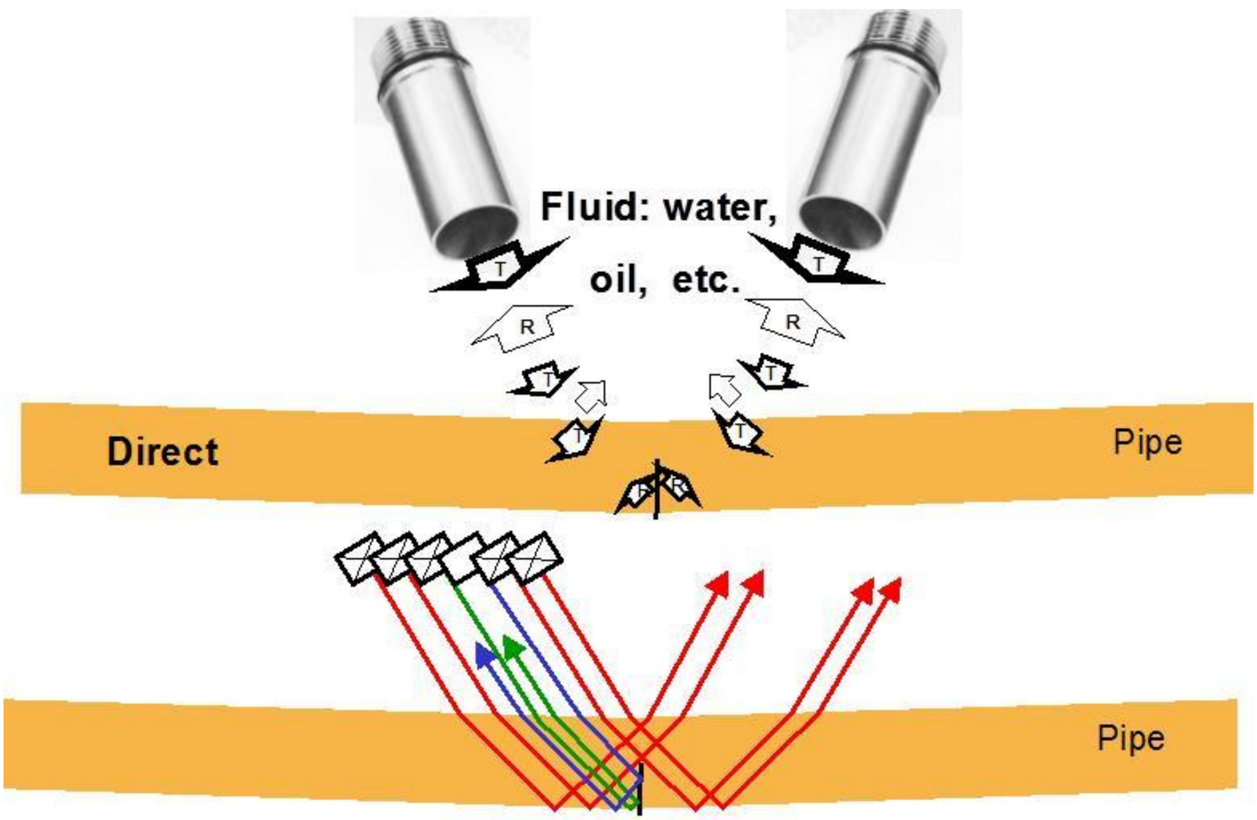


Figure B3. Detection and sizing aspects of UT systems.

Electromagnetic Acoustic Transducers

EMATs based ILI is an ultrasonic method that can work in natural gas pipelines for detecting axial pipeline anomalies. The major advantage of this method is that it does not require the liquid coupling needed for angle beam UT inspection; there are other advantages and limitations discussed later. This emerging technology was first prototyped for pipelines in the 1980's[8], and functional commercial systems became available for pipe in the last decade. Ultrasonic waves are generated directly in the pipe by an electromagnetic pulse from a coil in the presence of a strong magnet as illustrated in Figure B4. These sensors can be configured to propagate in almost any direction including around the circumference of the pipe. While the method does not need a liquid for coupling the ultrasonic energy into the pipe, this method will work in a liquid line Unlike MFL, where there are a few basic magnet configurations, the variety of EMAT implementation is endless. Stating that EMATs do not work on a particular pipeline based on past experience is not correct since this technology is evolving with many configurations possible.

