TransCanada’s State of the Art Development and Utilization of High Strength Materials, Fully Automated Welding and Automated Ultrasonic NDE Testing

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ABSTRACT

The technologies and methods utilized in large-diameter pipeline construction have evolved significantly since TransCanada constructed the gas mainline across the Canadian Shield in the 1950s. In today’s social and political climate pipeline companies are expected to clearly demonstrate improving quality and safety to Regulators, stakeholders, and the general public. TransCanada meets this challenge, in part, by utilizing the latest technology and modern materials thus ensuring that new pipelines are constructed to operate even more reliably and safely than previous generations of energy pipelines.

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INTRODUCTION

Pipeline technology has greatly advanced since carbon steel pipelines were first placed into service. Advanced technologies have improved safety and reliability and allowing for construction in increasingly difficult environments. Modern steels and pipe manufacturing methods have increased the integrity of pipelines while allowing them to operate at higher pressures and larger diameters. Mechanized welding processes with advanced NDE methods have greatly increased the quality and production of pipeline construction and increased the reliability of their operation. In combination, these construction advancements have allowed for higher quality pipelines within shorter construction seasons, and with more challenging requirements. Future advancements promise further improvements to the quality, production, and safety of pipelines.

PIPELINE STEELS AND MANUFACTURING

Pipeline steel and manufacturing have improved dramatically since the first pipelines were installed in North America. In general these processes have improved for two reasons: to increase the capacity of the pipelines; and to increase their integrity. For non strain-based (also known as stress-based) designs, a simplification of pipeline design is had through application of Barlow’s formula:

\[ P = (2St/D) \times F \]  \hspace{1cm} (1)

where \( P \) is the design pressure, \( S \) is the specified minimum yield strength, \( t \) is the minimum wall thickness of the pipe, \( D \) is the outside diameter, and \( F \) is a safety factor. In order to move more product (higher pressure and/or diameter) one must either increase the yield strength, or increase the wall thickness. It is more desirable to increase the yield strength as opposed to wall thickness, because it decreases the amount of steel to make the pipe, it decreases the weight thereby making transportation easier, and it decreases the number of weld passes, and hence time, required to weld the pipe together.

The main threats to pipelines are third party damage, corrosion, stress-corrosion cracking (SCC), fatigue, geotechnical hazards, and defects caused through manufacturing and construction. Modern metallurgy, pipe manufacturing, welding, and NDE processes have essentially nullified the threats of manufacturing and construction related defects, while advances in coating have greatly reduced the threats of corrosion and SCC. Improvements to steel making and pipe manufacturing have greatly increased the strength and toughness of modern pipelines, which in turn makes them more resistant to damage, but it also necessitated improvements to welding and NDE methods for construction.

The first major pipelines to transport hydrocarbons across Canada were constructed of steel made with practices from the 1940’s and 1950’s; it was melted in massive open-hearth furnaces; it had very high levels of carbon, and impurities like oxygen, sulphur, and phosphorous; and it was relatively low strength and brittle. Pipeline manufacturing was in its infancy; commonly, steel plates were rolled into cylinders, placed into furnaces, and the edges were forced together with no inspection of the seam. Typical pipeline grades were designated X42 or X52, where the number after the X designates the yield strength in ksi.
Beginning in the 1960’s open-hearth furnaces started making way for basic oxygen furnaces, electric arc furnaces, and continuous casting. These steelmaking practices significantly lowered the impurities in the steel allowing for higher strengths and toughness. Pipe manufacturing similarly improved with the furnace butt welding process being replaced by submerged arc welding. Radiographic inspection became standard practice within the pipe mills, and ultrasonic inspection was used to look for laminations in the steel. The resulting improvements allowed for higher grade pipelines up to X65.

X70 became possible with further refinements in microalloying, in conjunction with controlled thermomechanical rolling and the acceptance of ultrasonic inspection in the pipe mills.

