REPORT

February 04, 2006
EWI Project No. 47960GTH
DoT Other Transaction Agreement No. DTRS56-04-T-0011

Review of X80 and X100 Pipeline Welding

Task 1 Report
Optimizing Weld Integrity for X80 and X100 Line Pipe

Submitted to:

U.S. Department of Transportation
Research and Special Programs Administration
Washington, DC

EWI

MATERIALS JOINING TECHNOLOGY

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Executive Summary

This report was prepared by Edison Welding Institute, as an account of work on EWI Project No. 47960GTH (Task 1), under the Other Transaction Agreement (OTA) No. DTRS56-04-T-0011 to the U.S. Department of Transportation. This report is intended to be a comprehensive survey of X80 and X100 pipeline welding technologies including the development of line pipe steels, different girth welding processes, a description of design considerations, a short review of several specific X80 and X100 line pipe construction projects, and finally a discussion on the welding consumables. An allied activity under Task 2 of this project prepared a "best welding practices guide" for X80 pipelines. In both these tasks, the technical direction and the contributions of EWI's cost-partners were important. These were EWI Microalloying, TransCanada, BP, El Paso Pipelines, Cranfield University, Miller/Hobart, and CANMET. During the literature survey, EWI found many outstanding papers (see extensive bibliography), which provided good synopses of topic areas covered in this report. While the authors of this report made every attempt to summarize the findings or conclusions from these papers, sometimes the best way to express the latter was close to the way originally written – especially in such cases, EWI gratefully acknowledges the efforts and contributions of the papers' authors.

This report forms the basis of X100 welding consumable development (undertaken under Task 3 of this project). A 2-dimensional finite element model was created and calibrated with respect to the experimental results published by Mark Hudson (former student at Cranfield University). This model predicts the cooling rates during various weld passes in narrow groove welding of X100 pipes. The results of this model also matched very well with the data supplied by Cranfield University. The cooling rate data predicted by the FE models have been used to correlate the welding parameters with the observed microstructure and material properties. These data points were used as input to create a neural network (NN) model through which eight weld chemistries were finalized by the project team. The selection of weld chemistries, target mechanical properties for X100 pipes, and the welding process to be used were guided by the findings in this report.

Acknowledgements

This report was prepared by Edison Welding Institute, as an account of work on Project No. 47960GTH, under Transaction Agreement No. DTRS56-04-T-0011 to the U.S. Department of Transportation. Edison Welding Institute (EWI) would like to gratefully acknowledge the valuable suggestions received form its cost-sharing partners: BP, TransCanada, CANMET and Miller/Hobart.

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1.0 Introduction

The trend to higher strength pipelines has resulted in the development and use of high strength, microalloyed, thermo-mechanically processed steels. Welding of these high strength steels poses a range of challenges due to their sensitivity to variations in heat input, preheat, and interpass temperatures. This requires close control of the welding process. A substantial amount of development has been completed to characterize the properties of X80 and X100 welds made under specific conditions. These programs have confirmed that weld metal can readily match the X80 and X100 pipe using commercially available welding consumables in combination with carefully developed welding procedures. However, the move towards higher strength steels also comes at a time when design practices are evolving and there is greater focus on overmatching criteria for pipeline girth welds to ensure that weld metals overmatch the actual pipe material properties rather than SMYS. This has led to a minimum weld metal tensile requirement of almost 100 ksi for X80 pipe and 120ksi for X100 pipe while still maintaining high toughness and CTOD properties. As a result X80 pipe is welded with consumables of X100 grade and X100 pipe is welded with X120 grade consumables. Extensive tests have been performed on commercially available X100/120 grade welding consumables, but they tend to provide either low tensile properties or very high tensile properties in combination with low toughness and all are very susceptible to minor variations in cooling rate. Weld metals tested under very minor changes in cooling rate have shown a +/- 15% variation in yield strength, which can lead to either girth weld undermatching or very high strength, low ductility girth welds. There is therefore a need to optimize weld metal chemistry for weld tensile properties higher than 100ksi to produce consumables that are more tolerant of field welding process variations. This effort (Task 1) is dedicated to reviewing the current status of X80 and X100 pipeline welding technology and examining the trend towards overmatching weld metals. A best practice guide was developed under another task (Task 2) for X80 welding based on existing commercially available welding technology and optimized welding consumables and welding procedures will be developed for X100 pipelines.

Although the current experimental approach of making full scale welds with a range of filler metals and process conditions is time consuming and expensive it has produced a valuable body of data that can be used for further analysis. The Task 3 of this project will use the available data as initial input and apply a modeling approach to determine the influence of weld metal chemistry on physical properties and assess the optimum weld metal chemistry for the required balance of metallurgical properties when strength levels over 100ksi are necessary.

It will therefore provide a better understanding of the factors that control strength and toughness in high strength girth welds and will enable high integrity girth welds to be more reliably and economically achieved. This scope of this can be summarized as follows:

- Weld procedure information and test results collected/used to determine optimum welding combinations for normal girth and tie-in welds.
- Include manual, semi-automatic, and mechanized welding.
- Insight into material performance, construction, and pipeline integrity on the Colorado Interstate Gas X80 Cheyenne Plains Pipeline.
- Examine weld metal overmatching and overmatching criteria – relate it to variations in distribution of mechanical properties of manufactured pipe.
- Examine the overmatching criteria in the light of transverse and longitudinal weld metal properties.

2.0 Line Pipe Steel Development

Over the years, pipeline steelmaking has evolved from the use of low yield strength construction steels to the use of microalloyed steels and specialized manufacturing processes. In the late 1950s the production of line pipe steels consisted primarily of normalized C-Mn steels with a specified minimum yield strength (SMYS) of 52 ksi or X52 steel. In the 1960s microalloying of normalized C-Mn steels became the preferred manufacturing process for pipeline steels. In 1965, the microalloyed normalized C-Mn steel X60 with a C content of about 0.20% was introduced. A few years later, manufacture of microalloyed steels up to grades X65 and X70 began. Further increases in strength of the normalized C-Mn steels were not feasible because the large amounts of alloying required would result in decreased toughness making the steel unweldable. The next evolution in pipeline steel manufacturing started in the 1970s with the use of thermo-mechanical treatments for steel. The chemical composition of the thermo-mechanically treated steels is characterized by significantly lower C, Mn, and Si contents, and the addition of microalloying elements. This allowed for the manufacture of X70 grade. In the 1980s incremental development led to X80 line pipe steels. Laboratory-scale research on X100 occurred in the mid-1980s, and in the 1990s, several large projects were undertaken by oil and gas companies. In the mid-1990s, early development of X120 was initiated. Figure 1 is a schematic which shows the progression of line pipe steel development. Note that a portion of this historical account appeared in Reference 1.

2.1 Steel Processing

Over the past three decades steel processing has undergone a considerable evolution, with many of the advances being essential to the continuous development of high-strength low-alloy (HSLA) steels.

2.1.1 Melt Practice

Basic oxygen steelmaking (BOS) and continuous slab casting have replaced open-hearth steelmaking and ingot casting. More recently, there has been an emerging trend in steelmaking to electric arc furnace and direct thin slab casting for strip and thin plate products. Another major development in steelmaking has been the introduction and expansion of secondary refining processes in the steel ladle, or ladle metallurgy. Ladle metallurgy includes vacuum degassing, steel ladle injection with Ca-Si powder, and inert gas stirring. Specialized and high-quality clean steels can now be produced on a large volume basis. Carbon levels of less than 0.003% for the production of interstitial-free steels can consistently be achieved using modern vacuum degassing units. Iron pretreatment and steel ladle injection can achieve S levels of less than 0.001% resulting in fewer sulfide inclusions in the final product, which is particularly important for steels required for sour service applications. Finally, the addition of alloys during vacuum degassing allows for enhanced compositional control enabling narrow ranges of specified elements to be achieved by tightly controlling microalloying additions under the inert atmosphere.(2)

2.1.2 Alloying Additions

The major alloying elements in steel manufacturing include carbon, manganese and silicon. Nickel, chromium and molybdenum are also frequently added for improved strength, toughness, corrosion resistance or to promote specific microstructural features. Microalloys such as titanium, boron, niobium, and vanadium may also be added for grain refinement or precipitation strengthening. The effects of the various alloying elements are discussed below.

Carbon is the primary alloying element and is present in all steels. The level of carbon influences the primary solidification microstructure of the steel and contributes significantly to its hardenability. Carbon also profoundly changes the phase relationships, microstructure and properties of steel, and forms the basis of the hot workability and heat treatability of steels. In general, carbon is kept low in steels that require good toughness, ductility, and weldability.

Manganese is a solid solution strengthener and is used extensively in steels to promote hardenability. Manganese is also used for desulfurization. Higher amounts of manganese may degrade ductility and weldability, so it is generally limited to about 1.65%.

Silicon is used in steel making as a deoxidizer. Typical silicon contents in steel plate and pipe may range from very low levels up to about 0.6%. Silicon also acts as a strengthener, although it is a less potent strengthener than manganese. Higher silicon levels can also degrade toughness and weldability.

Nickel is added to low-alloy steels primarily to improve toughness, but also for added strength. Nickel does not form any carbide compounds, and as a result, it will stay in solid solution in ferrite, thereby promoting strength and toughness. Nickel is also useful in that it reduces the critical cooling rate, making heat treating easier.

Molybdenum may be added to pipeline steels in the range of 0.1 up to about 1%, although additions of about 0.3-0.6% are more typical. Molybdenum is a solid solution strengthener and is often added to steels to enhance elevated temperature properties and creep resistance. It can also induce secondary hardening during tempering or stress relieving of steels.

Chromium is generally added to steel to improve corrosion and oxidation resistance, to increase hardenability, and to enhance high temperature strength. Chromium is a strong carbide former. Consequently, if a chromium-containing steel is to be re-austenitized, a longer time at temperature may be required to fully dissolve the carbides. Higher chromium contents tend to be detrimental to toughness.

Other elements found in steels may include copper, aluminum, sulfur, phosphorus, and lead. Copper is sometimes added to improve corrosion resistance or for precipitation strengthening. Aluminum is used primarily for deoxidation. Sulfur, phosphorus, and lead are sometimes added to steels to improve machinability; however, because they form low melting phases with iron, they are very detrimental to weldability. For this reason, the level of these elements should be kept as low as possible.

2.1.3 Microalloying Additions

Microalloying is a common practice in steel processing to achieve required strength and toughness. The elements which increase hardness tend to have an adverse effect on weldability. Microalloying elements can usually be controlled within a very tight range, which results in a narrow range for the overall carbon equivalent of the steel, typically of about 0.05%. Vanadium, niobium, and titanium react preferentially with carbon and/or nitrogen and form a fine dispersion of precipitated particles which act to strengthen the steel matrix and provide grain refinement. Minimization of impurity elements such as N, O, S, P, and H largely contributes to the improvement of ductility, inner soundness, and hydrogen-induced cracking and stress corrosion cracking (HIC/SSC) resistance. Figure 2 suggests that the chemical composition and manufacturing conditions influence the properties of line pipe steels although the relationship is not easily understood.(3)

Adding titanium in amounts ranging from 0.005% to 0.025% to high strength low alloy (HSLA) steels has become common practice. Titanium has a strong affinity for N which results in the formation of TiN precipitates during solidification and subsequent cooling. Under cooling rates encountered in the continuous casting of slabs, a fine dispersion of TiN precipitates is produced, which restricts austenite growth during rolling and welding. The restricted austenite grain growth can result in a finer ferrite grain size and improved low-temperature toughness. In welding, TiN has been also found to restrict the width of the heat-affected zone (HAZ) and the austenite grain size of the coarse-grained region in the HAZ. This refinement of the weld HAZ has been shown to significantly lower the HAZ hardness.(2)

Vanadium is typically added to microalloyed steels in amounts ranging from about 0.02 to 0.10%. Besides precipitation strengthening, it can also improve toughness by reacting with dissolved nitrogen in the steel. However, it also has the effect of increasing the impact transition temperature.

Niobium is also a strong carbide/nitride former, but its function is more one of grain refinement than of strengthening, although it also has a strengthening effect. Niobium forms precipitates above the transformation temperature which retard the transformation of austenite, thereby promoting a fine-grained microstructure with good strength and toughness. Niobium concentrations in microalloyed steels typically range from about 0.02 to 0.10%.

Another element that has a strong influence on the strength of the material is boron. While yield strength requirements of 690 MPa (range of X100) can be realized with both B-free and B-bearing steels, studies have shown that a combination of B microalloying and optimized processing can result in a microstructure of ultrafine ferrite with significantly improved toughness. Mo-B steel in the range of X100, under standard thermo-mechanically controlled processing (TMCP) conditions, showed a microstructure of lath-like bainite. By optimized finish rolling, it was transformed into ultrafine ferrite. Strength levels of X120 demand even more complex alloying. Fine cementite platelets within ferrite laths, similar to conventional lower bainite seem to be beneficial for lower Charpy V-notch (CVN) transition temperatures for these grades of steels.(18)

2.1.4 Microstructural Considerations

For steels of grade X80 and above, the balance of strength and notch toughness can be achieved through structural refinement resulting from bainite. Bainitic steels are more difficult to produce and optimize than other conventional steels. Bainite is obtained by alloying with Mn and Mo or other bainite-promoting elements such as Cr, Cu, Ni, and B, all of which increase the hardenability of the steels.(18)

A study was performed on X120 grade line pipe by Nippon and ExxonMobil which describes the development in plate manufacturing. In order to maintain good weldability for field girth welding, the C content of high-strength line pipe is typically less than 0.1%. Use of as-rolled steel or TMCP steel without heat treatment is essential for supplying large amounts of line pipe to big pipeline projects over relatively short periods of time.(18)

Figure 3 illustrates the relationship between transformation temperature and tensile strength (TS) for three steels with C contents of 0.1% or lower. It appears that a lower bainite microstructure steel with a low C content (lower than 0.06%) and an upper bainite microstructure steel with a rather high C content (close to 0.10%) can be considered for X120 steel, while the upper bainite microstructure steel with low-C content is a candidate for X100.(18)

Dual-phase steels composed of ferrite and martensite, produced by quenching the steel after ferrite is generated during air cooling, can also be considered for high strength line pipes. Figure 4 shows the typical microstructure of low-C TMCP steels with high strength of around 1000 MPa. For X120 steel, the austenite-to-ferrite transformation temperature being low, makes it rather difficult to produce dual-phase steels in large quantities. Therefore, for developing X120 steels a lower bainitic microstructure with interrupted direct quench (IDQ) has been employed, which is schematically illustrated in Figure 5.(18)

2.2 Plate Processing

Strength of X70 grade material is highly dependent on chemistry and to lesser extent on plate processing parameters. Controlled rolling (CR) is recently a developed process which offers many advantages. During CR the heating temperature and the rolling conditions are closely controlled to develop a microstructure that produces high strength and excellent toughness. It is possible to achieve high production of quality plates by means of CR. On-line accelerated cooling (OLAC) aids in further refining the steel plate microstructure. CR and OLAC are collectively known as the thermomechanical control process (TMCP) and are gaining in popularity. TMCP leads to improved strength and toughness of steel through an increase in hardenability and grain refinement.(3)

Figure 2 schematically represents the effect of chemical composition and TMCP on the properties of line pipe steels through various metallurgical mechanisms.(3) For example, the yield strength (YS) of TMCP MnNbTi steel can be increased by the use of accelerated cooling, without adversely affecting the Charpy toughness. This is explained by the fact that the transition from a ferritic-pearlitic structure to a ferritic-bainitic structure brings about a beneficial effect not only on the material's strength, but also on its toughness properties.