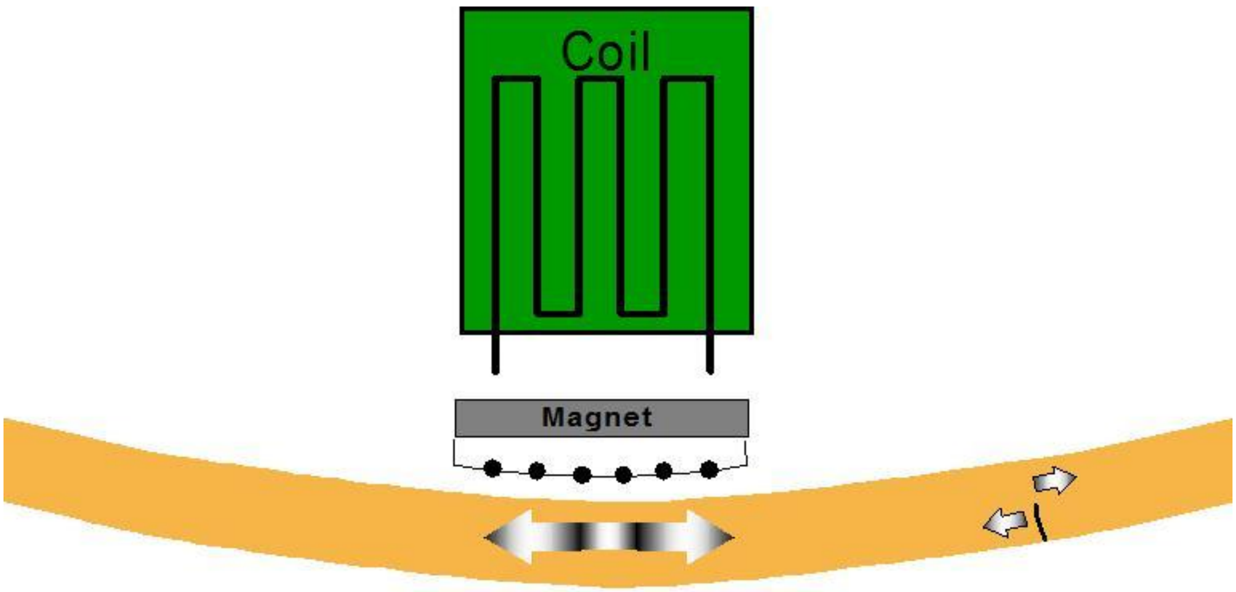


Figure B4. Electromagnetic acoustic transducer inspection for the inspection of pipes for cracks.

Compared to the angle beam ultrasonic systems, circumferentially guided ultrasonic waves that are generated by EMATs have significant differences, which lead to advantages and disadvantages. Unlike MFL, but like UT systems, EMAT methods are not significantly influenced by the crack opening as long as anomaly does not transfer stress. A primary difference is that the frequency of the EMAT generated ultrasonic waves is an order of magnitude lower than liquid coupled UT. Since frequency times the wavelength is equal the sound propagation velocity, the lower frequency translates to a longer wavelength which adversely influences resolution. The EMAT generated sound waves tend to be less responsive to upset and trim associated with the fabrication of the weld, as well as inclusions and laminations in the base metal; however, EMATs can be sensitive to the exterior coating adherence.[9] EMAT systems have fewer larger sensors than angle beam ultrasonic systems[8]; each sensor interrogates a larger volume of material than UT systems and combines the anomaly response over the aperture of the transducer. Since the EMAT sensors are up to an order magnitude larger than UT sensors; these systems will have limits on detection of smaller anomalies and determining if anomalies are continuous or stitched. EMAT tools also can operate in both pulse echo and thru-transmission mode. The depth sizing is based to the signal from both sensor configurations where the angle beam method often uses multiple sensors to assess an anomaly. The longer wavelength and size of EMAT transducers currently challenges implementations for pipe smaller than about 12 inches in diameter. It should also be noted that EMAT systems can be configured in many more ways than MFL or UT tools. This is due to the fact that there are many sensor configurations and the frequency of operation can be varied to control the wave type and mode of propagation(8). Hence, EMAT inspection tools from different ILI vendors can have more unique performance attributes and constraints than MFL or UT systems from different ILI vendors.

In summary, these three classes of inspection technology have the capability to detect seam weld anomalies that can cause pipelines to fail. However, the nature of some of the critical anomalies, the variation within the manufacturing processes, and the pipeline operating conditions can potentially constrain the capability of these technologies to find all critical anomalies. Furthermore, the engineering considerations made during the design process of these tools, based on the current understanding of the inspection goal, also can potentially limit the capability of these technologies. Potential performances improvements can be expected as ILI tools for seam weld issue evolve.

Assessment of Performance of ILI Tools

Pipeline owners and government regulators benefit from knowing the detection and sizing capability of ILI tools. One source of information that relates ILI tool performance to anomalies found in pipelines is available in papers written by pipeline owners or their contractors who discuss rehabilitation jobs that involve ILI, in the ditch assessment, and hydrotesting. An assessment of use of circumferential MFL as a substitute for hydrotesting was investigated for a pipeline with a history of failure due to hook cracks(10). It was concluded that while confidence in circumferential MFL method to detect seam-weld cracks was achieved, similar confidence in inspection tolerances relative to anomaly discrimination and sizing was not present. The repair methodology was based on anomalies detected by ILI and in the ditch sizing to determine sections for replacement.