Further improvements to steelmaking led to the development of X80 pipelines in the 1990’s, and X100 in the early 2000’s. TransCanada was the first pipeline operator to operate X80 and X100 transmission pipelines. TransCanada currently operates over 6,400 km of large-diameter X70 pipelines, 400 km of X80 pipelines, and 20 km of X100 pipelines. TransCanada is the only operator to install and operate X120 pipelines, with 1.6 km installed in a joint project with ExxonMobil.

Figure 1 shows the progression of line pipe steels in North America\(^1\).

![Fig. 1: Evolution of Line Pipe in North America](image)

**Fig. 1:** Evolution of Line Pipe in North America

**STRAIN-BASED DESIGN**
Higher grade steels have also evolved for use in areas where the pipeline could be subjected to permanent deformation such as seismic activity or discontinuous permafrost. This is referred to as strain-based design, whereby the operator must account for the properties of the steel and welds after yielding, and must account for the properties in both the longitudinal and hoop directions, which are anisotropic by their nature. Strain-based designs require advanced, higher strength steels to accommodate the plastic strains during operation. Strain-based designs are further challenged because the properties of the girth welds in the field must be carefully controlled to over-match the parent pipe, and the NDE must be sufficient to prevent any defects in the final pipeline that could fail under plastic deformation.

WELDING

Overview of mechanized gas metal arc welding

First used in 1969, the mechanized gas metal arc welding (GMAW) process has become the standard for major, large-diameter, cross-country pipelines in Canada and is increasingly used in the USA and Mexico. Mechanized GMAW systems use lightweight tractors running on a band to carry the welding head around the pipe. The systems use small-diameter wires at relatively high current (to give high metal deposition rates), carbon dioxide or argon-carbon dioxide shielding gas mixtures, vertical-down welding progression with a reduced bevel opening (compared to manual welding with a 60 degree included bevel angle). This narrow gap compound bevel is precisely machined on the pipe ends immediately ahead of the welding crew. The root bead (first pass) is either completed with an internal welding machine (IWM) line-up clamp with the welding heads incorporated into the IWM (Figure 2), or applied with external tractors (fastened to the OD of the pipe) with the molten root bead weld layer being supported by copper backing bars which is incorporated into an internal line-up clamp. High quality, usually metal, welding shelters or “shacks” provide protection from wind and weather.

![Internal Welding Machine](image)

Fig. 2: Internal Welding Machine

With proper welding procedures and appropriate bevel design there is little to no preference between the use of an internal welding machine or copper backing shoes, as both produce good quality welds and exhibit good productivity. Internal welding machines are generally considered to be less sensitive to high-low, and for onshore pipelines do not require a shelter to be in place when welding the root pass. For very large diameter pipe, internal welding machines have the advantage of having six or eight welding heads, which reduces the time to complete the root pass.
so the root pass productivity will be higher than that with a copper backing system. However, the root pass produced with a copper-backing shoe is usually thicker than that of the internal welding machine and there may be one less pass required to complete the whole weld. This can be advantageous when the total productivity is limited by factors other than welding. In this case, the target rate in welds per day may be achieved with fewer welding stations, and fewer welders.

Since the development of the first external welding heads in the late 1960s, there have been significant changes in the mechanical design, and the electronic and computer control systems which have improved reliability, data acquisition, and weld quality. Typical external welding heads in use today are shown below in Figures 3 and 4.

Figs. 3 & 4: CRC-Evans P-260 (Left), Serimax Saturnax 05 (Right)

As seen in the figures, the welding head on the external welding tractor or bug can be single torch or dual torch. The Saturnax 05 is very different to the CRC-Evans P-260 in that it deposits two passes simultaneously, has a remote wire-feed system, and each welding bug is connected to an electronic control unit and data acquisition system. The welder controls the welding bug and the two arcs by means of a remote control or pendant. The CRC-Evans system is a self-contained platform with the data acquisition built into the control box on the welding tractor as well as the control buttons for the welders to use during production. Both systems can be programmed for various welding passes. The short-circuiting gas metal arc welding (GMAW-S) process is commonly used by both of these welding systems although they are equally capable of pulsed gas metal arc welding (GMAW-P). The Saturnax 05 tractor is modified with two concentric flow torches to accommodate the wider separation required for GMAW-P.