Advanced vacuum treatment and continuous casting are the required processes for X80 and X100 grade steel. Table 1 describes the required properties of these two steel grades. To achieve the properties of this high grade steel use of TMCP with high cooling rate and low cooling temperature almost becomes mandatory.(18)

In one study, the optimization of X100 base chemistry was performed under the optimized rolling and accelerated cooling conditions. Figure 6 shows the relationship between the TS of the base metal and the base metal chemistry. A steel containing 0.05 to 0.06%C, 0.15%Mo and varying Nb levels, with carbon equivalents ranging from 0.37 to 0.45% was used for examination. The steel was rolled with 1150ºC as the reheat temperature, 700ºC as the rolling finishing temperature and with a cooling rate of 25ºC/s. The addition of Nb and an increase in C_{eq} are effective in obtaining higher strength; hence, a steel containing 0.04%Nb with a C_{eq} greater than 0.42% is adequate for achieving X100 grade steel strength.(4)

2.2.1 Cooling Rate Effects

To achieve the properties of X100 grade material the plate rolling techniques and accelerated cooling conditions play very important roles. The effect of accelerated cooling, slab reheating temperature, and rolling finishing temperature on the mechanical properties were examined using 20-mm-thick steel plates similar to X80. Figure 7 shows the effects of cooling after rolling on the tensile strength of 0.05C-0.15Mo-0.01Nb steel. Tensile strength increases with an increase in cooling rate as cooling rates increase above about 15ºC/s.[4]

In order to explain the strengthening mechanism under a higher cooling rate, the transformation behavior during cooling was examined. Figure 8 demonstrates continuous cooling transformation after hot deformation. In this examination, a reheat temperature of 1150°C and a hot deformation of 50% at 700ºC were adopted before transformation start and finish temperature measurement. Note that the microstructure consists of upper bainite when the cooling rate is less than 15ºC/s. Microstructures with a combination of upper and lower bainite are achieved with cooling rates greater than 15ºC/s resulting in an increase in tensile strength. Thus, it can be concluded that for this composition, a cooling rate greater than 15ºC/s and a finishing temperature less than 300ºC seem to be adequate for accelerated cooling of X100 to produce higher strength.[4]

2.2.2 Finish-Cooling Temperature (FCT)

FCTs play a very important role in achieving the mechanical properties of steel grades of X80 Figure 9 shows the yield strength and tensile strength changes with respect to the FCT in an X80 grade 1.6Mn-0.25Mo-Nb-V steel. All the steel plates in Figure 9 were finish rolled in the austenite single phase region and then cooled at rates above 10ºC/s to the various finish cooling temperatures. The yield strength is related to FCT: the yield strength decreases with decreasing FCT. When the FCT is above the bainite finish temperature the tensile strength is in the same range, but when the FCT fell below bainite finish temperature, the tensile strength increases rapidly. Therefore, the optimum strength was obtained when FCT was around the acicular ferrite finish temperature.[17]

Figure 10 shows the changes of CVN toughness as a function of FCTs and test temperature. The maximum CVN energy was obtained when the FCT was equal to the acicular ferrite finish temperature which is similar to the case for YS. This resulted in a CVN energy transition temperature below -80ºC. The transition temperature increased to around -60ºC when the FCT was around or below the bainite finish temperature.[17]

The relationship between the rolling finishing temperature and toughness was investigated by Nagae, et al. Figures 11 and 12 show the shear area percentage for drop weight tear testing and absorbed energy for CVN testing at -20°C. The horizontal axes in the figures relate to the difference between the rolling finishing temperature and Ar_3 temperature calculated using Ouchi's equation. Shear area increases and the absorbed energy decreases with a decrease in rolling finishing temperature. The improvement of shear area seems to depend on the appearance of separation on the fracture surface and a decrease in tensile strength. Based on these results, it is preferable to decrease the rolling finishing temperature in order to improve shear area percentage of the drop weight tear test. By contrast, however, a decrease in rolling finishing temperature tends to lessen the absorbed energy of both the drop weight tear test and CVN tests. Therefore, it is also important to optimize the plate rolling conditions, such as rolling finishing temperature, to obtain high absorbed energy.(4)

2.2.3 IDQ

Figure 13 shows the effect of the IDQ stop temperature on strength and toughness. With increasing IDQ stop temperature the tensile strength gradually decreases; however, the change is relatively small up to 400ºC. At an IDQ stop temperature of about 450ºC the ductile-to-brittle transition temperature of the CVN test starts to increase which results in decreased CVN energy. The increased ductile-to-brittle transition temperature results from a change in a microstructure dominated by lower-bainite to one dominated by upper-bainite. This is due to the fact that the structure in a lath of lower bainite is much finer than that of upper bainite.(18)

2.2.4 Effect of Reheating

The effects of slab reheating temperature on strength and toughness were also investigated by Nagae, et al. Figure 14 shows the effect of the reheating temperature on the tensile strength of a steel containing 0.05C, 0.15Mo, and 0.03Nb. The toughness of the steel is shown in Figure 15. The steel was cooled at a rate of approximately 25ºC/s, and had a finishing temperature of 200ºC and a rolling finishing temperature of 700ºC. The arrow in the figure indicates the Nb(CN) dissolution temperature of the steel. This temperature is calculated using Irvine's equation. It can be seen from the figure that up to the dissolution temperature the tensile strength increases with increasing reheating temperature, and further increases in reheating temperature do not influence the strength. By contrast, the CVN fracture appearance transition temperature changes slightly with an increase in the reheating temperature up to the dissolution temperature. In the higher reheating temperature region, toughness deteriorates with an increase in the reheating temperature.(4)

2.3 Pipe Manufacturing

The yield strength of pipe relative to steel plate can be altered significantly due to various steps such as rolling leveling, sizing, and post-sizing pressure testing which take place during pipe manufacturing. Changes in strength from plate to pipe are governed by the work hardening and Bauschinger phenomena. It is very important to understand both material and forming factors that make it possible to target the optimal strength of steel plates before the pipe-forming operation in order to meet the final strength requirement of the pipes.(17)

The plate properties are required to be well defined considering the pipe forming process involved, as both impact energy and drop weight tear test (DWTT) transition temperatures drop from plate to pipe due the cold deformation. Special attention must be focused on the change in strength (YS, TS) from plate to pipe.(18)

- **Pipe-forming parameters.** The change in properties from plate to pipe depends on pipe forming parameters, wall thickness, and diameter. In principle, an increase in yield strength after pipe forming can be observed because of work hardening as a function of t/D ratio.(18)

- **Bauschinger effect.** The Bauschinger phenomenon also plays a very important role in influencing the pipe tensile results. Yield strength is reduced because of the generation of residual stresses that accumulate due to pipe forming and flattening of the specimens. Consequently, the higher the grade of steel, the greater the difference in yield strength between plate and pipe.(18)

- **Cold expansion of pipes.** Work hardening which results from cold expansion after pipe forming can increase the yield strength. But if the pipe mill does not use the expander a greater difference between plate and pipe yield strength can be found. Therefore, the yield strength must be higher to begin with (see Figure 16).(18)

- **Microstructure.** Because microstructure has an impact on the yield and tensile strengths of plate, changes in microstructure will result in changes in the strength of both plate and pipe. Furthermore, different microstructures respond differently to pipe forming, which can result in further changes in strength from plate to pipe.(18)

- **Tensile test specimens.** The type of tensile testing specimen also has an effect on the results. Rectangular specimens are taken as full thickness specimens and have to be flattened which can influence the yield strength, whearas, the round bar specimens do not require the same treatment.(18) Many codes and standards now allow pipe manufacturers to qualify the pipe hoop strength using round bars instead of flattened straps.

- **Post-weld heat treatment.** Strength properties are generally reduced as a result of PWHT, and thus if PWHT is part of the resultant operation the property changes must be considered by an appropriate steel design.(18)

2.4 Long Seam Fabrication

Pipes may be longitudinally submerged arc welded by three- and four-wire systems using a multi-layer technique (see Figure 17). It is very important to properly control the tracking of wire in the weld groove. Achieving the right combination of strength, hardness, and toughness in the HAZ for high grade steel is also a major challenge and must be considered in the design of steel.

Large-diameter transmission line pipe may also be spirally formed and welded using continuous submerged arc welding (SAW). Spiral pipe is limited in the number of welding heads which may be used to produce the weld. While longitudinal welds may be made with up to five or more welding heads, the fact that the spiral pipe is rotating as the welds are being produced limits the amount of heat which can be put into the weld. The rotation of the pipe also reduces the amount of time the weld is covered by flux and slag, which results in faster cooling of the weld. Consequently, the choice of welding consumables may need to be adjusted to offset the higher strength levels that may be expected due to the faster cooling rates.

2.4.1 Double SAW

Selection of the right consumables to guarantee both the yield-to-strength ratio and sufficient toughness is very important. The addition of alloying elements such as Ni, Mo, Cr, and/or TiB has been proven to be very useful in achieving the required property combinations. It is also very important to control the heat input in order to achieve sufficient toughness, especially near the fusion line.(18) Table 2 summarizes the general requirements for seam-welded line pipe. The strength of the pipe in the circumferential direction determines the pressure-carrying capacity of the pipeline and, therefore, is an essential requirement.(18)

The carbon and carbon-equivalent levels need to be restricted as much as possible in order to achieve low temperature weld metal toughness in the long seam. Addition of Ti and B which helps in refining the microstructure can be used to improve the low temperature toughness.(3)

The weld metal O and N content strongly affect the properties of Ti-B welds which means the optimum amount of Ti and B in the weld will vary with O and N contents Figure 18 illustrates the effect of Ti and N on weld metal CVN toughness. When a C-Mn-Ni-Mo-Ti wire is employed to produce high strength and high toughness, a higher N content leads to the necessity of a larger amount of Ti being added. Also, in a C-Mn-Ti wire, the optimum range of Ti to be added is almost the same as in the C-Mn-Ni-Mo-Ti wire when the nitrogen content is kept constant.(3)

The Mn content in the weld metal has also been found to be an important factor on toughness. Figure 19 illustrates the effect of the Mn content on weld metal CVN toughness. The maximum toughness can be achieved with manganese content of 1.4 to 1.6% because of the refinement of the microstructure caused by retardation of the formation of grain boundary ferrite. With lower levels of Mn the toughness decreases because of coarse grain boundary ferrite, and with higher levels of Mn the toughness again decreases due to the formation of upper bainite. Thus, it is very important to maintain the Mn levels between 1.4 to 1.6%.

In seam welding of line pipe, it is possible to obtain excellent low-temperature toughness weld metals free from undercutting or slag inclusions by the combination of SiO_2-CaO-CaF_2-Al_2O_3-B_2O_3 highly basic flux for high speed welding and C-Mn-Ni-Mo-Ti wire.(3)

2.4.2 Long Seam HAZ

The toughness of the HAZ must be considered when designing the chemical composition of the base metal since the base metal composition plays a key role in HAZ toughness. Figure 20 shows the effect of C and B content on the base metal 50% shear fracture area transition temperature (vTrs) of Charpy impact test samples located in the HAZ. With lower carbon contents the vTrs of HAZ improves. Improvement is greatly when C is less than 0.05% in boron-free steel due to a microstructure that is a mixture of lower bainite and grain boundary ferrite. This microstructures leads in to good toughness in HAZ with value of vTrs lower than -50ºC.(3)

A CTOD test may be required for line pipe steels to investigate resistance to brittle fracture. Figure 21 shows the effect of notch location on the temperature ($T_{0.2}$) at which crack tip opening displacement (CTOD) exhibits a value of 0.2 mm. The graph shows that the value of CTOD decreases to the minimum at a distance from the fusion line, L, of 2 to 2.5 mm. Low-C B-free steels exhibit better CTOD values as compared to low C B-containing and ordinary C steels. [3]

Candidate steels with chemistries appropriate for high-strength line pipe were subjected to a simulated HAZ thermal cycle corresponding to a seam weld with a peak temperature of 1400ºC. Figure 22 shows CVN impact energies at -20ºC as a function of hardenability index value, β. In this case, poor toughness was seen in B-free steel especially with C contents exceeding 0.05%. Transmission-electron microscopy showed that a lower bainite microstructure is formed in the coarse-grained HAZ (CG-HAZ) of the B-containing steel, while upper bainite microstructures dominate the B-free steel. It is very important to note that the Charpy test is only a rough indicator of fracture initiation resistance. The final verification of the ability to resist fracture initiation is conducted by performing fracture mechanics tests such as CTOD tests or J-integral tests.[18]

Because excess boron accelerates the formation of B carbide, the amount added should be limited to a very narrow range above the minimum content necessary. The addition of Mo to the steel is also useful in suppressing the formation of B carbides.[18]

3.0 Pipeline Girth Welding Processes

The pipeline industry has traditionally been an extremely conservative one and, despite the fact that cross-country pipeline construction essentially involves the repetition, from forty to eighty times per kilometer, of the same joint, manual shielded metal arc welding (SMAW) remains the dominant process. Limited use has been made of the manual gas metal arc welding (GMAW) process, but such a repetitive operation is an obvious candidate for mechanization. Since the early seventies, mechanized GMAW has been applied to large-diameter projects, both cross-country and, more particularly, offshore; the limitations of manual SMAW are strongly evident under the restrictive circumstances of lay-barge operation.

It has also been characteristic of the pipeline industry, at least in North America, that it is strongly cyclic; this can pose problems in terms of work-force stability, which may be of great importance to an operation which relies heavily on highly-specialized craft skills as does the manual, fixed position SMAW technique used for pipeline welding. It thus should come as no surprise that increasing efforts are being made to develop alternative methods of welding pipelines of all size ranges, with the aims not only of improving economics and efficiency, but also of providing weldment properties which are engineered for specific project requirements and reproducibly maintained in the field. The growing trend toward a fitness-for-purpose approach to weld defect acceptance places increasing importance on the second of these factors.

The economics of pipeline construction are determined by two aspects of the pipeline welding method:

- The root pass welding speed governs the overall productivity of the pipeline construction spread.

- The fill pass welding deposition governs the number of welding stations needed to maintain pace with the root pass.

Although the fill passes do not control progress of the pipeline construction, the efficiency of fill and cap processes determines the overall joint completion rates and the number of fill stations required. The size of the welding spread can be adjusted according to the nature of the terrain and the productivity required.