The literature also contains papers illustrating the number of flaws that were detected by a specific ILI technology, including papers on angle beam ultrasonics(11), EMAT(12), and circumferential MFL(13). These papers provide detailed data to illustrate the potential of ILI to detect, identify, and size anomalies in the seam weld. However, the information in these papers is typically limited to the anomalies that are detected by the ILI tool. A comprehensive assessment of probability of detection needs a large population of representative anomalies of sizes ranging from inconsequential to service limiting, which is typically not available in this type of survey.

Analysis and Conclusions

After anomalies are detected, assessment models are used to determine the severity. Assessment models require dimensions of the anomaly and mechanical properties of the pipe. As compared to crack assessment models, assessment models for corrosion are more widely used, simpler to apply, and require more readily available and accurate information. An example of more readily and accurate information is the geometry of the anomaly. Both assessment models need both length and depth of a flaw. A typical specification for length and depth measurement for ILI tools is tighter for corrosion anomalies than for planar anomalies including ERW seam anomalies. For MFL systems, the depth sizing accuracy for corrosion is ±10 percent of the wall thickness with an 80 percent certainty. For most circumferential MFL systems, the specification increases to ±15 percent of the wall thickness with an 80 percent certainty. For axial slotting and planar anomalies, the specifications can increase to ±20 or 25 percent of the wall thickness with an 80 percent certainty. For ultrasonic systems, the crack depths are reported in bins that are nominally 1/8 (12.5%) of the wall thickness. This assessment models would either need to be improved to be less sensitive to depth sizing accuracy or depth assessment information from ILI tools would need to be improved to make better anomaly assessment decisions.

Along with better anomaly geometry data, the crack assessment models need knowledge of mechanical properties including yield strength and fracture toughness. Again, corrosion assessment models are relatively simple in that they require only the specified minimum yield strength. In contrast, assessment models for planar anomalies require an additional parameter, fracture toughness at the crack tip. The toughness parameter, along with being a function of temperature, can vary since the crack tip could be in the bond line, the heat affected zone, or the base metal. Some models use assumed values based on the location of the position of the anomaly; if the anomaly is on the bond line, a lower value is assumed. Identifying this position of the detected anomaly relative to the bondline is a challenging task for an ILI tool. The accuracy of position determination for an ILI tools is determined by the resolution. For MFL and liquid coupled UT ILI tools, this is spacing between sensors, which is on the order of 0.1 to 0.2 inches. For EMAT tools where the wave propagates in the pipe material, the resolution is determined by the wavelength of the sound wave, which is on the order of 0.2 to 0.8 inches. While the heat affected zone varies in width, the fracture toughness varies the most within the first 0.1 to 0.2 inches, which is on the order of the resolution. The second problem is precisely identifying the location of the ERW weld. For a solid ERW seam that is smoothly trimmed, the bondline and heat affected zone are not always easily detected. On some occasions, the suspected area must be cleaned, polished, and etched to verify the location. However, it is common for the seam weld to have been over trimmed or under trimmed at production. For ILI tools, the ultrasonic thickness tools can see a local change in wall thickness. The magnetic method may see small signal in response to a change in magnetic permeability, more commonly in welds that have not been heat treated. Again, as with the location of the anomaly around the circumference, the position of the weld is subject to the same resolution constraints. It should be noted that the trim imperfections, while helpful in identifying seam locations, produce a signal that can mask anomalies and hamper detections. Also, while a general trim anomaly is helpful in identifying the location of the seam weld, a local trim anomaly can be falsely identified as a seam weld anomaly. In summary, attributing the location of the detected anomaly to the bond line, heat affected zone or base material is a complex process.

As ILI technology continues to evolve and experience is gained through the use of these tools, the performance of ILI tools in the detecting, locating and sizing of anomalies will increase enabling pipeline owners the ability to better assess seam weld anomalies.

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ANNEX C:
IN THE DITCH SEAM INSPECTION TECHNOLOGIES

Prepared by Dr. J. B. Nestleroth of Kiefner and Associates.

Annex C: In the Ditch Seam Inspection Technologies

In the ditch (ITD) methods for seam weld inspection are used to provide more information on anomalies detected by in-line inspection tools. These methods can also be used to inspect day-lighted pipe, a practice more often performed when pipeline has had a history of seam weld problems and when the weld seam is of specific fabrication method and vintage to assess the potential for potential future problems. The ERW inspection process involves detecting the weld, screening the weld, and detailed sizing. The details of the common methods used are outlined next. It should be noted that the seam weld has been blasted clean for detecting the weld.

Identifying the Seam Location

The first step in assessing the ERW seam weld is identifying the location of the seam. For an ERW seam that is smoothly trimmed, the seam can be difficult to detect. Depending on the manufacturer, the ERW seam is sometimes detectable by excess metal, electrode markings, or other production features. If there are no external marking, the next step is to check the seam weld for a slight wall thickness variation due to over trimming at production. A manual method of lightly gliding our fingertips around the circumference of the pipe is often used. A more quantitative approach uses a handheld ultrasonic equipment used to measure changes in wall thickness. Pulses of ultrasonic energy between 10 to 20 MHz are launched from a piezoelectric transducer. These pulses are reflected by the inside and outside surface of the pipe. By measuring the time between the reflections and knowing the speed of sound in steel pipe (nearly constant for most pipes and in the seam weld), it is possible to establish the thickness of the pipe. The industry standard thickness measurement accuracy for handheld ultrasonic thickness gauges is nominally 0.001 inch (0.025 mm).