In 1999, CRC-Evans introduced their P-600 dual-torch welding head (Figure 5). This welding system utilizes the GMAW process with an argon/CO₂ mixed shielding gas with a pulse arc mode of metal transfer (GMAW-P), has remote wire feeding and a pendant control for the welder, but also has the capability for through-arc sensing to guide the welding torch in the weld bevel (horizontal tracking). GMAW-P is the preferred welding process. The use of through-arc sensing is also used for control of the vertical height of the welding torch on both the P-260 and P-600.

Recently, CRC-Evans has added the single-torch P-450 and Serimax the dual-torch Saturnax 09. Both have full horizontal and vertical through-arc tracking and enhanced data acquisition and welding procedure/parameter control.
With the exception of the Saturnax 09, all of the aforementioned mechanized welding systems have been utilized on TransCanada construction projects, as well as earlier, less sophisticated versions of the same equipment, over the past 30 years. In addition to the CRC-Evans and Serimax systems, TransCanada has successfully used similar welding technology and processes from RMS Welding Systems and Vermaat.

Welding procedures for higher strength steels

As long as GMAW-P is used, all mechanized and automated gas metal arc welding systems are valid options for any major, long-distance pipeline project that may utilize the higher strength pipe steels ($\geq$ 550 MPa). Wire chemistries, shielding gas mixtures and precise metal transfer conditions will have to be optimized for each of the candidate mechanized welding processes in order that the appropriate weld deposition characteristics, weld integrity, and required mechanical properties for either a stress-based or strain-based design are produced. Large development programs have been undertaken over the last 25 years with consumable manufacturers and welding equipment suppliers. As a direct result, C-Mn-Si-Ti and Ni-Mo-Ti wires have been either developed or identified and, together with either Ar-CO$_2$ or Ar-He-CO$_2$ shielding gases, implemented and established for routine pipeline construction. For more demanding applications anticipated in future construction, even more sophisticated alloying approaches are being investigated.

Future welding

Mechanized/automated GMAW is considered well established in the industry. These systems will continue to improve in terms of process control and advanced automation as the welding equipment suppliers take advantage of technology developments with welding power sources and rapidly increasing computing capability.

TransCanada has chosen to focus on the development and implementation of tandem pulsed gas metal arc welding for improved productivity in the welding of higher strength steels. The principle benefits of tandem GMAW-P are high travel speed and high deposition rate. At high travel speeds, single-wire welds are sensitive to undercut, incomplete fusion and porosity. Tandem GMAW-P can alleviate these problems.
Multi-wire or tandem GMAW-P differs from conventional single or dual torch welding configurations GMAW-S or GMAW-P as two welding wires are passed through the same welding torch. A single torch with two contact tips is used to feed both wires into a single weld pool.

If there is to be a next generation of even higher productivity and more automated pipeline welding processes, they are expected to be based on hybrid laser/GMAW-P. TransCanada has successfully initiated research with industry partners such as PRCI and the US DOT, into the use of hybrid laser welding.

The industry has still to realize the full potential of multi-wire and multi-torch GMAW-P systems to increase welding speed and welding spread flexibility for major large-diameter pipelines, especially those in more remote locations with varying right-of-way conditions. Hybrid laser welding systems are not yet at a stage where field implementation or large-scale trials have been conducted.

NON-DESTRUCTIVE EXAMINATION

NDE of pipeline welding was introduced to the pipeline industry in the 1940’s. The most commonly used method was radiography (RT). Throughout the following years these inspections proved to be an asset in ensuring welding quality in the finished pipelines, and the industry standards implemented mandatory requirements for NDE based on percentage. While the percentage inspection has remained in the industry standards (CSA and ASME), TransCanada has implemented 100% NDE on the pipelines since the late 1970’s. Standard NDE platforms have remained very consistent in the main applications used in the industrial inspection sectors, but technological advancement in electronics has allowed for companies to expand on standard NDE platforms, utilizing advanced components, computers, and software.