3.1 SMAW

By correct choice of consumables and welding technique, the SMAW process can be used in all welding positions and will allow a wide range of property requirements to be met. It is thus an extremely versatile process; however, it is very dependant on the welder's manual skills for the attainment of defect-free welds having acceptable properties, and its productivity is inherently limited by its intermittent nature. Most developments in pipeline welding have been aimed at overcoming one or both of these limitations of the manual, SMAW technique.

3.1.1 Cellulosic SMAW

Traditionally, mainline welding is carried out using electrodes with a coating of cellulosic materials which break down in the heat of the arc to generate a voluminous gas shield containing carbon monoxide, carbon dioxide and hydrogen; these electrodes develop a strong plasma jet which gives excellent penetration, allowing a "keyhole" technique to be used for the root pass, and only a small amount of light, fast-freezing slag is formed which makes the electrode very suitable for positional welding with a vertical down progression. Hydrogen-assisted cold cracking is the most disruptive, if not the most statistically prevalent, quality problem associated with manual, shielded metal arc pipeline welding using cellulosic electrodes. The presence of hydrogen in the arc atmosphere results in a high diffusible hydrogen content in the deposited weld metal and this can lead to weld metal and/or heat-affected cracking unless a controlled sequence of welding such as the use of pre-heat, hot-pass techniques, and limited time delay between initial passes, is strictly adhered to.

3.1.2 Low-Hydrogen SMAW

Low-hydrogen, vertical-down (LHVD) SMAW electrodes are available which, when compared with cellulosic electrodes, can provide superior weld metal toughness with a reduced susceptibility to hydrogen-assisted cracking, and still retain some of the productivity benefits of stovepipe welding. The main drawback of these electrodes is the speed of completion of the root pass which, based on welding speed alone, is some 60% slower than with cellulosic electrodes, and this difference is exacerbated when the additional grinding of stop-start locations is taken into account. Overall weld completion times are comparable, but this is of little consequence for cross-country pipeline construction, where progress is dependant on the time to complete the root pass. In view of the fact that the mechanized GMAW process has the advantages of both a low-hydrogen deposit and improved productivity when compared with conventional pipeline welding with cellulosic electrodes, the potential for application of LHVD electrodes on large-diameter mainline construction is limited. LHVD SMAW can be considered for short sections of pipeline where the economics would not support the utilization of mechanized welding, and they are routinely used on tie-in and repair welding to complement mechanized GMAW.

3.2 Flux-Cored Arc Welding (FCAW)

Two variants of FCAW have been used for pipeline applications: gas shielded (FCAW-G) and self-shielded (FCAW-S). FCAW-G electrodes offer good operating characteristics and excellent control of weld properties, but may suffer from loss of shielding in the presence of moderate winds. The use of E71T-1/E71T-12 electrodes have been investigated for a number of pipeline applications but these electrodes have not been deployed extensively for girth weld production in North America. Self-shielded flux-cored wires are designed to operate in air and control the higher O and N levels by chemical reactions in the weld pool.

The FCAW-S process has been used in pipeline construction for over 20 years with outstanding success. FCAW-S electrodes are alloyed with Ni, Mn, and other micro alloying elements to achieve weld metal with the necessary strength. These electrodes, typically 1.7- and 2.0-mm diameter, are used with small wire feeders and lightweight gun and cable assembles allowing easy manipulation of welding system for the welder.[25]

The most common welding process employed for root pass is with SMAW which, in recent years, has increasingly been replaced by solid wire electrode (GMAW) processes with subsequent passes using the FCAW-S process. FCAW-S has generally shown fewer repairs and less grinding time per joint as compared with SMAW. Shown in Table 3 are the parameters used to evaluate the welding cost of a typical joint. The calculated amount of weld metal needed to fill and cap the joint is 5.76 kg. These figures represent about a 40% savings with the FCAW-S process over SMAW. Not included are the improved quality advantages. Typical repair rates for the SMAW process are in the 3 to 5% range. For FCAW-S, repair rates are normally <1% and usually <0.5%.[25]

FCAW-S wires have lower burn-off rates because of high slag volumes and the core that contains metallic and non-metallic materials which vaporize to provide additional shielding. Additional energy is required to melt the slag-formers and vaporize the volatile components which results in lower deposition rates and decreased fusion of the parent material.[17]

The self-shielded electrodes have found application in mechanized welding but also have a tendency toward porosity formation, thus slight variations in the weld pool fluidity can lead to weld imperfections.[17]

3.3 GMAW and Principles of Operation

The GMAW process incorporates the automatic feeding of a continuous, consumable electrode that is shielded by an externally supplied gas. The process is illustrated in Figure 23. Equipment required for GMAW is shown in Figure 24. The gun guides the consumable electrode and conducts the electrical current and shielding gas to the work, thus providing the energy to establish and maintain the arc and melt the electrode as well as the needed protection from the ambient atmosphere.[12]

The characteristics of the GMAW process are best described in terms of the three basic means by which metal is transferred from the electrode to the work:

- Short-circuiting transfer
- Globular transfer
- Spray transfer, including pulsed spray transfer.

Short circuiting encompasses the lowest range of welding currents and electrode diameters associated with GMAW. This type of transfer produces a small, fast-freezing weld pool that is generally suited for joining thin sections, for out-of-position welding, and for bridging large root openings.[12]

Globular transfer takes place when the current is relatively low, and at wire feed speeds between short circuit and spray transfer. However, with CO_2 and He, this type of transfer takes place at all usable welding currents. Globular transfer is characterized by large drop size relative to the wire diameter, and heavy spatter. This makes it an impractical mode of metal transfer for most welding applications including line pipe welding.[12]

With Ar-rich shielding gases (with CO_2 at or below 20%) it is possible to produce a very stable, low spatter "axial spray" transfer mode as illustrated in Figure 25. This requires the use of direct current and a positive electrode (DCEP), and a current level above a critical value called the transition current. The factors affecting the transition current include the electrode material, electrode diameter, and shielding gas type.[12] Above the transition current, the transfer occurs in the form of very small drops (relative to the wire diameter) that are formed and detached axially across the arc gap at a high rate.

The lower material thickness and welding position limitations of axial spray arc transfer have been largely overcome with inverter-based pulsed current power sources developed in the 1980s and subsequently refined. As shown in Figure 26, they provide two levels of current: (1) one a low background current which sustains the arc and (2) the other a current pulse with amplitude greater than the transition current. The energy of the pulses controls the droplet volume, and together with the pulse frequency, determines the rate at which the wire melts. By pulsing the current the desirable features of spray transfer are available at a wide range of wire feed speeds for joining metal thickness ranging from sheet to plate and in all welding positions.[12]

3.3.1 Mechanized GMAW

With the GMAW process, the continuous nature of the wire electrode and the virtual absence of slag covering lead to high productivity, and the process is ideally suited to mechanization and automation. First used for pipeline girth welding in 1969, the mechanized GMAW process has become the standard for major, large-diameter, cross-country pipelines in Canada and is being increasingly used in the U.S.

Mechanized GMAW systems use lightweight tractors (see Figure 27) running on a band or track 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, and a reduced-gap, compound bevel which is accurately machined on the pipe ends immediately ahead of the welding crew. The major difference between the systems is in the deposition of the root bead; either it is completed with welding heads incorporated into the internal line-up clamp to produce a root bead from the inside of the pipe (see Figure 28) or all passes are completed externally, with the root bead being run on to a copper backing bar which is incorporated into the internal line-up clamp.

Mechanized welding is an expensive option. As mentioned, it can involve an internal root pass welding system, external welding heads and special, field-machined bevels. For cross-country pipeline construction, high-quality welding shelters or “shacks” (see Figure 29) are also required to provide protection from wind and weather.

Consequently, equipment costs are relatively high and economic viability is not always achievable for the shorter, large-diameter construction projects. However, since the early 1980s, a number of process and equipment developments have improved the overall productivity and economics of mechanized welding. In addition, the mechanical property requirements either already specified or being proposed for X80 or X100 pipelines have effectively made mechanized GMAW the only viable mainline welding process for these higher strength materials.

With good weld procedures and appropriate bevel design, it is hard to choose between the use of an internal welding machine or copper backing shoes as both produce good quality welds and good productivity. Internal welding machines are generally considered to be less sensitive to high-low and, for cross-country pipelines, they 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. Below 610-mm (24-in.) diameter, it is not practical to use an internal welding machine whereas copper backing shoes have been used for pipes as small as 168.3-mm (6.6-in.) diameter.

To achieve the highest quality weld possible in X80 material, pulsed GMAW (GMAW-P) has been used to date in hot, fill, and cap passes, whereas short-circuiting GMAW (GMAW-SC) has been used with an internal welder for the root pass because of the susceptibility of GMAW-P to the effects of residual pipe magnetism. The GMAW-P process has been able to consistently produce defect-free welds at a joining rate equivalent to that of conventional GMAW.(13)

GMAW-P power sources are produced by all major power source manufacturers including Lincoln, Miller, ESAB, Fronius, and others. The controlled-drop-transfer (CDT) power source has been widely deployed through CRC-Evans. This power source, in common with most other GMAW-P equipment has full synergic control of pulse parameters including peak currents, pulse time, and background current. This allows the GMAW-P to perform out-of-position pulse-arc welding. By having individual programs that are defined by wire type, wire diameter, and shielding gas, the GMAW-P power sources select the pulsed current parameters from embedded control algorithms to provide stable spray transfer over a broad range of wire feed speeds. The user selects the wire feed speed and the power source selects the pulse parameters to obtain stable metal transfer.(13)

The most common mechanized GMAW system used for line pipe girth welding in North America is manufactured and supplied by CRC-Evans. Similar equipment has also been developed and commercialized by Serimer-Dasa, RMS Welding Systems, and Saipem. Although the basic equipment concept has been the same for over 25 years, many improvements have been incorporated into the equipment, as well as the welding procedures, to improve productivity, equipment reliability, and weld quality. In addition to single-torch systems used throughout the 1980s and 1990s, dual-head systems have now been developed and used in the field by both CRC and RMS welding systems. The Vermatt system with single and dual heads has also been used to deposit external root/fill passes in narrow groove joints. The Lincoln AutoWeld system, employing their surface tension transfer (STT) technology for the root pass, uses a conventional joint and does not require internal backing.

The CRC-Evans mechanized welding system employs an internal root pass in conjunction with the external passes deposited into a narrow gap bevel. A typical joint design is shown in Figure 30. The external passes are applied using mechanized welding machines. The normal process is CV GMAW using Ar/CO_2 mixtures for the root and cap pass and 100% CO_2 for the hot and fill passes. The welding procedure approach taken is to use GMAW-P for all external passes, and CV GMAW for the internal root pass.

3.3.2 Single-Torch Systems

The original mechanized GMAW system used a single torch and wire feed and the short arc or "dip" mode of metal transfer. In Canada, all major large-diameter X80 projects since 1994, totaling some 456 km, have been welded with this process. In essence, for a stress-based design, the mechanized welding technology required to weld X80 need be no different than that used to weld lower strength pipelines. Details of the most recent X80 pipeline construction project in Canada will be given in Section 5.

For the welding of X100 with single-torch systems, conventional dip-transfer welding with 100% carbon dioxide shielding gas will not provide the appropriate combination of weld metal strength and toughness and Ar-rich shielding gas mixtures and controlled-dip or pulsed welding conditions are required. For the first pipeline construction project using X100 pipe in Canada, GMAW-P was used; this is described in more detail in Section 5.

A version of controlled dip transfer used with rotating electrode GMAW (RE-GMAW) is presently being used to develop external root pass welding for X80 pipe using a closed root and no copper backing. Welding speeds in the range of 0.7 to 0.8 m/min have been achieved using this single wire process in which the internal portion of the torch is rotated mechanically. The system is being developed using a Serimer-Dasa STX welding tractor and track for 36-in.-diameter pipe (see Figure 31).

The prototype system (shown in Figure 31 mounted to 16-in. pipe) incorporates variable travel angle control, onboard data acquisition, and CTWD control.

3.3.3 Dual-Torch Systems

Orbital pipe welding systems with two torches provide many of advantages for the pipeline industry. The two torches can be programmed independently and provide impressive deposition rates, as two weld passes can be deposited in one run. The use of dual-torch mechanized welding makes the speed of the line-up crew the limiting factor to the progress of the pipeline construction spread. The possibility of running the root and hot pass simultaneously brings new benefits to the welding contractor including reducing the number of welding crews needed for construction.[14]

Vermaat Technics has developed the new Veraweld computer-controlled automatic pipeline welding system with two torches. The use of split cap weld passes increases the deposition rate by more than 100%, as is the case with fill passes. All of the equipment is in the welding shack and facilitates mobile welding stations, of which contractors may need only three; whereas, five or six were previously required.(14)

Several pipeline contractors now offer dual-torch welding equipment (see Figure 32) although single-torch systems still remain the most widely used.

With dual torches, the deposition rate is not always twice that of the single-torch systems. In the limited experience that TransCanada has with a dual-torch system, it was found to have a deposition rate (kg/hr) of 1.4 times that of a single head system. However, dual-torch systems are capable of a higher travel speed and require fewer workstations than single-torch systems. More recent experience with the dual-torch welding system on the Cheyenne Plains Pipeline X80 project in the U.S. will be discussed in Section 5.

3.3.4 Tandem GMAW

Although the fill passes do not control progress of the pipeline construction, the efficiency of fill and cap processes determines the overall joint completion rates and the number of fill stations required. They take on increasing significance as the pipe wall thickness and diameter increase. The economic viability of many future projects depends on the ability to complete the fill passes with as small a pipeline spread as possible in order to reduce labor and equipment costs. An alternative to multiple torches on one welding tractor is to have multiple wires through one welding torch.

Multi-wire or tandem GMAW differs from conventional GMAW 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 (see Figure 33).

Although the potential of the multi-wire GMAW process was first explored as early as the 1950s, it has not become commercially viable until relatively recently due to performance limitations associated with the power source technology that resulted in process instabilities. However, with the advent of modern microprocessor-controlled inverter power sources and an improved understanding of metal transfer characteristics, tandem GMAW is now being successfully applied.

Single-wire welds when used at high travel speed are sensitive to undercut, incomplete fusion, and porosity; whereas, tandem GMAW offers benefits including high travel speed and high deposition rate without any of the problems mentioned above.

Faster welding speeds and higher deposition rates are possible by the use of multi-wire systems because smaller diameter wires are generally used which result in increased melting and thus higher deposition. Furthermore, two wires increase the molten pool area over which the arc force for a given current is applied, thus allowing the use of higher currents before undercuts becomes a problem. Defects like lack of fusion (LOF) are also reduced due to the elongated weld pool which exposes the molten metal to the sidewall for a longer time thereby increasing the occurrence of fusion. This also reduces the susceptibility to solidification cracking.[15]

Figures 34 and 35 show cooling curves for a variety of different pipeline welding processes. Each weld was made at the same calculated arc energy and the curves have been adjusted to align the 1400°C point on each curve. Figure 34 was produced from a thermocouple plunged into the weld pool. It can be seen that the tandem GMAW process with one welding torch has the same cooling rate as the single GMAW torch. Hence, welding consumable selection for single-tandem welding is the same as that for conventional single-wire GMAW.[16]

The use of two power sources and electrically isolated contact tips provides for control of welding parameters on each wire for tandem GMAW. Tandem GMAW is considered to be at its most stable when pulsed currents are used and the current pulses are synchronized with a set phase shift to minimize any electromagnetic interaction between the arcs. For example, the pulsed waveforms are synchronized such that the peak of one occurs in the background of the other as shown in Figure 36.