Screening the Weld Seam for Anomalies

Figure C1. An example of an MPI inspection.

The second step is to screen the entire weld using Magnetic Particle Inspection (MPI). This non-destructive testing (NDT) is used in many industries to detect surface and slightly subsurface discontinuities such as cracks in ferromagnetic materials, steel being the most common. In magnetic particle inspection (MPI), a magnetic field is induced in a test piece. Magnetic fields are typically illustrated as magnetic lines of force (flux lines) that flow through the magnetized specimen; the flux deflects and leaks out in the vicinity of a flaw. The magnetic flux leakage attracts particles, which cluster at the discontinuity to form an indication. The particles remain at the discontinuity after the field is removed until they are physically moved.

The MPI method is an efficient screening tool with the inspection of a standard pipe joint taking less than an hour; the documentation time is proportional to the number of anomalies detected. For daylight inspection, the most common approach for pipelines, a very thin white layer of paint is applied to the weld seam and black particles are used to detect flaws. A technician performing and MPI inspection is shown in Figure C1. An interesting result is shown in Figure C2; two parallel flaws were detected, a bold line flaw and a potential series of linked cracks in the heat affected zone about a tenth of an inch off the fusion line.

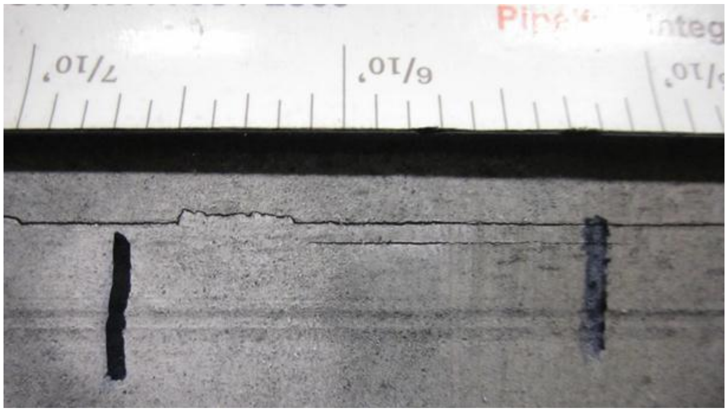

Figure C2. Result of an MPI inspection.

MPI detects most surface breaking flaws. On occasion, subsurface flaws can be detected; the ability to detect subsurface flaws depends on the proximity to the surface, the width, and the area of the discontinuity, and also pipe surface condition such as smoothness and pitting. The length of the anomaly is visually determined, with experience needed to apply sufficient particles to enhance the ends of the anomaly. While there is a tendency to assume the width of the line is proportional to the depth, the MPI method is not an accepted method to determine the depth of the flaw. The primary reason is that the amount of particles that accumulate at narrow crack-like anomalies is the width of the anomaly; the secondary reason for particle accumulation is the depth of the anomaly.

Ultrasonic Crack Detection

Many ultrasonic methods have been developed to detect and size cracks in metals. When cracks were detected, the amplitude was used to assess the size of the cracks. While many processes have been developed, measuring the amplitude of reflected signal is a relatively unreliable method of sizing defects because the amplitude strongly depends on the orientation of the crack. The pipeline industry most commonly uses two automated methods for the inspection of seam welds that uses time information rather than amplitude to size cracks:

- Time of fight diffraction,
- Phased array ultrasonic.

Typical application of these methods for seam inspection is discussed next.

Time of Flight Diffraction (TOFD)

TOFD uses the time of flight of an ultrasonic pulses to determine the position of a reflector. In a TOFD system, a pair of ultrasonic probes sits on opposite sides of a weld. One of the probes, the transmitter, emits an ultrasonic pulse that is picked up by the probe on the other side, the receiver. Figure C3 shows a typical inspection head and a pipe with calibration notches in the seam weld.

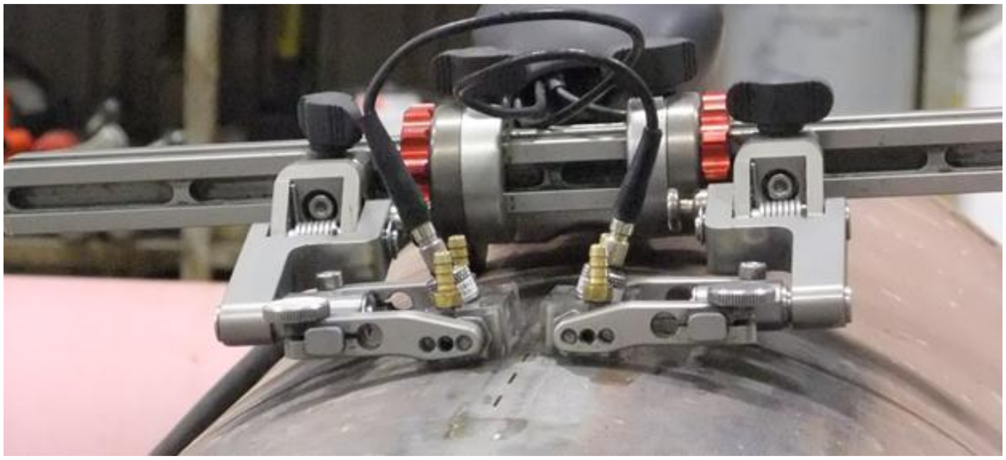

Figure C3. Time of flight diffraction head for seam weld inspection.