Addressing inspection challenges of emerging welding technology

With advancements in mechanized GMAW processes made through the 1980’s, using narrow gap, multi-angled bevels, concerns were raised with the probability of detection of critical weld flaws at particular locations in the weld using RT. To address these concerns, TransCanada began research on the capabilities and effectiveness of automated ultrasonic testing (AUT). AUT displayed an advanced variation of basic ultrasonic technology and theory; utilizing numerous, fixed-position, ultrasonic beams specifically targeted at precise locations and angles in the vertical extent of the bevel configuration; and providing the ability to produce an unmasked, full volume, side view of the weld. This technique has become known as the zone focus approach.

The zone focus approach utilized “multi-probe” ultrasonic arrays, containing a range of wedges cut at specific angles and ultrasonic transducers designed for their specific application. The numbers of configurations of wedges and transducers are dependent on the weld bevel configuration and wall thickness. To obtain full coverage of the weld in a single pass it is necessary to divide the weld bevel into discreet zones, typically 1 to 3 mm high, and to dedicate a designed transducer to interrogate each zone. The weld is also divided into two halves with identical, but separate arrays to inspect both sides (up-stream and down-stream). Calibration
references are machined from project specific pipe material using an assortment of flat bottom holes and notches providing point reflector targets for each specific zone for the designated bevel. Transducers are designed and tailored to each portion of the bevel (zone) being interrogated and the type of expected flaw. Wedges are machined for each inspection zone based on the measured acoustic velocity of the production pipe material. This ensures correct inspection angles are generated in the pipe material.

In 1989 TransCanada initiated field trials for AUT using the zone focus approach applying both AUT technology and RT technology. AUT provided advanced abilities in planar flaw detection due to application and inspection orientation while RT produced consistent detectability of volumetric defects, and acted as an industry baseline comparison to prove the AUT technology. Data collected by both methods was compared in order to determine the technical limitations of AUT, and proper protocols for interpretation, sizing, and application, to enable AUT to produce consistent, quality inspection. Through collaboration between TransCanada and our NDE providers, TransCanada successfully implemented the use of AUT on all GMAW mainline pipeline construction in 1994.

With the successful implementation of AUT inspection of GMAW mainline construction, subsequent benefits became apparent. The ability to work in close proximity of welding crews and accurately identify welds flaws in both circumferential and vertical position enabled AUT technicians to provide instantaneous feedback to welding crews to monitor and troubleshoot recurring welding problems. Accurate flaw sizing capabilities in length and vertical extent also justified the use of alternative weld acceptance standards based on engineering critical assessment (ECA). The use of ECA criteria drastically reduced unnecessary repairs of flaws that, on any rational basis, have no effect on the overall integrity of the pipeline.

**AUT weld data recording and retention**

Initial AUT systems used ultrasonic probe arrays attached to motor drives that travelled on guide bands placed on the pipe. Incoming analog ultrasonic data from each transducer was printed in strip chart format on paper in a time base format. Individual strips would be reviewed and circumferential position of data was dependant on an estimated travel speed of the motor drive and the printer. This posed several problems as the accuracy of AUT scanner position versus data presentation is imperative for both flaw location and sizing. Possible deviations in drive speed or printing speed would not only create an issue in correctly marking a discontinuity position circumferentially on the pipe but it also would have a drastic effect on the determination of the length of the flaw. The large paper records also presented issues for the organization and retention of inspection records.

**Introduction of AUT techniques to the digital age**

The advent of available computer technology brought great advancements to AUT for pipelines. Conversion of incoming analog data to digital output resolved many of the issues with the initial AUT techniques. With the use of motor drive mounted encoders, the computers could correlate the data display to accurately record incoming signals from each transducer for every 1 mm increment of scanner travel. Software provided user friendly interfaces, and visual viewers of AUT data, utilizing circumferential positioning, gated signal response, time-of-flight

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measurements, amplitude-based sizing calculations, and 6dB drop length measurement algorithms. The electronic records provided recordable, traceable and retrievable data.