For synchronization to be achieved, the pulse frequency on the master and slave electrodes must match. To minimize any electromagnetic interference effects during droplet transfer the background current level should be keep low while still maintaining a stable arc.

Similar to conventional mechanized GMAW, tandem GMAW-P may be used with a single- or dual-torch arrangement. Single tandem involves one torch with two wires and dual tandem involves two torches each with two wires.

The first field implementation of tandem GMAW-P took place on 2 km of X100 in Canada in 2004 and this will be discussed in Section 5.

Commercial torches are generally designed for robotic applications as shown in Figure 37. These are too bulky for pipeline applications and do not allow access into the narrow bevel preparation (3- and 6-degree bevel angle) normally used for mechanized pipeline girth welds.[15]

Figure 38 shows the Cranfield air-cooled design fitted to a CRC-Evans pipeline welding bug. As seen in Figure 39, long narrow contact tips are used to gain access to narrow bevel preparations in thick-section materials. Gas nozzles are available in various lengths which allow access into the bevel and provide good gas coverage.(15)

3.3.5 Dual-Tandem GMAW

In 2001, Cranfield University (Cranfield) developed the concept of dual-tandem GMAW for pipeline and developed the Cranfield Automated Pipe Welding System (CAPS). CAPS involves the use of two tandem welding torches fitted on one pipe welding bug so that four arcs operate simultaneously. The head in this case is fitted on a sensor-based control system which eliminates the need for a skilled operator to monitor the welding.(15)

CAPS involves one welding bug for each side of the pipe carries two tandem welding torches spaced 60 mm apart (see Figure 40). The typical tandem welding speed of 1 m/min can also be used for dual tandem. Cranfield has demonstrated 5G welding at high travel speeds in conjunction with a laser-camera seam-tracking system integrated with the welding bug. A complementary metal oxide semiconductor (CMOS) camera detects break-points in the laser stripe, which helps in seam tracking. Geometrical triangulation can be used to determine the height above the bevel and to control contact tip-to-work distance. Figure 41 shows the bevel geometry used which is the same as that used for mechanized GMAW. Conventional radiography and automated ultrasonic testing can be used for inspection since the completed weld has a profile similar to conventional mechanized pipeline. At the productivity levels obtained in the laboratory, one 14.9-mm pipeline could be welded using an IWM and two welding stations at the same productivity as would be achieved from an IWM and eight welding stations using single-torch mechanized GMAW.(15)

3.3.6 Three Wire "Trinum" Torch

A three-wire approach, dubbed "Trinum" has been considered in terms of potential productivity and deposition rate improvement over tandem GMAW. Workscope to develop a three-wire torch and conduct some evaluation of the potential of such a system is currently underway within a group sponsored project being conducted by EWI, Cranfield University, and the University of Wollongong, Australia. Cranfield has responsibility for the Trinum torch development and at the time of writing, a prototype torch was being built. A drawing of the torch head assembly shows the concept (see Figure 42). The evaluation will consider the potential benefits of the three wire torch as an alternative to two tandem torches for mechanized pipeline girth welding. If successful in terms of future development, two torches, and a total of six power sources would be required for double down welding rather than four tandem torches and eight power sources.

4.0 Design Considerations

4.1 Strain-Based Design

Many pipelines are designed based on the peak loadings being applied by internal pressure. Others are designed with loadings in the axial direction being larger that those from internal pressure. The axial direction loadings are usually applied by mechanisms that are better described as displacement controlled rather than load controlled. That is, the forces drop as the displacement gets closer to the set displacement condition. This can occur for many types of loading such as seismic, slope instability, and freezing and thawing of surrounding soil.

Given a large axial displacement requirement, it is advantageous to design the pipeline and the girth welds to withstand a given level of strain in excess of this requirement. Thus, procedures for strain-based design have been used. These are found in some standards, but not at the level of detail used for the stress-based design for resisting internal pressure.

The design of girth welds for strain-based design pipelines can include considerations of both axial compression strain and axial tension strain. Axial compression strain will cause either global or local buckling. Some amount of buckling can be considered the limit state. This limit comes at lower strains than the failure condition when the wall is breached. The girth weld has been demonstrated to have a limited effect on the buckling limit state, tending to allow buckling at slightly lower strains adjacent to the weld. Since this effect is not strongly dependent upon the material properties of the weld metal, no further consideration of the compressive behavior will be included here.

The axial tension load case, on the other hand, has been demonstrated to depend for its limit state, fracture, on the specifics of the weld metal properties. The resistance to fracture will depend upon the local material properties and imperfections of the material at the location of fracture, as well as the relationship of these to the properties of more remote areas.

It has long been recognized that plastic strain, that is strain in excess of the yield strain, can be concentrated in areas that have lower yield strength. Thus, girth weld metals for pipelines have been recommended to achieve greater yield strength than the adjacent pipe material. This goes beyond the normal requirements that the yield strength of the girth weld metal exceed the standard minimum yield strength for the pipe material grade.

In addition to requirements for strength, there must also be sufficient ductility in the presence of any welding imperfection to prevent fracture from those imperfections at or below the desired limiting strains. Several kinds of measures of toughness can be used to demonstrate the acceptability of the weld metal, alone or in combination with one another.

The use of higher strength pipeline materials, such as X80 and X100 steels, adds several factors of importance to the decision about appropriate girth weld metal for strain-based design pipelines. The greater strength of these materials compared to conventional grades means that the weld metal must also achieve a higher strength to avoid concentrating strain in the weld metal. The greater strain energy in a pipe at the same strain but with higher strength also leads to greater need for toughness to resist fracture, even for imperfections of the same initial size. Also, as welds are made in X80 and X100 steels, the HAZ can soften with respect to the base metal, creating another region which can act to concentrate strain from the remainder of the pipe.

4.2 Longitudinal versus Transverse Weld Strain Capacity

Three simple types of test, a hoop direction tensile test of the pipe, an all weld-metal tensile test, and a transverse tensile test across the weld would be sufficient for nearly all applications of stress-based design of girth welds. This list is insufficient for strain-based design. Two areas need extra attention in particular: the axial tensile properties of the pipe material and the distribution of tensile strains across the girth weld area.

Measurement of the axial stress-strain curve for the base pipe material is particularly valuable for strain-based design since the plastic strain is applied in that direction. Pipe making procedures can easily result in differing tensile properties in the hoop and axial directions. Pipes that are expanded in the last operation to achieve accurate dimensions, for instance, tend to have a lower axial strength than hoop strength. The ultimate strength and yield-to-tensile strength ratios are also usually lower in the axial direction.

Measurement of the distribution of tensile strain in cross-weld tensile tests is well beyond the scope of most such tests, which are completed to demonstrate that the final failure is located in the parent material rather than the weld area or that the overall specimen achieves sufficient tensile strength. Strain-based design can require more information than this about the strains in the weld area. This can be achieved by surface measurements using interferometry. It is also possible to infer the behavior based on mechanical tests that measure the stress-strain properties of local areas of the weld.

4.3 Pipe Tensile Properties

As noted above, the capacity for axial strain will depend upon the axial properties of the pipe material, while the pipe material grade will be dependent upon the hoop direction properties of the pipe. Thus, the distributions of both of these properties must be considered in strain-based design.

The pipe materials for strain-based design pipelines may have additional requirements beyond those for stress-based applications. Three areas have been considered in standards: minimizing variance of material properties, minimizing variance of pipe geometry, and minimizing risk of imperfections.

Minimizing the variance of material properties will prevent high concentrations of strain in the weaker material, such as when a weaker material is across a girth weld from a stronger material. Some standards, such as DNV 2000, use a special category pipe for high strain applications where the variance on yield strength is limited to 100 MPa. Grades X80 and X100 already have a somewhat tighter limitation on the range of yield strength than other lower strength grades, since the chemistry and processing must be more greatly modified to achieve strengths well in excess of the standard minimum yield strength for the grade.

4.4 Defect Tolerance

The methods of demonstrating sufficient defect tolerance for strain are more complicated than those commonly used for girth welds in pipelines where stress-based design can be used. It has been common to use full-scale or nearly full-scale tests to demonstrate defect tolerance, using either a complete pipe with a flaw or a wide-plate specimen with a flaw. Complete pipe testing has been used primarily when there is a more complicated loading situation, such as from the cyclic loading of a reeled pipe.

Smaller-scale tests are also available to gain information on the toughness of the material against cracking mechanisms such as tearing and ductile fracture. Brittle fracture can also participate in failure modes, but the toughness needed to have both reasonable imperfection sizes and large axial strains usually means that brittle behavior occurs only after ductile cracking behavior has initiated.

Toughness levels at the lowest operating temperature are usually specified as sufficient to be the same as to reach plastic collapse in a load controlled estimate. Values such as x and y have been specified.

Once toughness, strengths, and applied strains are defined around a girth weld, the last parameter that must be controlled is the size of the imperfections that can be allowed. Inspection techniques are available to achieve greater accuracy than manual ultrasonic methods that were the basis for earlier design codes.

The choice of allowable imperfection size must include an engineering critical assessment of the fracture process. This can be relatively simple and similar to that for stress-based design for relatively low strains, such as those near 0.5%, but larger strains above 2% need to be assessed with specialized methods. Special methods are needed for the cyclic strains applied by reeling, as well.

Constraint effects on fracture have been recognized as important in defining the strain capacity of cracked pipes. It is important to define the constraint as greater in any toughness tests than in the service condition. The relatively low constraint found in uniaxially-loaded surface-cracked pipes may allow the use of lower-constraint test specimen geometries, such as the single-edge notched tension (SENT) specimen. The biaxial loading applied by internal pressure in combination with axial strain can change the constraint, possibly making SENT specimens inappropriate.

One additional effect that is a focus of current research can also be mentioned. Some specific cases of pipe and weld geometries can concentrate strain in the HAZ. Both the X80 and X100 grades can soften compared to the base metal strength in the HAZ. These softer areas do not usually act to concentrate the strain, since they are supported by the adjacent regions. However, if the HAZ can allow a shear band to extend from the inner surface to the outer surface the support of the adjacent regions is much less. This can occur in thin pipe with a relatively wide HAZ and a bevel close to 45 degrees. Pipes in excess of 14-mm thick should not exhibit this behavior.

4.5 Weld Metal Target Properties

The target weld properties for the specification of welding procedure for X80 and X100 are defined in four areas: tensile properties, Charpy toughness, CTOD toughness, and uniform elongation. The tensile properties are limited to fall into a range of values, while the other parameters should meet minimum required properties.

A standard approach is to require the minimum weld metal yield strength to be at or above the reasonably expected maximum of the axial yield strength of the base metal. This value can be obtained from the pipe grade standard minimum yield strength by adding the difference between the axial and hoop direction yield strength and adding the range of axial yield strength of the pipe. For expanded pipe, the axial direction yield strength is smaller than in the hoop direction, so the difference between axial and hoop is a negative quantity.

The yield strength of the weld metal is commonly also limited on the upper side, to prevent the use of more crack sensitive materials and to help avoid strain concentrations adjacent to the weld metal. One reasonable choice is to limit the variability in tested yield strength to 100 MPa, the same range of strength allowed by some specifications for the base pipe.

The limitations on minimum Charpy toughness are usually defined at the minimum loading temperature, although special considerations may need to be applied when the installation and operation temperatures differ. The value of Charpy energy at this temperature should be sufficient to demonstrate at least upper transition behavior, such as achieving greater than 50 J (36 ft-lb). Most modern weld procedures will not have difficulty meeting this or a slightly higher requirement, except in cases of very low test temperature, such as below -20C.

The limitations on minimum CTOD toughness of the weld metal are also usually defined at the minimum loading temperature, although again special considerations may need to be applied when the installation and operation temperatures differ. The value of CTOD should be sufficient to demonstrate avoidance of unstable brittle fracture and pop-in cracks that advance quickly by a brittle fracture jump. A value of 0.10 mm (0.004 in.) should provide sufficient performance, although other values have been widely used. As for Charpy toughness, most modern welding procedures that included some consideration of toughness will not have difficulty meeting this requirement, except in cases of very low test temperature, such as below -20°C.

Uniform elongation is the strain at the ultimate strength. This parameter has been correlated with the behavior of the base pipe under compression loading. It is one of a set of parameters that have been used to describe the shape of the plastic part of the stress-strain curve, such as the yield-to-tensile ratio. Yield-to-tensile ratio for grades such as X80 and X100 can give difficulties in interpretation for strain-based design, since it can be hard to choose an appropriate ratio for a specific applied strain. The values of yield-to-tensile ratio for these materials are always close to 1.0. Uniform elongation on the other hand, can be correlated directly to the required strain level. A reasonable choice would be to limit uniform elongation to more than the required remote strain plus a safety factor. This safety factor should be roughly 1%, although it may be valuable to consider other values based on the relative strength of the base pipe in the axial direction and the weld metal.

5.0 Review of X80 and X100 Girth Welding

5.1 Types of Pipeline Welding

Developments in steelmaking have resulted in pipeline steels with relatively low carbon contents, even at the higher strength levels, and HAZ cracking need not be a problem. However, with the increasing use of higher strength steels and the requirement for a matching or overmatching combination of strength and toughness from the weld metal, the weld metal itself can be at risk. Use of GMAW with solid wire consumables has an obvious advantage. High labor costs, the ease of mechanization of GMAW, and the repetitive nature of the girth welding process, all lend themselves well to increased interest and use of this process for girth welding.

The use of metal-cored wires offers advantages such as maintaining low hydrogen potential, increasing alloying flexibility and control of microstructure. Because material is added to improve the arc characteristics and wetting of joint, the process tolerance is improved. The oxygen content in metal-cored wires is higher than in solid wires which improves the wetting of joints but at the same time has the tendency of reducing the weld metal toughness. As a consequence, Ni may be added to counteract the loss of toughness caused by the higher weld metal oxygen levels.[19]

Pipeline welding may be divided into mainline welding, where speed is critical and there is access for backing systems; tie-in and repair welding, where speed may be less important and there is no internal access; and double jointing, where it is possible to roll the pipe and to weld in the flat position.

5.1.1 Mainline Welding

The use of mechanized systems which allow the use of narrow joint preparations is gaining popularity for mainline welding. The advantages of narrow compound bevels include increased productivity since less metal is required to fill the bevel and high deposition rates. Also because of higher weld cooling rates than are normally found in structural welding, the weld metal tensile strength is found to be higher when using a narrow joint.[19]

5.1.2 Repair and Tie-In Welding

For repair or tie-in welds the use of a backing system, internal welders, or onsite re-beveling is rarely possible. For this reason, cellulosic electrodes are widely used for root-pass welding in these cases. For greater ductility and crack resistance it is common to use softer E6010 for the root pass. For fill and cap passes, flux-cored wires, which are suitable for wider bevel angles, are being increasingly specified.[19]

5.1.3 Double Jointing

Double jointing is usually performed at pipe mills or in fabrication yards and as a result, speed is not as for critical as welding offshore or for onshore pipeline construction.[19] For more remote and distant reserves double jointing in the field is being considered.