In a typical seam weld inspection, the signals picked up by the receiver probe are from two waves: one that travels along the surface and one that reflects off the far wall. For a good weld, the signals are consistent as the inspection head rolls along the pipe. Figure C4 shows 2 meters of pipe with a good seam weld with the surface wave illustrated in red and the bottom reflected wave in green. The small variations are the natural variation in seam welds. While this limits the capability to detect small defects, the burst tests reported elsewhere as part of Task 2 show that many non critical anomalies can be detected.

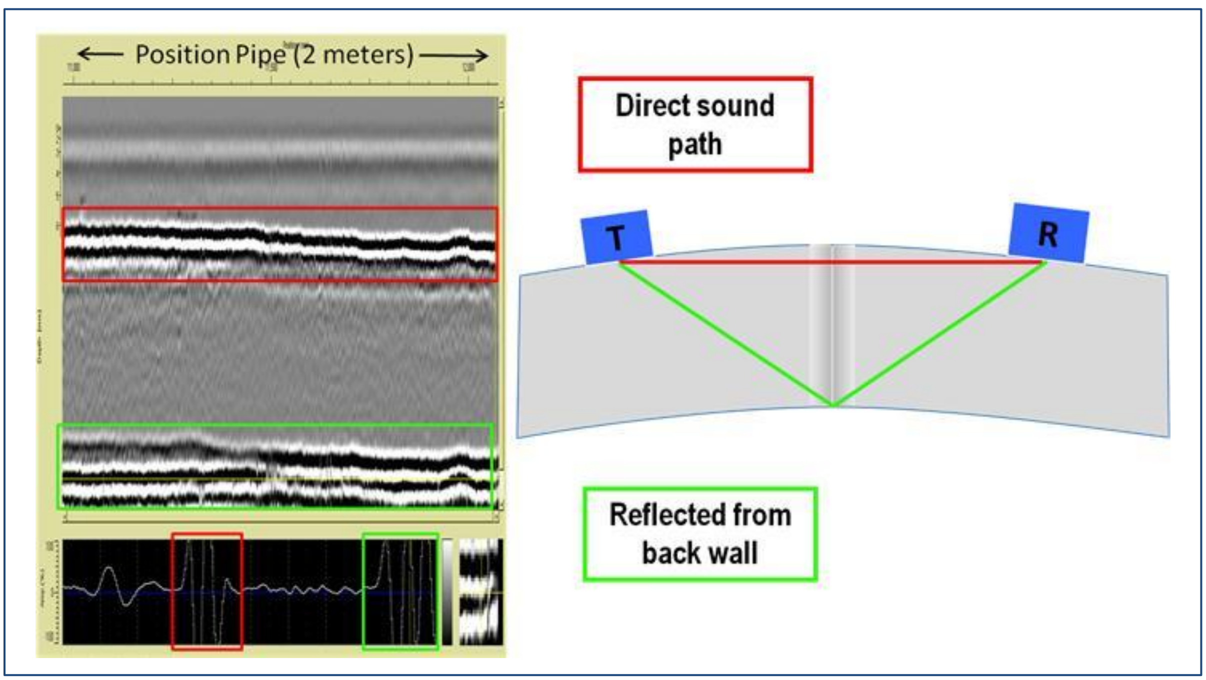

Figure 4. Typical inspection result for 2 meters of anomaly free seam weld.

The direct path signal is in the red box with the signal reflected off the ID boxed in green.

When a seam weld defect interrupts the sound path, the wave has different travel time. Furthermore, there is a diffraction of the ultrasonic wave from the tip(s) of the crack. Figure C5 shows 2 meters of pipe with anomalies that require additional analysis approximately at the half meter point.