Further advancements came to AUT with the implementation of tools such as time-of-flight diffraction (TOFD) and stacked A-scan displays (mapping channels) being integrated into the overall display. TOFD provided excellent surface connecting crack detection as well as through-wall defect positioning abilities that could be used in conjunction with a-scan displays to accurately size flaws in the vertical and circumferential plane. A typical display of the zone focus approach with TOFD is shown in Figure 6.

![RTD computerised strip chart including integrated TOFD data](image)

Further use of computers enabled the creation and display of A-scan data in what is known as a “Mapping”. Mapping is the modern equivalent of a B-scan where stacked A-scans are collected and assigned colours based on signal amplitude ranges. The use of mapping technology and theory resulted in an improved ability to discriminate between signals received from flaws and surface geometries. In addition, mapping was able to display volumetric flaws such as porosity in life-like formation on the computer screen.

Ultrasonic applications created, techniques developed and methodology implemented by TransCanada and our NDE vendors helped push the application of AUT technology to a more wide-spread use in pipeline construction, to the point that it is considered common practice for large-diameter pipelines in North America.

Proven techniques with advanced platforms

The conventional multi-probe systems have proven very reliable for TransCanada; however, the up-front preparation is considerable for a pipeline project to be successful. The inspection design developed for each wall thickness and weld bevel combination made it necessary for the AUT contractor to machine wedges for each inspection setup, making wall thickness changes a time consuming task. The scanning frame can be very complex and susceptible to deviation of
probe positioning. AUT systems were bulky and required specialized custom adaptations to vehicles to produce the required power and space to contain all of the necessary equipment.

With growing advancement in phased array ultrasonic technology, TransCanada, UT Quality and GE Inspection Technologies successfully conducted a field trial in 2007 using multi-probe AUT as a baseline to compare phased array automated ultrasonics (PAUT) utilizing zone focus inspection design. PAUT using zone focus inspection design exhibited advantages in flaw sizing due to the ability to accurately manipulate the focusing of zones, giving the capability to generate many smaller zones without the cost of adding additional probes and wedges in traditional AUT.

The PAUT system consists of one phased array transducer on each side of the weld accompanied by separate TOFD and transverse detection transducers. The simpler arrangement significantly reduces the ongoing fine adjustments necessary with the multi-probe system. In addition, the upfront preparation time was reduced to inputting the focal law parameters (e.g. material velocity and inspection angles). The logged information required to maintain the necessary focal laws provided the ability to accurately monitor/audit AUT data at any time with the correct viewer software. Most PAUT systems are compact in size making it very simple to install in a pick-up truck with simple power inverters. PAUT technology using zone focus inspection design has been used on all the large-diameter pipeline projects for TransCanada since its implementation in 2007. Figures 7 and 8 shows the typical display for PAUT.

Fig 7: UT-Scan® PAUT weld scan presentation
Looking into the future

As computers and electronics become more powerful and compact, capabilities to collect, manipulate and automate more NDE data are constantly expanding. Growth in pipeline inspection quality has reached a point where the newest leaps and bounds will likely be made in refining the current NDE techniques and methods. Technology is almost limitless but the human factor still remains; qualified technicians still play an extremely large role in the success of pipeline inspection. Future advancements are focussed on the need for more advanced yet simplified inspection processes to reduce operator error. One of the current prospects is the use of inverse wave field extrapolation (IWEX), which was developed by Applus RTD and is currently planned for trials with TransCanada to prove the feasibility of the technology.

IWEX utilizes common PAUT hardware with modified inspection techniques and advanced proprietary software. Similar to PAUT there is a band-mounted drive unit but the probe carriage only contains two phased array probes, one for each side of the weld. IWEX results in a complete image of the inspected volume rather than a plot of collected signals. The IWEX methodology allows for data visualization in both two and three dimensions and provides more accurate characterization of flaw sizing, position, and orientation (see Figures 9 and 10).
Fig. 9: Inspected steel bar containing artificial defect, 2D IWEX image of artificial defect and IWEX 3D result for the artificial defect.

Fig. 10: Screen shot of the same ID weld crack taken from an interactive 3D image produced from IWEX technique

REFERENCES