5.2 X80 Pipeline Welding

The first X80 pipelines were laid in the 1980s. Other major pipelines have been executed by Transco and TransCanada beginning in the late 1990s. The technology and weld metal property requirements for X80 welding have changed since the 1980s. New welding consumables and procedures have been developed with have thus far performed well in the field.[19]

A few kilometers of X80 pipeline were laid in Germany in the 1980s, and following that, around 250 km were laid by Ruhrgas in 1992-1993. Nova Corporation in Canada started laying X80 pipeline using mechanized welding at around the same time.[19]

The Cheyenne Plains Pipeline (discussed below) is the highest strength pipeline, and the first major X80 pipeline, in the U.S. However, the material has already seen some limited use world-wide, including the 250-km Ruhrgas Werne-Shulchtern pipeline in Germany, and over 400 km of pipelines which have been installed in Canada by TransCanada Pipelines.[19]

5.2.1 Cheyenne Plains Pipeline (U.S.)

The Cheyenne Plains Pipeline, which was constructed in the Fall of 2004, is the first X80 cross-country gas pipeline constructed in the U.S. and the longest X80 gas pipeline in the world. The pipeline is 380 miles long commencing at the Colorado Interstate Gas Compressor Station near Cheyenne, Wyoming, and progressing in a southeasterly direction from Wyoming across Colorado and culminating at the Greensburg Compressor Station in Kansas. The main pipeline was constructed from 36-in.-diameter × 0.464-in.-wall X80 pipe. Road bore and river crossings were constructed using 36-in.-diameter × 0.667-in. wall X80 pipe. In addition to the 36-in. line pipe, approximately 5 miles of 30-in.-diameter × 0.386-in.-wall pipe was used to construct laterals near the Greensburg Compressor Station.

The 36-in.-diameter line pipe was procured from the following pipe mills:

- IPSCO: 300 miles of spiral-welded line pipe (0.464- and 0.667-in. wall)
- NAPA: 60 miles of long-seam welded line pipe (0.464- and 0.667-in. wall)

The total weight of pipe provided to the project was ~181,000 tons, with IPSCO's order totaling ~143,000 tons and NAPA's order totaling ~38,000 tons. The IPSCO pipe was produced from plate from the IPSCO Regina, Saskatchewan, and Mobile, Alabama, plate mills. The NAPA pipe was produced from plate supplied by Oregon Steel Mill (OSM).

The 30-in.-diameter line pipe used for the laterals was supplied by NAPA.

5.2.1.1 Mechanized Main Line Welding

The main line was welded in three spreads using CRC-Evans' automatic welding process. Associated Pipe Line supervised northwest spread one, while U.S. Pipeline directed spreads two and three. The root pass was welded internally using mechanized gas metal arc welding short-circuit transfer (GMAW-S) while vertical down GMAW-S was used for the external welding. A narrow-groove joint, specifically designed for mechanized welding, was used to minimize weld volume and the number of weld passes.(5)

The consumables used for the root pass (an internal bead pass) and the hot pass (an external pass) were done using 0.035-in. ER70S-G solid wire and 75/25 Ar/CO_2 gas mixture. The fill and cap passes (one each) were done using 0.040-in. ER70S-6 solid wire, and 85/15 Ar/CO_2 shielding gas mixture.(5)

5.2.1.2 Manual/Semi-Automatic Tie-In Welding

The tie-in procedure used on the Cheyenne Plains Gas Pipeline involved making a downhill root, or bead, pass with a 5/32-in. E6010 electrode running at 135 to 155 A and 22 to 25 V. For the hot pass, 3/16-in. E9010 electrodes were used and E101T-1GMH8 (Lincoln Pipeliner G80M) for fill and cap passes.(5)

Welders made the downhill hot pass, which consumes most of the bead pass, with a 3/16-in. E9010 electrode running at 150 to 185 A and 25 to 30 V. This increased the weld's strength and toughness and eliminated root bead slag inclusions.(6)

The fill and cap passes were made with 0.045-in. E101T1-K2 flux-cored wire and a 75/25 Ar-CO_2 shielding-gas mixture, running at 165 to 175 A (a wire feed speed of 275 to 290 ipm) and 23 to 24 V. The properties of this electrode are compatible with the properties of the base metal, addressing concerns about HAC, YS, and toughness.(6)

5.2.1.3 Weld Inspection

Inspection of the 5G girth welds was performed by Weldsonix in accordance with API 1104.

5.2.2 Canadian X80 Pipeline Projects

5.2.2.1 Empress East Crossover Project

It was decided in fall of 1989 to construct the Empress East Crossover using Grade 550 pipe. The diameter and wall thickness combination which was necessary to accommodate the high operating pressure and flow requirement justified the use of the high grade steel (see Table 4).(7)

Welding Qualification

A 42-in.-diameter, 10.6- and 16.9-mm (0.42- and 0.68-in.) WT pipe was used to qualify the procedures at CRC-Evans, Houston. The welding procedures are shown in Table 5. A bevel geometry designed to minimize the number of fill passes on the heavy wall was used on both thicknesses and is shown in Figure 43.(7)

The results of tensile tests with reinforcement on and reinforcement removed are given in Table 6. All tests fractured outside of the welds, indicating that the weld metal was overmatching.(7)

Hardness traverse taken near the OD and ID of the pipe welds are shown in Figure 44. It can be seen from the traverse that the weld metal matches or overmatches the base material, and while some softening of the HAZ was present, it was less than is typically seen with conventional SMAW.

All procedure qualification welds were qualified by radiographic inspection according to Clause 6.2.9 and destructive testing to Clause 6.2.5 of CSA-Z184. In addition to these requirements, the following tests were conducted:

- CVN tests at -5°C in the weld metal and HAZ.
- Microhardness traverses (Hv 500)
- Metallographic examination.[7]

The various combinations of manual welds qualified are summarized in Table 7. A typical SMAW procedure is given in Table 8.[7]

Production Mainline Welding

Production welding consisted of 98 welds in 10.6-mm WT pipe and 28 welds in 16.9-mm WT pipe. Only one welding station was used for each pass as opposed to the multiple fill and cap stations that would normally be provided.[7]

The most common rejectable defect found at the commencement of production was lack of fusion in the first fill pass. The defects were found primarily at the 3 and 9 o'clock positions of the weld. This discontinuity was detected first by automated ultrasonic testing and was confirmed by metallographic examination and thereafter was also detected with use of radiographic examination. The type of indication and the location indicate that it was related to technique.

Figure 45 shows schematically that good penetration into the hot pass had been achieved and the sidewall had been melted. However, slag had been allowed to run between the molten pool and the sidewall and the weld failed to fuse.[7]

Because of design of the torch wherein the gas cup surrounds the contact tube and because the limited contact tube-to-work distance required by the GMAW-P process, the welder has limited visibility of the weld pool from behind. In order to produce a weld in the 5G position, the welder must change his position from standing to lying down when going from the top to the bottom of the weld. This, combined with intense brightness of the pulsed arc, further exacerbates the visibility problem. The visibility improved as additional passes were produced and as a result it was noted that the majority of the defects occurred in the first and second fill passes.

In order to overcome the problems a revised welding procedure with a small change in the bevel angle was qualified to improve the visibility and succeeded in reducing the incidence of the defect, although it but did not eliminate it. The repair rate on the final day of mainline welding was 14%.[7]

Manual and Tie-In Repair Welding

Because of extra care taken during the fit up of joints the time taken to complete tie-ins was only slightly greater than for conventional tie-in welds of same size. Twenty-six tie-ins were completed with eight requiring repair.[7]

A total of 70 repairs were completed with 14 rejectable, primarily due to porosity. Repair welds were made using low H downhill electrodes. Some of the repairs were performed internally using a special crawler and the 4.0-mm low H downhill electrode.[7]

5.2.2.2 Eastern Alberta System

The construction of Eastern Alberta System main line consisted of welding 33 km of 1219-mm OD × 2 mm WT pipeline for 33 km in 1994. This was the first North American long-distance, large-diameter pipeline project that used Grade 550 steel.

The mechanized GMAW used consisted of an internal welding machine (IWM), one unit with two tractors (one welding "shack") for the hot pass, four shacks for fill passes, and four shacks for the cap pass. Welding productivity was 110 joints/day with a repair rate of 6%.

The tie-in welds were made with a combination of cellulosic SMAW (AWS A5.5 E8010G) for the root and hot pass, with 100°C preheat, followed by self-shielded FCAW for all remaining passes. Proper optimization was performed by the self-shielded electrode manufacturer in order to achieve a good combination of weld strength and toughness at the -5°C design temperature. The tie-in welds made using the self-shielded FCAW electrode were completed approximately 40% faster compared to welds made using cellulosic electrodes throughout.

The repair welds were made using LHVD SMAW with AWS A5.5 E10018G electrodes.[8]

5.2.2.3 Central Main Line Loop

NGT's Central Alberta System consisted of the construction of a 91-km length of pipeline (1219-mm OD; 12- and 16-mm WT) in 1997. Welding procedures similar to those used in the Eastern Alberta System were used with additional fill passes. The spread of mechanized welding equipment involved an additional fill-pass shack; 130 joints/day were achieved at a repair rate of 7%.[8]

5.2.2.4 Eastern Main Line Loop

The Eastern Alberta System main line loop consisted of welding a 127-km pipeline (1219-mm OD; 12- and 16-mm WT) in 1997 using all external mechanized welding.

One welding shack would complete the root pass, and three additional shacks would each complete the remaining hot, fill, and cap passes of the weld. Seventy welds/day were achieved during production with a repair rate of 5%. LHVD SMAW with cellulosic root and hot passes were used for tie-ins and repairs.[8]

5.2.3 Cambridge to Matching Green Pipeline Project (U.K)

Mechanized welding has been gaining popularity in the U.K. since the turn of the century. The first production pipeline welds made using metal-cored wire were produced in 2000. Mechanized GMAW using 0.8% Ni metal-cored wire was used for the mainline welding. [19]

Because of limited access and the impracticality of re-beveling for tie-in and repair welds, the most commonly used bevel angle is a 60-degree included angle. The welds are typically made using cellulosic electrodes for the root and hot pass with either basic electrodes used down hill or rutile flux-cored wire used uphill for the fill and cap pass.[27]

The Cambridge to Matching Green project is a 48-in.-diameter (1220-mm) high-pressure cross-country gas pipeline, which was constructed for gas pipeline operator Transco in 2002. Murphy Pipeline teamed with CRC-Evans Automatic Welding in order to weld the X80 material for this project.[9]

The mainline procedure for the 14.27-mm-thick pipe (API X80) consisted of downhill GMAW. The internal welding machine had three welding heads each welding at a speed of 12 mm/s, for an effective welding speed of 36 mm/s. Fill passes were deposited at a speed of 7.6 mm/s and cap passes were at 6.3 mm/s.

The mainline welding crew consisted of six stations, including a root-pass station, hot-pass station, three fill-pass stations, and one cap-pass station (see Figure 48).

The root, hot, and first fill passes were welded with manual SMAW, and the weld was completed with mechanized FCAW deposited using CRC-Evans M300 EWM (see Figure 49). [(9)]

5.3 X100 Pipeline Welding

The use of high-strength steel has a number of benefits, including the use of higher allowable operating pressures, and lower material and installation costs. Production of X100 pipes has been limited until fairly recently, and as a result, only limited information is available with regard to welding the material.[(22)]

5.3.1 Welding Procedure Development for X100 Line Pipe Steels

Table 9 provides mechanical properties of single- and dual-tandem welds using the 1.0Ni-0.3Mo welding consumable. Note that dual-tandem welds have lower YS and do not achieve the overmatching criterion. This can be attributed to the difference in cooling rates presented in Figures 34 and 35.[(16)]

The cooling rate (in Figure 34) was monitored by a thermocouple, which was plunged into the weld pool of the second welding torch. An additional thermocouple embedded in a drilled hole under the welding pass produced the traces shown in Figure 35. It was found that due to the tempering of the first weld deposit by the heat cycle of the second weld deposit (for dual-torch GMAW), it is difficult to qualify overmatching weld procedures for X100.[(16)]

A 2.0Ni-0.5Mo-0.3Cr welding consumable was initially chosen for dual-tandem welding of X100. However, this significantly overmatched the pipe material and was considered to be too strong. To overcome this problem, the two welding consumables were used in combination with one as the first wire and one as the second wire in each tandem torch. Since the arcs are in the same weld pool the wires are mixed during welding. The weld procedure parameters for DJ-DT-N012 are shown in Tables 10 through 12. Mechanical test results are shown in Tables 13 through 17. The Charpy impact transition curves for the root area are shown in Figures 46 and 47. While the YS is lower than the single-tandem weld procedure the overmatching criterion has now been achieved with a YS of 838 MPa.[(16)]

Previous research on the X100 welding procedure with single-wire GMAW found that a 1.0Ni-0.3Mo welding consumable provided an overmatching YS as well as excellent toughness properties. The same consumable was, therefore, selected for single-tandem welding. A 1.0-mm wire was used with Cranfield's pulsed waveform and an 82.5Ar-12.5CO_2-5He shielding gas. The other weld procedure parameters for ML-ST-S006 are shown in Tables 10, 11, and 18. Mechanical test results are shown in Tables 13 through 17. From these tables it can be seen that the fill pass travel speeds are at least twice those normally used for mechanized GMAW while the overmatching YS criterion has been easily attained while excellent toughness is retained. The Charpy impact transition curves for the root area are shown in Figures 46 and 47.[16]

5.3.2 Cranfield University X100 Study

This study reports the results of girth welding trials conducted in X100 pipe at Cranfield University and discusses their implications for use in the field.

5.3.2.1 Mainline Welding

CRC-Evans pipe facing machines were used to generate the bevel geometry on both the 30- and 36-in.-diameter pipes (see Figure 48). The 36-in.-diameter pipes were beveled to accommodate the use of a six head CRC IWM with ER70S-6 wire and the 30-in.-diameter pipes were beveled to accommodate a Cu backing ring for the all-external welds.[22]

Previous welding and testing performed at Cranfield indicated that pulsed-arc metal transfer coupled with an 82.5Ar-12.5CO_2-5He shielding gas provided enhanced mechanical properties over dip transfer with Ar/CO_2- and CO_2-based shielding gases. Thus, 82.5Ar-12.5CO_2-5He shielding gas was during the study [22]

A yield strength range from 810-860 MPa (120 MPa over specified minimum yield strength) was considered optimal. The initial consumable chemistry selected contained 2.3Ni-0.5Mo-0.3Cr. To develop a suitable pulsed synergic curve for a given wire/gas combination a Lincoln Powerwave® 455 with the Wavedesigner® software were used. The bevel gap was reduced to enable the weld metal to hold up when competing against gravity.[22]

Using the guidelines in EN 1011 for the prevention of HAC, preheat temperatures ranging from 50 to 80°C were specified. However, as an added assurance for the prevention of HAC, the initial trials were conducted using a 100°C preheat and interpass temperature.[22]

The combination of low heat input and the 2.3Ni-0.5Mo-0.3Cr wire generated a good combination of strength and toughness.