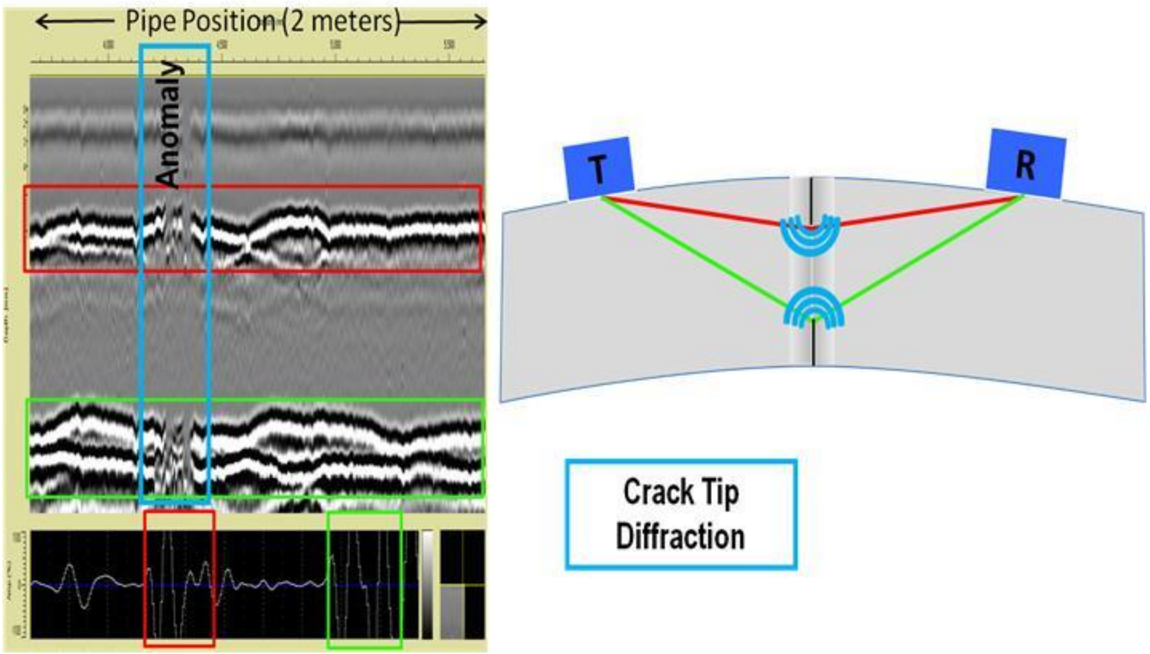

Figure C5. Typical inspection result for 2 anomalies, which requires additional analysis.

The inspection system displays the reflected and mode converted waves. Using the measured time of flight of the pulse, the depth of a crack tip can be calculated automatically by simple trigonometry. This method is more reliable than traditional amplitude based ultrasonic testing, as summarized by the study undertaken by Electric Power Research Institute[(2)] to assess the performance of commonly used ultrasonic techniques and procedures for pressure vessels. Techniques assessed in this study include TOFD, backward-scattering tip-diffraction and conventional ultrasonic techniques. This study was performed before phased array ultrasonic methods were widely practiced. While the arrival time of the pulses can be used to provide reliable depth information, sizing assumes a vertical crack. The signal does not contain information on whether the crack is vertical, at an angle, curved, or other geometrical variation.

Linear Phased Array Inspection Technique

A linear array probe contains a series of long, thin transducers closely spaced and parallel to one another. It resembles a conventional, monolithic transducer element that has been repeatedly sliced by a slitting saw. Each array element is connected to a separate pulser, receiver, analog-to-digital converter, and delay generator. All the array elements are pulsed, and then their received waveforms are summed and the resultant A-scan is recorded. By adjusting the timing of the pulsing and reception of each element, the angle and focal point of the ultrasonic beam can be controlled. The beam angle and focal depth can be changed from one pulse to the next by this electronic control process. In this manner a single array probe can be used to produce beams at many different angles. When an array produces consecutive beams of slightly different angles, a fan-shaped image called a "sector scan" is formed as shown in Figure C6. (The sector-scan image is familiar to most people from their experiences with fetal ultrasound imaging and the "pie-wedge"-shaped images of infants in utero.) As the operator moves the probe along the surface of the part being inspected, the instrument displays and updates in real time a wedge-shaped cross-sectional view of the interior of the component and any flaws that are present in it. The sizes of the flaws are represented directly in the image.

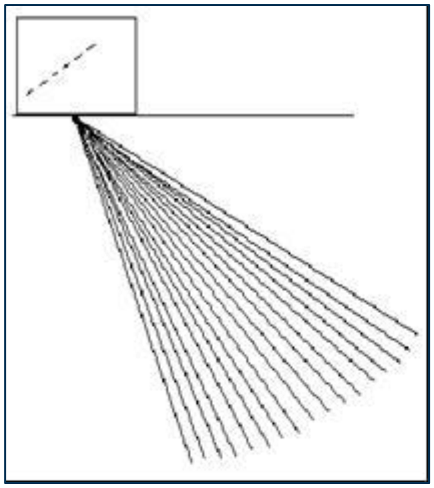

Figure C6. Principle of a sector scan.

For industrial applications, a linear array produce sound waves between 2 and 10 MHz, the higher frequency selected for its high sizing resolution and the lower frequency selected for better detection. The number of elements in the array in commercial equipment is typically a power of 2, and usually 32 or 64 elements. The shear wave mode is typically selected to allow the cracking to be imaged in the full-vee path, after the sound beams had reflected from the pipes' inside surface (Figure C7). Phased array systems can best programmed to perform sector scans over a range beam angles to ensure the ensure weld is assessed. A typical range is from 30 to 60 degrees. The angle is swept in discrete angle increments, from 0.1 to 0.5 degree increments. A smaller angle the increment allows more precise depth measurements, but scanning takes more time. At 0.2 degree increments, a phase array system would have a precision of about 0.001 inch (0.025mm) for a depth measurement. Each beam was focused at the ¾-vee path position, which is at mid-wall after the reflection from the inside surface (Figure C8).