The weld metal tensile testing was carried out on a rectangular-shaped specimen that includes all layers of the weld in the testing; this is in contrast a to round bar specimen that is taken from a localized position within the joint.(22)

Additional trials were conducted using various wire chemistries, heat input, and preheat conditions to obtain the desired 810- to 860-MPa YS Figures 49 and 50 show typical all external and internal/external weld macro sections from the pipes.(22)

5.3.2.2 Repair Welding

Internal root repairs were conducted using GMAW and SMAW while the external repairs were conducted using FCAW and SMAW. A preheating temperature of 100°C was applied in both cases and a 78Ar-20CO_2/2O_2 shielding gas was used for both GMAW and FCAW. GMAW was performed using the same electrode as was used in the follow-up welding (i.e., 0.5Ni-0.5Cr-0.5Mo). A 2.0Ni-0.4Mo alloyed basic electrode (AWS A5.5 E11018-M) was used for SMAW electrode and a 2.7Ni-0.3Mo (AWS A5.29 E111T1-G) rutile flux-cored wire was used for FCAW.

The internal repairs involved back grinding, and in many cases, overhead welding. The overhead position is the location which tends to be most susceptible to LOF defects due to the positioning of the IWM.

Partial-penetration (3 o'clock) and full-penetration (6 to 4'o clock) welds were also completed after arc air gouging/grinding (see Figure 51 for typical repair macros). The mechanical testing on repair welds (partial- and full-penetration repair welds) consisted of hardness surveys, impact toughness tests carried out at -20°C and side bends. There was cross weld tensiles and nick break conducted on full-penetration repair welds.(22)

5.3.2.3 Tie-In-Welding

A manual tie-in procedure was performed on 36-in.-diameter pipe using SMAW for the root and hot passes and FCAW for the fill and cap passes. The pipe was prepared with a 30-degree bevel and a 2-mm root gap with a 2-mm land. The welding was performed using a vertical-up progression. The preheat temperature used on the procedure was 100°C with an interpass temperature of 120°C maximum. The heat input was maintained at ~1.4 kJ/mm in order to achieve the highest possible strength with the FCAW consumable. For the SMAW, basiccoated LHVU electrodes were chosen over LHVD electrodes for their greater flexibility with respect to poor fitup.[22]

Tables 19 through 21 summarize the tensile, hardness and CTOD properties attained in the mechanized girth welds, tie-in and repair welds. Figures 52 and 53 show impact toughness levels for both the weld metal and fusion line with respect to temperature.[22]

For cross weld tensile testing only 4 tests out of 21 performed failed. It should be noted that the pipe used for parent material tensile property testing was not used during the welding trials. It was also noted that some of the side-bend and nick-break specimens contained gas pores.[22]

The above study indicates that there are no major obstacles in welding X100 steels, although some minor changes are required in the selection of welding consumables and welding parameters. In order to guarantee the 810- to 860-MPa desired YS range, optimization is required for the PGMAW welding consumable chemistry.[22]

5.3.3 Snam Rete Gas X100 Weldability Study

A study performed at Snam Rete Gas (SRG) on X100 weldability focused on the following points:

- Define the minimum welding requirements with reference to pre-heating temperature, in order to avoid cold-cracking problems; this part of the activity was carried out by means of laboratory tests, specifically the Implant and Tekken tests.

- Execution of test girth welds both with manual (SMAW) and mechanized (GMAW) methods in order to collect as much information as possible about every technical problem arising from full-scale welding of high-grade steel.[23]

5.3.3.1 Laboratory Tests: Implant and TEKKEN (SUHAS)

The occurrence of cold cracking is due to three primary factors: a susceptible microstructure, the presence of hydrogen, and tensile stress. The results are influenced by the C equivalent of the steel, the preheating temperature, and the welding heat input.[23]

Using the least favorable heat input condition (high speed, vertical-down welding) the effect of preheating on cold-crack formation for X100 grade steel pipe has been investigated by means of laboratory tests performed at SRG facilities (Implant and Tekken). An analysis of the Implant test results (see Table 22) seems to indicate that the preheating temperatures are overly conservative, if the carbon-equivalent value (CE IIW = 0.48) is also considered.(23)

In fact, the Implant sample did not represent a real joint because the stress state in the girth weld is mainly due to residual stresses, while in an Implant sample it is caused by an external load. Since Implant tests are more severe than the root pass of a girth weld, the results of the tests were checked using the Tekken test, a method more fit for the purpose, even though it does not allow the derivation of a numerical relationship between the applied load and $t_{8\text{-}5}$. Table 22 shows the preheating temperatures obtained from both the Implant and Tekken tests.(23)

5.3.3.2 Field Weldability on X100 Pipes (DN 56 in. × 19 mm and DN 36 in. × 16 mm)

Based on the results of the previous X100 testing, weldability has been verified by means of full-scale tests. Girth welds have been produced with SMAW and GMAW following the WPS based on laboratory activity. The details of welding conducted in six welding tests are provided in Tables 23 and 24.(23)

The radiographic inspection showed some degree of porosity on all SMA welds, while the GMA welds were found to be sound. The results of mechanical testing are as shown in Tables 25 and 26.(23)

The investigation showed the well-known correlation between strength properties and toughness properties of the weld metals. This is especially indicated with respect to the CTOD values of weld metals. CTOD values measured in the weld were generally not very high (from 0.03 to 0.15 mm) for the 56-in. welds as compared to the 36-in. weld.(23)

For the welds produced using GMAW the results obtained with all of the electrodes (also at -20°C) are very good, although it must be noted that the CTOD values obtained using GMAW are considerably lower than those obtained with the same technique but on lower strength materials (X60, X65).(23)

Based on the results obtained, preheating temperatures, heat input, interpass times, materials, and procedures used proved to be satisfactory, even though the number of tests executed cannot be considered sufficient for the full-scale welding qualification of X100 steel and the skill of the welders must be taken in consideration.(23)

5.3.4 Peerless/Godin Lake Project (Canada)

In March 2004 new pipeline facilities were commissioned in the Peerless/Godin Lake areas. These pipelines were installed and welded by TCPL using 17.7 kilometers of X70 pipe, with a 3.6 kilometer loop made from NPS 36. Additionally, X100 and X120 high strength line pipe were evaluated as part of the project, and employed mechanized welding. These pipeline facilities provide additional gas service to the oil sands region in Canada. For the Godin Lake pipeline loop, two kilometers of 36-in diameter X100 line pipe were evaluated from a winter construction perspective. A 1.6-kilometer length of 36-in diameter X120 line pipe was also assessed as an emerging technology. The productivity capabilities of advanced mechanized welding were also assessed.

6.0 Welding Consumables

While a variety of welding processes can be utilized for pipeline girth welding, repairs and tie-ins, SMAW remains the most widely used. Solid wire (GMAW) and metal and flux-cored arc welding are gaining increasing popularity, especially with the increased drive toward mechanization. In many cases, a combination of processes may be specified, for example, SMAW or GMAW for the root and hot pass, and FCAW for the fill passes.

6.1 Shielded Metal Arc Welding

As mentioned previously, there are essentially two types of SMAW electrodes: cellulosic and low hydrogen. The cellulosic electrodes, primarily of the EX010 type, have been used extensively for pipe welding, especially for root-pass welding. Electrode manufacturers have responded to the need for higher strength consumables with the introduction of E7010, E8010 and even E9010-type stick electrodes. The E9010 electrodes are designed for welding X80 grade pipe. There are currently no cellulosic electrodes available for welding higher grade pipe, so the options for root-pass welding in X100 are either to use undermatching cellulosic electrodes, or to use an alternative process. Because cellulosic electrodes are inherently high in hydrogen, the more prudent choice is to use GMAW for the root pass.

In addition to cellulosic electrodes, many manufacturers now offer low-hydrogen vertical-down welding electrodes, which are specifically designed for fill and cap pass welding of pipes. The low-hydrogen vertical down electrodes are available in grades up to E10018-G, which again can be used for pipe grades up to X80. Additionally, electrodes of the E11018M and E12018M are available and can be used with vertical-up progression. Because many of the higher strength low hydrogen electrodes were developed in accordance with US military specifications, they must adhere to a relatively tight yield strength range, rather than minimum yield and tensile strength requirements. Consequently, a product which is sold as an E12018M2 will achieve a yield strength of between 102 and 123 ksi (704 to 849 MPa). The tensile strength is recorded for information only. As a result, E12018M2 may be an appropriate choice for welding X100 if a matching strength weld metal is desired, however if an overmatched weld metal is desired, its strength level may not be adequate.

While there was a push in the 1970's to develop both SMAW and GMAW consumables for welding HY130 steel for the US military, these efforts have largely been abandoned. Two manufacturers (Airco and McKay) successfully developed and produced E14018 electrodes. However neither of those manufacturers exist today other than as name brands owned by other companies, and the E14018-type electrodes are no longer produced. Several other smaller manufacturers do offer E14018 electrodes, but the quality of these products has not been confirmed.

6.2 Gas Metal Arc Welding

Gas metal arc welding electrodes are readily available in tensile strength levels up to 120 ksi. There is also limited availability of 140S-type solid wires, although they are getting increasingly difficult to obtain due to their high expense and limited demand.

For welding X70 and X80 line pipe, GMAW consumables ranging from ER70S-6 or ER70S-G up to ER100S-1 have typically been specified. In many cases, the lower strength consumables are specified for root and hot pass welding while higher strength consumables are specified for the fill and cap passes. The lower strength/higher ductility in the root pass helps to accommodate the higher stresses associated with that region. Using an ER90S-type consumable for the fill passes will generally provide sufficient strength for X80 pipeline welding.

The ER70S type filler wires rely on silicon and manganese for strengthening. Some products, such as Thyssen's K-Nova (ER70S-6), ESAB's XTi (ER70S-7) and Bohler's SG-Pipe (ER70S-6) utilize small additions of titanium to improve strength and toughness. For higher strength consumables, such as the ER90S and ER100S classifications, additions of nickel and molybdenum help to provide adequate strength. The weld deposits produced with these consumables are typically dominated by acicular ferrite. Grain boundary polygonal ferrite and small amounts of ferrite with aligned second phase (MAC constituent) are also typically present. The percentage of acicular ferrite generally increases with the addition of nickel and molybdenum, while the percentage of grain boundary ferrite is typically less.(29)

For X100 welding, lower-strength welding consumables may again be specified for root pass welding, whereas the balance of the welding may be done with ER100S or even ER120S welding consumables. The chemical compositions of the ER100S and ER120S are similar, with 120S typically having a higher nickel content and the addition of a small amount of chromium. As the strength level increases, the microstructure may rely more heavily on some degree of martensite formation. As the strengthening mechanism changes, so too does the weld's sensitivity to cooling rate. Gianetto, et al, found that an ER120S-1 consumable with a nominal weld deposit chemistry of 0.05C-1.4Mn-2.23Ni-0.5Mo-0.3Cr had lower strengths when used with an arc energy of 1.5 kJ/mm than a much leaner ER100S-1 weld metal deposited with arc energies of approximately 0.8 kJ/mm. This sensitivity to cooling rate also makes it difficult for the higher strength welding consumables to achieve adequate toughness over a range of welding procedures.

6.3 Flux and Metal-Cored Arc Welding

A number of flux and metal-cored wires are now available for welding on higher strength pipe materials, up to X80. The flux-cored consumables include both gas-shielded and self-shielded varieties. Cored wires offer advantages over SMAW and GMAW in terms of deposition rates and ease of use. Potential disadvantages may include higher weld metal diffusible hydrogen (compared with GMAW and low-hydrogen SMAW), increased weld metal oxygen content (depending on type) and higher fume generation rates.

6.3.1 Self-Shielded FCAW

A number of self-shielded flux-cored electrodes have been introduced in recent years which offer a good combination of strength and toughness. The best toughness among self-shielded FCAW electrodes is found in the T8-type slag systems. The addition of various levels of nickel offers improved toughness and helps these electrodes meet fairly stringent CTOD requirements. The majority of the T8-type electrodes fall into the E71T8-XX classification and may not be suitable for welding pipes above X70 grade. However at least one manufacturer offers an electrode of the E91T8-G classifications which is designed specifically for welding of X80 pipe.

6.3.2 Gas-Shielded FCAW

Gas shielded flux-cored arc welding electrodes are available in strength levels up to 110 ksi. For X80 welding, the most widely used flux-cored consumables are those of the E101T1-XX classifications. Electrodes of the E101T1 classification are designed to meet a minimum yield strength of 88 ksi (607 MPa) and a minimum tensile strength of 100 ksi (690 MPa). The T1 designation indicates that the electrodes have an acid-based slag system. The acid-based slag systems are more user friendly than the basic slag systems (the T5 designation) which offer better toughness and crack resistance. Basic FCAW electrodes tend to produce heavy spatter and a convex bead and are generally not useable out of position, making them unsuitable for use on pipe. The somewhat limited toughness associated with acid-based slag systems may make some users reluctant to specify them for critical applications, making their future applicability for welding X100 pipe doubtful.

6.3.3 Metal-Cored Electrodes

Metal-cored electrodes offer the higher deposition rates, improved penetration profile and ease of operation of flux-cored electrodes along with the low spatter and slag-free welding of solid wires. They also have the advantage that alloy adjustments may be made relatively easily and inexpensively to accommodate increases in pipe strength.[30] The major disadvantage associated with metal-cored electrodes is that the metal powder fill is inherently high in oxygen, which translates into somewhat limited toughness properties as compared with solid wires. Typical toughness properties for an E110C electrode are about 30 – 45 ft-lbs at -60°F (41 – 61J at -51°C) as compared with typical toughness values of 2 – 3 times that for ER100S-1 and ER120S-1 electrodes.

Metal-cored electrodes with strength levels up to the E110C classification are commercially available for welding pipe up to X80. These electrodes are generally used with argon with 10 to 25% CO_2 shielding gas and can be used with pulsed spray transfer for better handling out of position. While these products typically produce tensile strengths of around 120 ksi (828 MPa), they may require additional alloying to meet X100 property requirements.

The Vector Pipeline Project, a 344 mile, 42-in.-diameter, 0.417-in. wall X70 pipeline has been constructed through Michigan, Indiana, and Illinois. For the first time, metal-cored wires were approved and used in the construction of this pipeline. An E80C-Ni1 (AWS A5.28 specification) metal-cored wire was used in the vertical-down progression in a semi-automatic pulsed mode using 90Ar-10CO_2 shielding gas to replace the traditional SMAW electrodes used for tie-ins and repairs. Metal-cored wires were not used on any automatic welding systems on the mainline due to a lack of time prior to construction necessary for developing the proper operating parameters with the different systems and the lack of pulsing capabilities with one of the systems.[30]

6.4 Experimental Metal-Cored Electrodes

An extensive program was undertaken at Cranfield University several years ago to evaluate the consumables that are currently available for welding X100 and to use experimental metal-cored electrodes to gain a better understanding of the effects of chemistry variations on weld metal microstructure and properties. A solid wire composition of nominally 0.9% Ni/0.3% Mo was chosen as the baseline. A "control" metal-cored electrode was produced which yielded approximately the same weld metal composition, and variations in carbon, nickel, molybdenum, and chromium were investigated. The deposit compositions for the metal-cored electrodes are shown in Table 27.