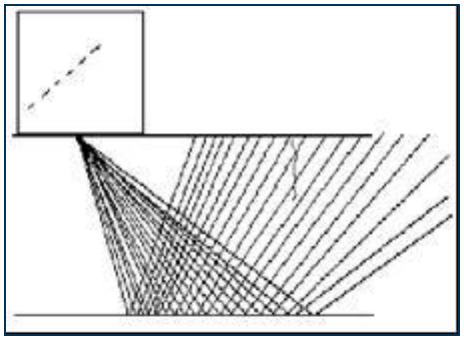

Figure C7. Imaging a crack at the full-vee path using a sector scan.

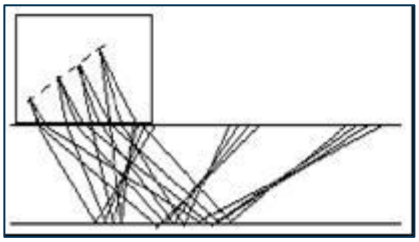

Figure C8. Focused beam can be attained at the ¾-vee path so that the entire HAZ is assessed.

Manual Examination

In areas where MPI and TOFD methods had detected cracks, the crack depths can be assessed with manually phased array imaging. In manual examination mode, the operator moves the probe over the pipe's outside surface and views the continually updated sector-scan image. When the image of the anomaly of interest is presented, the operator uses on-screen cursors to measure the crack depth. Specifically, the operator positions one cursor at the position of the crack tip response and the other cursor at the position of the low-amplitude responses that are received from the roughness of the outside surface of the pipe. The difference between the vertical positions of the two cursors is equal to the height of the crack. In this way, the depth measurement does not rely on a nominal value of the pipe thickness, but includes a measurement of the thickness at the crack location. An example is shown in Figure C9, for which this manual examination was both quick and effective.

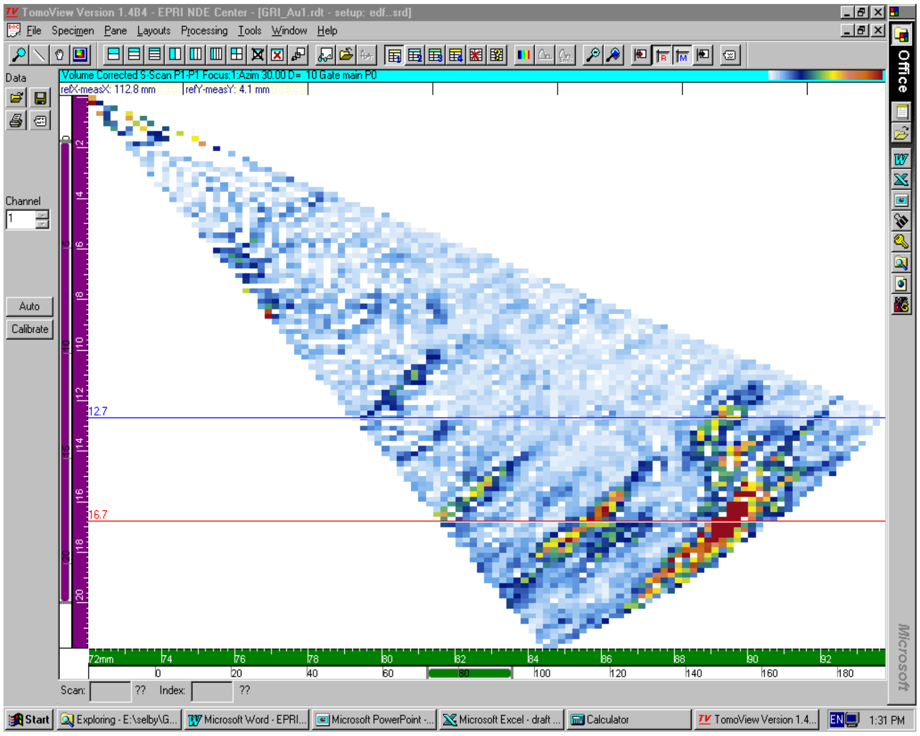

Figure C9. Sector-scan image of a crack

The red cursor is positioned at the outside surface and the blue cursor is at the crack tip; the crack depth is 0.161 inch (4.1mm).

Automated Examination

To assess the entire seam weld and not just one axial location, automated measurements can be performed. A 3-dimensional scan can be attained by attaching to a computer-controlled scanning device and data acquisition system. The probe was scanned in the pipe axial direction, every 0.25 inch (6.3mm) acquiring a sector scan as described above. At the end of the scan line the probe was incremented 0.125 inch (3.1mm) in the circumferential direction, and the cycle was repeated. Once the computer assembled the data into a volumetric image, the ultrasonic coverage was quite robust; every point within the material was hit by several different beam angles because the sector scans overlapped significantly, as shown in Figure C10.

Figure C11 shows an example of the three orthogonal views for one of the scan areas. The lower-left part of the figure is the top view, showing the surface configuration of the cracking. The lower-right part of the figure is the end view, showing the cross-section of the cracking along the vertical red cursor in the top view. Note that the vertical cursor crosses the strong responses of two parallel cracks in the top view; the through-wall height of these two cracks is shown in the end view. The upper part of the figure is the side view, showing the variation in the depth of one of the cracks as a function of its length; this view is a cross-section corresponding to the horizontal cursor in the top view.

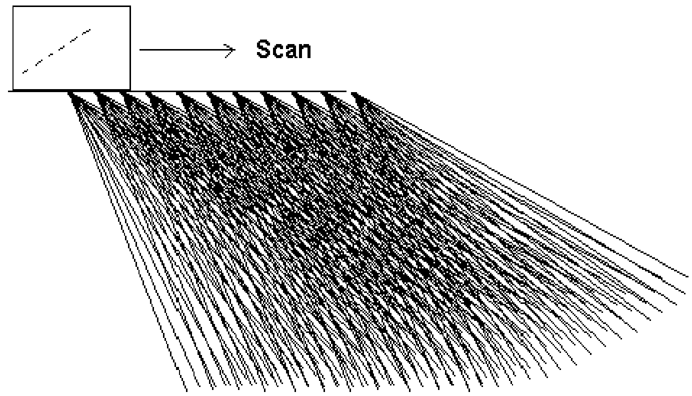

Figure C10. Dense overlap of sector scans circumferentially indexed by 0.12 inch (3mm).

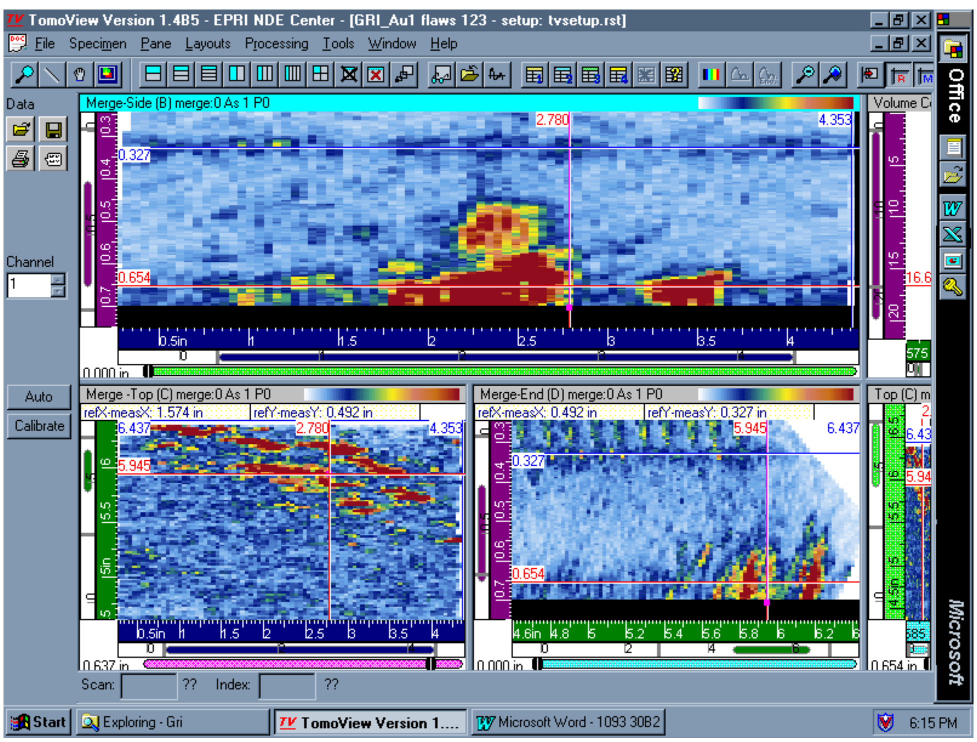

Figure C11. Crack images obtained by automated scanning and volumetric reconstruction.

Conclusions

Magnetic particle inspection is an accepted screening method for surface breaking anomalies in ERW weld seams. Time of Flight Diffraction and Phase Arrays are accepted approaches to assess seam weld integrity ITD. However, there are limits to sizing because of variation in the anomaly parameters, (angled bond line, hook crack, etc), and sizing remains challenging because the signal caused by the reflection at the defect is very dependent on defect orientation. ToFD has sizing capabilities, but is limited by anomaly variables. In phased arrays inspection, the image obtained from sector scans cannot be precisely related to defect size and orientation(5).

The level of maturity and acceptance of available technology can sometimes be assessed by the research requests and emerging technologies that address limitations. The maturity of existing technologies can also be gauged by the emergence of new competing technologies. In this context, a very different NDT approach to imaging anomalies is being developed that overcomes the limitations of TOFD and phased array methods(5). The additional performance information and new technology should help close the inspection needs gap identified by government agencies and pipeline owners.

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