A comparison of the mechanical properties of the weld produced using the metal-cored wire with that of the solid-wire chemical equivalent indicated a decrease of approximately 40 MPa in yield strength (0.2% offset) values for welds made with the metal-cored wire (see Table 28).[31] A comparison of microstructures (see Figure 54), revealed a somewhat more bainitic micro structure in the solid wire weld metal as compared to the metal-cored weld metal. This difference can only be seen at high magnification (500×); at lower magnification the microstructures appear very similar (see Figure 55).[17]

The global cooling curves that were obtained using the two wires are similar for each layer deposited, but closer examination of the cooling rates (Figure 56) and transition temperatures (Figure 57) helps to explain the microstructural changes and the differences in strength which were observed. The solid wire exhibited both higher cooling rates (at 800 and 600°C) and lower transformation temperatures than the metal-cored wire, which is consistent with the formation of a more "bainitic" microstructure from the solid wire.[17]

All-weld metal tensile, hardness and impact toughness measurements for the alloy variant plate trials are shown in Tables 28 and 29.[17]

The variations of strength and toughness as a function of alloy level are summarized in Figures 58 and 59. It was observed that the strength increases as alloy addition increases except in the case of Mo variants.

The lower Mo wire actually had a somewhat higher strength level than was observed for the mid-range wire. It is unclear, however, whether this was simply a case of normal scatter, since the amount of variation was low.

It was difficult to determine the effect of individual alloying additions on impact toughness levels (Figure 59) because of the level of scatter associated with CVN testing, and because of the relatively small changes in the individual elements changes.[17] An increase in the Cr level did show an actual decrease in toughness. The addition of Ni increased toughness up to about 1.3 wt% Ni, above which increases in the Ni level showed a significant drop in toughness levels.[17]

Figure 60 shows the effect of each alloy as a function of its weight percent on strength and toughness. It shows with increasing Cr levels the strength increases with a commensurate drop in impact toughness levels, while Ni shows similar behavior but to a lesser extent. With an increase in C content it shows the strength increases with no apparent change in impact toughness levels. Note that this figure is only relevant to the metal-cored study referred here.[17]

Finally the effect of changes in chemistry on weld metal microstructure can be seen in Figures 61 through 66. Increases in C, Ni and Cr levels resulted in reductions in grain size which explains the increase in strength levels. A reduction in primary (grain boundary) ferrite with increasing Ni was also apparent (see Figure 61). An increase in the Mo level (see Figure 62) showed only a slight change in microstructure and overall grain size. The 0.5 wt% Cr addition produced a fine grain size (see Figure 63) which, coupled with the high aspect ratio constituents (martensite/bainite), explains the high strength/hardness levels and low impact toughness as compared with all other variants. Raising the C levels exhibited the smallest relative increase in high aspect ratio constituents, although the overall grain size decreased (see Figure 64). The high-C, low-Mo alloy exhibited a slightly smaller grain size but without an increase in high aspect ratio constituents (see Figure 65). The low-C, low-Si, low-Mo, high-Ni alloy exhibited the greatest change in microstructural appearance of all the alloys investigated (see Figure 66).[17]

6.5 Shielding Gas

The primary function of the shielding gas is to exclude the atmosphere from contact with the molten weld metal. This is necessary because most metals, when heated to their melting point in air, exhibit a strong tendency to form oxides and nitrides. Oxygen will also react with C in molten steel to form CO and CO_2. The various reaction products may result in weld deficiencies, such as trapped slag, porosity, and weld metal embrittlement. Nitrogen will also cause porosity due to over-saturation if it is present in amounts exceeding about 300 ppm. It has a severe embrittling effect if it is present in the form of iron nitride. Reaction products of oxygen and nitrogen are easily formed in the atmosphere unless precautions are taken to exclude them.

In addition to providing a protective environment, the shielding gas and flow rate also have a pronounced effect on the following:

- Arc characteristics
- Mode of metal transfer
- Penetration and weld bead profile
- Speed of welding
- Undercutting tendency
- Cleaning action
- Weld metal mechanical properties.(12)

Shielding gases can be divided into two primary types: inert gas shielding (such as argon and helium) and active gas shielding (such as inert gas mixtures containing oxygen and/or CO_2 and 100% CO_2). Inert gas shielding is used primarily for gas tungsten arc welding and gas metal arc welding of reactive metals, such as aluminum and magnesium. Helium has a higher thermal conductivity than argon, and produces a rounder, deeper weld bead. An arc shielded by argon produces a bead profile characterized by a "finger"-type penetration.

The majority of GMA welding of steels is done using argon with small additions of oxygen and/or CO_2 or with straight CO_2. Pure Ar shielding on ferrous alloys causes an erratic arc and a tendency for undercutting to occur. Additions to Ar of from 1 to 5% oxygen or from 3 to 25% CO_2 produce a noticeable improvement in arc stability and freedom from undercutting by eliminating the arc wander caused by cathode sputtering.(12)

The optimum amount of O or CO_2 to be added to the inert gas is a function of the work surface condition (presence of mill scale or oxides), the joint geometry, the welding position or technique, and the base metal composition. Generally, 2% oxygen or 8 to 10% CO_2 is considered a good compromise to cover a broad range of these variables.(12)

CO_2 additions to Ar may also enhance the weld bead appearance by producing a more readily defined "pear-shaped" profile. Adding between 1 and 9% oxygen to the shielding gas improves the fluidity of the weld pool, penetration, and the arc stability. Oxygen also lowers the transition current. The tendency to undercut is reduced, but greater oxidation of the weld metal occurs, with a noticeable loss of Si and Mn.(12)

Additions of CO_2 up to 25% raise the minimum transition current, increase spatter loss, deepen penetration, and decrease arc stability. Ar-CO_2 mixtures are primarily used in short-circuiting transfer applications, but are also usable in spray transfer and pulse arc welding.(12)

There are a number of specialty gas mixtures available which involve various combinations of argon, helium, CO2 and oxygen. These gas mixtures may offer specific benefits for specific situations (e.g., improved arc characteristics, improved penetration or increased deposition rates).(12)

CO_2 is a reactive gas widely used in its pure form for GMAW of carbon and low-alloy steels. Higher welding speed, greater joint penetration, and lower cost are general characteristics which have encouraged extensive use of CO_2 shielding gas. With a CO_2 shielding, the metal transfer mode is either short circuiting or globular. Axial spray transfer requires an Ar shielding and cannot be achieved with straight CO_2 shielding. With globular transfer, the arc is quite harsh and produces a high level of spatter. This requires that CO_2 welding conditions be set to provide a very short "buried arc" in order to minimize the spatter. In an overall comparison to the Ar-rich shielded arc, the CO_2 shielded arc produces a weld bead of excellent penetration with a rougher surface profile and much less "washing" action at the sides of the weld bead, due to the buried arc. Very sound weld deposits are achieved, but mechanical properties may be adversely affected due t the oxidizing nature of the arc.(12)

The standard CRC-Evans welding system uses the GMAW process with 100% CO_2 as shielding gas. This has been the standard for welding X60, X65, X70 pipe steels during recent years. The pulsed GMAW process, however, requires the use of principally inert gas shielding. Use of inert gas rather than CO_2 greatly increases the notch and fracture toughness of the weld metal in addition to reducing weld spatter, provides a more stabilized arc, and virtually eliminates lack of sidewall fusion defects. In an evaluation performed during weld procedure development at CRC-Evans, Houston for the pulsed GMAW process it was found that a mix of 82.5% Ar, 12.5 vol.% CO_2, 5 vol.% He offered good resistance to arc wander and deflection in the very narrow joint design which helped to minimize lack-of-fusion defects.(13) The He addition to the tri-mix gas effectively reduces the arc length for a given arc voltage. Additionally, He has a higher thermal conductivity so that more heat is produced at any given current than with Ar or CO_2, thus increasing penetration. Consequently, the tri-mix has been adopted as the standard shielding gas for the pulsed GMAW welding.(13)

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Table 1. Specified Properties of Riser Pipes with X80 and X100 Grade

Property	X80	X100 (in discussion)
YS, MPa	≥552	≥690
TS, MPa	621-827	≥760
Y/T	≤0.93	Not yet defined
A2", %	≥20.5	Not yet defined
CVN, Test Temp., °C	Depending on project	Not yet defined
CVN, Energy, J	≥68 (API 5L)	Not yet defined
Hardness, HV 10	≤280 (Customer)	Not yet defined

Table 2. Specified Tests of API 5L and Project Specifications (PWHT: <600°C/1 hr)

API 5L	Tensile and impact test, transverse, delivery condition
Project Specification	Tensile (transverse and longitudinal), impact (transverse) and hardness tests, delivery condition, and delivery condition plus PWHT

Table 3. Comparison of SMAW vs. FCAW-S Process, Welding Costs

Item	SMAW	FCAW-S
Cost of Filler Metal	%6.65/kg (4.8 mm)	$12.35 (2.0 mm)
Deposition Efficiency	50%	83%
Operating Factor	25%	40%
Amount of Consumable Needed per Joint (electrode cost/efficiency) × 5.76	$76.60	$85.69
Labor and Overhead (estimate)	$47.50	$47.50
Amperage	170	250
Travel Speed	30.5 cm/min	43.2 cm/min
No of Passes	7	6
Arc Time per Joint	294 min	111 min
Cost per Joint: Labor	$186.00	$70.22
Electrode Cost	$76.60	$85.69
Total	$262.60	$155.91

Table 4. Empress East Crossover – Design Details

Design Pressure	8700 kPa
Diameter	NPS 42
Design Factor	0.8 for line pipe
	0.5 for plant pipe
Length	2.0 km of line pipe
	0.5 km of plant pipe
Wall Thickness (Gr 550)	10.6 mm for line pipe
	16.9 mm for plant pipe

Table 5. GMAW-P Procedure

Consumables	Root	0.9-mm-diameter Thyssen K-Nova
	Hot, Fill, and Cap	1.0-mm-diameter Thyssen K-Nova
Shielding Gas (%):	Root	$75Ar-25CO_2$
	Hot/Fills	$82.5Ar-12.5CO_2-5He$
	Cap	$87.5Ar-12.5CO_2$
Welding Direction	5G/Down	
Number of Welders	Internal: 6 Welding Heads	
	External: 2 Welding Heads	

Electrical Parameters for 10.6 mm WT:					
	Root (Internal) (Short Arc)	**Hot (Pulsed)**	**Fill 1 (Pulsed)**	**Fill 2 (Pulsed)**	**Cap (Pulsed)**
Arc Speed (mm/min)	720-800	970-1070	360-400	300-460	300-460
Wire Speed (mm/min)	9650	11430	7880	7880	7880
Gas Flow (cmh)	1.7-2.1	1.1	1.1	1.1	1.4
CTWD (mm)	9.0	12.5	12.5	12.5	12.5
Voltage (V)	19.-20	22-25	21-24	21-24	23-26
Amperage (A)	190-210	220-260	150-180	150-180	140-180
Electrical Parameters for 16.9 mm WT:					
	Root (Internal) (Short Arc)	**Hot (Pulsed)**	**Fill 1 + 2 (Pulsed)**	**Fill 3 (Pulsed)**	**Cap (Pulsed)**
Arc Speed (mm/min)	720-800	970-1070	360-400	300-460	300-460
Wire Speed (mm/min)	9650	11430	10920	10920	7880
Gas Flow (cmh)	1.7-2.1	1.1	1.1	1.1	1.4
CTWD (mm)	9.0	12.5	12.5	12.5	12.5
Voltage (V)	19.20-	22-25	22-25	22-25	23-26
Amperage (A)	190-210	220-260	190-220	190-220	140-180

Pulse Parameters	
Peak Width (ms)	2.75
Peak Current (A)	4.30
Background Current (A)	45

Table 6. Tensile Test Results for Pulsed GMAW

Type of Tensile Test	Sample	Yield Strength (MPa)	Ultimate Strength (MPa)
Reinforcement on	1	594	708
	2	621	723
	3	615	702
	4	598	707
Reinforcement removed	1	619	699
	2	572	698

Table 7. Material Combinations Qualified for SMAW

Tie-in on 10.6 mm WT × Gr. 550
Tie-in on 16.9 mm WT × Gr. 550
Tie-in on 16.9 mm WT × Gr. 550 to 17.5 mm × Gr. 483
Repair on 10.6 mm WT × Gr. 550 PGMA mainline welds
Repair on 16.8 mm WT × Gr. 550 PGMA mainline welds
Repair on 16.9 mm WT × Gr. 550 SMA tie-in welds

Table 8. SMAW Procedure for Tie-Ins

Weld Pass	Electrode Size (mm)	Electrode Class	Welding Direction	Amperage Range	Voltage Range	Travel Speed Range (mm/min)
Root	4.0	E48010-G	Down	110-160	21-30	200-365
Second	4.0	E48010-G	Down	120-180	24-36	250-450
Fill(s)	4.5	E62018-G	Down	170-270	24-34	215-550
Cap	4.0	E62018-G	Down	180-260	22-34	170-430
Alternate Fill & Cap	4.0	E62018-G	Down	130-200	22-30	175-450

Table 9. Comparison of All Weld Tensile Data for Single and Dual-Tandem GMAW

WHAT DO THE NUMBERS REPRESENT?????

Weld Type	?? ??	??	??	??
Single Torch Narrow Gap - internal/external 1.0%Ni/0.3%Mo	841 88	8	0.95	20.5
CAPS Dual Tandem Narrow Gap - internal/external 1.0%Ni/0.3%Mo	753 81	0	0.93	23

THIS IS SAME TABLE AS TABLE 6 ABOVE↓

Table 2: Summary of Girth Welding Procedures

Weld Procedure	Description	X100 Pipe OD x WT	Root Welding Consumable	Fill Welding Consumable	Fill Consumable Type
DJ-DT-N012	Dual-Tandem Double-Joint	52 in. x 22.9 mm	Bohler Thyssen K Nova	Oerlikon Nimo-1 Bohler Thyssen Union X85	1.0%Ni/0.3%Mo 2.0%Ni/0.5%Mo/0.3%Cr
ML-DT-N013	Dual Tandem	52 in. x 22.9 mm	Bohler Thyssen K Nova	Oerlikon Nimo-1 Bohler Thyssen Union X85	1.0%Ni/0.3%Mo 2.0%Ni/0.5%Mo/0.3%Cr
ML-ST-S006	Single Tandem	36 in. x 19.05 mm	Bohler Thyssen K Nova	Oerlikon Nimo-1	1.0%Ni/0.3%Mo

Table 10. Summary of Girth Welding Procedures

Weld Procedure	Description	X100 Pipe OD x WT	Root Welding Consumable	Fill Welding Consumable	Fill Consumable Type
DJ-DT-N012	Dual-Tandem Double-Joint	52 in. × 22.9 mm	Bohler Thyssen K Nova	Oerlikon Nimo-1 Bohler Thyssen Union X85	1.0%Ni/0.3%Mo 2.0%Ni/0.5%Mo/0.3%Cr
ML-DT-N013	Dual Tandem	52 in. × 22.9 mm	Bohler Thyssen K Nova	Oerlikon Nimo-1 Bohler Thyssen Union X85	1.0%Ni/0.3%Mo 2.0%Ni/0.5%Mo/0.3%Cr
ML-ST-S006	Single Tandem	36 in. × 19.05 mm	Bohler Thyssen K Nova	Oerlikon Nimo-1	1.0%Ni/0.3%Mo

Table 11. Bevel Parameters for Each Welding Procedure

DJ-DT-N012	A=1.0 mm	B=1.0 mm	C=4.0-5.0 mm	D=3.0 mm	E=37.5°	F=45°	G=5°
ML-DT-N013	A=1.5 mm	B=1.0 mm	C=4.0-5.0 mm	D=2.3 mm	E=37.5°	F=45°	G=5°
ML-ST-S006	A=1.0 mm	B=1.0 mm	C=4.0-5.0 mm	D=2.5 mm	E=37.5°	F=45°	G=5°

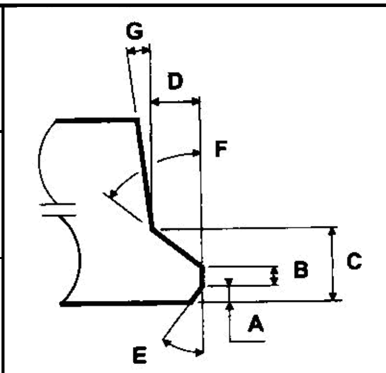


Table 12. Welding Parameters for Welding Procedure DJ-DT-N012

Pass	Lead Torch WFS (m/min)	Lead Torch Amps I (Average)	Lead Torch Volts V (Average)	Trail Torch WFS (m/min)	Trail Torch Amps I (Average)	Trail Torch Volts V (Average)	Osc. Freq Beats per min.	CTWD (mm)	Travel Speed (mm/min)	Arc Energy (kJ/mm)
Int. root	9.60	187	20.5	--	--	--	--	10.0-11.0	710	0.32
Run 1	15.20	236/246	25/24.5	11.50	201/190.5	21/22	450	14/17.5	1422	0.5/0.36
Run 2	15.20	235/244	26/26	12.00	195/190	25/25	450	14-17.5	1422	0.53/0.40
Run 3	16.00	244/248	26/26	12.00	196/193	24/24	450	14/17.0-17.5	1422	0.54/0.39
Run 4	16.00	241/247	26/27	12.00	195/192	24/24	450	14/17.0-17.5	1422	0.54/0.39
Cap	16.00	244/246	25/27	12.00	194/192	24/24	450	14/16	1295	0.59/0.42

Table 13. All Weld Metal Strip Tensile Test Results

Weld No.	$R_{p0.2}$ (MPa)	R_m (MPa)	Yield/Tensile Ratio	A (%) [z(%)]
DJ-DT-N012 Double Joint	766 94	4.8	0.81	19
ML-DT-N013 Dual Tandem	838 96	5	0.87	25.5
ML-ST-S006 Single Tandem	909.6 93	4	0.97	19.5

Table 14. Hardness Test Results

Weld No.	Hv Survey Location	Hardness Surveys (2-mm sub root)						Hardness Surveys (2-mm sub cap)					
		Weld Metal Avg. HV10	Weld Metal Max HV10	HAZ Avg. HV10	HAZ Max HV10	Base Material Avg. HV10	Base Material Max HV10	Weld Metal Avg. HV10	Weld Metal Max HV10	HAZ Avg. HV10	HAZ Max HV10	Base Material Avg. HV10	Base Material Max HV10
DJ-DT-N012	3 o'clock	304	306	276	297	270	274	329	333	277	302	267	276
	Seam	298	302	358	373	304	317	315	317	343.5	357	270.5	279
ML-DT-N013	3 o'clock	241	243	268	294	277	281	335	342	293	327	272	281
	Seam	309	339	333	373	315	322	344	351	353	370	262	274
ML-ST-S006	3 o'clock	235	240	269.5	292	275	279	311	322	286	319	269	274
	Seam	257	264	302.5	345	278	285	335	342	342	370	281	287

Table 15. Cross-Weld Tensile Test Results

Weld No.	Cv -20°C (J) Weld Metal Root	Cv -20°C (J) Fusion Line Root	Cv -40°C (J) Weld Metal Root	Cv -40°C (J) Fusion Line Root	Cv -60°C (J) Weld Metal Root	Cv -60°C (J) Fusion Line Root	Cv -80°C (J) Weld Metal Root	Cv -80°C (J) Fusion Line Root
DJ-DT-N012	204 214 210 Avg. 209	258 260 256 Avg. 258	220 194 196 Avg. 203	256 250 252 Avg. 253	134 198 190 Avg. 174	48 56 50 Avg. 51	96 84 52 Avg. 77	56 18 38 Avg. 37
ML-DT-N013	258 260 248 Avg. 255	230 228 228 Avg. 229	250 240 244 Avg. 245	234 236 226 Avg. 232	228 232 242 Avg. 234	240 194 238 Avg. 224	210 172 230 Avg. 204	38 24 220 Avg. 94
ML-ST-S006	272 220 254 Avg. 249	236 256 238 Avg. 243	144 248 180 Avg. 191	212 236 240 Avg. 229	211 178 185 Avg. 191	76 130 60 Avg. 89	60 58 76 Avg. 65	34 34 66 Avg. 45

Table 16. Charpy Impact Test Results

Weld No.	X100 Pipe OD x WT	Rm (MPa) 45°	Fracture Location	RM (MPa) 135°	Fraction Location	Rm (MPa) 225°	Fracture Location	RM (MPa) 315°	Fracture Location
DJ-DT-N012	52 in. x 22.9 mm	765.3	PM Fracture	755.2	PM Fracture	769.6	PM Fracture	770.7	PM Fracture
ML-DT-N013	52 in. x 22.9 mm	767.3	PM Fracture	748.1	PM Fracture	748.7	PM Fracture	762	PM Fracture
ML-ST-S006	36 in. x 19.05 mm	809.4	PM Fracture	820.8	PM Fracture	820.4	PM Fracture	817.8	PM Fracture

Table 17. CTOD Test Results

Weld No.	CTOD -10°C Weld metal (mm)	CTOD -10°C Fusion Line (mm)
DJ-DT-N012	dm 0.36 dm 0.30 dm 0.42	dm 0.67 dc 0.23 dc 0.38
ML-DT-N013	Awaiting Results	Awaiting Results
ML-ST-S006	dm 0.14 dm 0.23 dm 0.17	dc 0.13 dm 0.45 dm 0.36

Table 18. Welding Parameters for Welding Procedure ML-ST S006

Pass	WFS (m/min)	Amps I (Avg.)	Volts V (Avg.)	Osc. Freq. (beats per min)	CTWD (mm)	Travel Speed (mm/min)	Arc Energy (kJ/mm)
Int. root	9.60	194	21.8		10.0-11.0	710	0.36
Hot	12.0	206	21	320	13.5	1270	0.43
Fill 1	11.00	191	21	320	13.5	1270	0.39
Fill 2	10.00	165	20	320	13.5	1270	0.34
Fill 3	10.00	180	21	320	13.5	1270	0.36
Fill 4	10.00	182	20.5	320	13.5	1270	0.37
Fill 5	10.00	180	21	320	13.5	1270 (±20%)	0.36
Fill 6	10.00	177	21.6	320	13.5	1270 (±20%)	0.36
Cap	8.00	140	21	280	15	889 (±20%)	0.40

Table 19. Weld Metal Tensile Test Results

Weld Type	All Weld Metal Strip Tensile			
	$R_{p0.2}$ (MPa)	R_m (MPa)	Yield / Tensile	A (%)
Mechanised narrow gap - internal/external WP1 2.5%Ni/0.5%Mo/0.3Cr	844	951	0.89	16
Mechanised narrow gap - all-external WP2 0.5%Ni/0.5%Mo/0.5%Cr	807	865	0.93	19.5
Mechanised narrow gap - internal/external WP3 0.5%Ni/0.5%Mo/0.5%Cr	791	833	0.95	14.9
Mechanised narrow gap - internal/external WP4 1.0%Ni/0.3%Mo	841	888	0.95	20.5
Full penetration repair 2.7%Ni/0.3%Mo	724	816	0.89	19.1
Tie-in 2.7%Ni/0.3%Mo	737	800	0.92	18.2

Table 20. Hardness Surveys

	HV 10 Hardness Survey (2 mm sub Root) 90°							HV 10 Hardness Survey (2 mm sub Cap) 90°					
Weld Type	**HV Survey Location**	**Weld Metal Avg.**	**Weld Metal Max.**	**HAZ Avg.**	**HAZ Max.**	**Base Material Avg.**	**Base Material Max**	**Weld Metal Avg.**	**Weld Metal Max.**	**HAZ Avg.**	**HAZ Max.**	**Base Material Avg.**	**Base Material Max.**
Mechanized narrow gap internal/external WP1	3 o'clock	238	242	265	292	288	304	**364**	**366**	304	345	275	281
	Seam	232	245	314	327	292	294	**370**	**370**	347	**383**	289	297
Mechanized narrow gap all external WP2	3 o'clock	264	292	269	274	281	292	267	270	264	281	268	281
	Seam	282	285	296	304	293	297	294	297	304	319	252	260
Mechanized narrow gap internal/external WP3	3 o'clock	268	274	267	287	295	304	303	309	261	274	272	276
	Seam	268	268	331	348	287	294	315	319	303	351	290	297
Mechanized narrow gap internal/external WP4	3 o'clock	216	222	257	285	297	314	302	306	268	285	280	285
	Seam	251	258	306	322	282	287	300	306	322	347	286	287
Part penetration repair[(a)]	3 o'clock	259	260	245	292	257	270	311	319	252	266	281	287
Full penetration repair[(a)]	6 o'clock	231	238	245	306	264	283	317	339	255	274	264	276
Cap repair FCAW[(a)]	3 o'clock							293	302	253	272	273	283
Cap repair SMAW[(a)]	3 o'clock							**378**	**387**	290	330	279	289
Backweld repair SMAW[(a)]	12 o'clock	305	306	262	317	273	279						
Multipass backweld repair SMAW[(a)]	12 o'clock	305	317	255	272	278	294						
Backweld repair GMAW[(a)]	12 o'clock	273	283	259	294	288	297						
Multipass backweld repair GMAW[(a)]	12 o'clock	274	276	271	292	298	312						
Tie-in	3 o'clock	233	235	259	272	271	283	281	304	259	272	271	283
	Seam	238	249	295	304	275	279	260	285	291	302	276	279

(a) WM values are for the repair only. HAZ values are for both GM and original NG GMAW affected by the repair weld HAZ. Figures in bold highlight those values above 350 HV10.

Table 21. CTOD Results

Weld Type	CTOD -10°C Weld Metal (mm)			CTOD -10°C Fusion Line (mm)		
Mechanised narrow gap Internal/external welding WP1 Fracture mode	0.16 Valid M	0.15 Valid M	0.17 Valid U	0.23 Valid U	0.27 Valid U	0.21 Valid U
Mechanised narrow gap All external welding WP2 Fracture mode	0.13 Valid M	0.15 Valid M	0.23 Valid M	0.40 Valid U	0.30 Valid U	0.45 Valid U
Mechanised narrow gap Internal/external welding WP3 Fracture mode	0.13 Valid M	0.17 Valid M	0.14 Valid M	0.36 Valid C	0.12 Valid C	0.34 Valid M
Mechanised narrow gap Internal/external welding WP4 Fracture mode	0.27 Valid M	0.24 Valid M	0.25 Valid M	0.25 Valid M	0.42 Valid M	0.38 Valid M
Tie-in Fracture mode	0.14 Valid M	0.11 Valid M	0.12 Valid M	0.26 Valid M	0.18 Valid M	0.16 Valid U

CTOD Results Validated in Accordance with BS 7448-1:1991

Table 22. Minimum Pre-Heating Temperatures

Electrode	Implant	Tekken
Basic E10018	200°C	100°C
Cellulosic E6010	/	150°C

Table 23. Welding Procedures used for Pipe 56 in. × 19 mm

Specifications SNAM RETE GAS	Test No.	Root Pass AWS Size Preheating T Heat Input	Hot Pass AWS Size Preheating T Heat Input	Filling and Cap AWS Size Preheating T Heat Input	Notes
Sal 1: Line Welding (SMAW)	1	E6010 (4mm) 180°C 11.2 kj/cm	E10018 (3.2 mm) 160°C 7.7 kj/cm	E10018 4+4.5 mm) 85°C 8.5 kj/cm	Root pass with cellulosic vertical down welding and the rest with basic vertical down welding. Ambient T between 6 and 11°C
	2	E7016 (2.5 mm) 120°C 14.4. kj/cm	E10018 (3.2 mm) 150°C 8.5 kj/cm	E10018 (4+4.5 mm) 90°C 9.47 kj/cm	Root pass with basic vertical up welding and the rest with basic vertical down welding. Ambient T between 6 and 11°C
Sal 1: Line Welding (GMAW "PASSO" Type)	3	ER 100 S-G 1 mm Gas: CO_2	Gas: CO_2	Gas: CO_2 60% Ar 40%	Preheating temperature between 85 and 110°C. Ambient T between 6 and 7°C

Table 24. Welding Procedures used for Pipe 36 in. × 16 mm

Specifications SNAM RETE GAS	Test No.	Root Pass AWS Size Preheating T Heat Input	Hot Pass AWS Size Preheating T Heat Input	Filling and Cap AWS Size Preheating T Heat Input	Notes
Sal 1: Line Welding (SMAW)	4	E6010 (4mm) 160°C 6 kj/cm	E6010 (4 mm) 150°C 6.6 kj/cm	E10018 4+4.5 mm) 120°C 9.18 kj/cm	Root pass with cellulosic vertical down welding and the rest with basic vertical down welding. Ambient temperature about 12°C
Sal 2: Line Welding (SMAW)	5	E7016 (2.5 mm) 120°C 13.2. kj/cm	E10018 (4 mm) 130°C 8.7 kj/cm	E10018 (4+4.5 mm) 85+100°C 9.1 kj/cm	Root pass with basic vertical up welding and the rest in basic vertical down. Ambient T about 13°C
Sal 1: Line Welding (GMAW "PASSO" Type)	6	A 5.28 ER100 S-G 1 mm Gas: CO_2 60% Ar 40%	1 mm Gas: CO_2	1 mm Gas: CO_2 60% Ar 40%	Ambient temperature about 14°C

Table 25. Mechanical Characterization of Weld Joints SMAW 56-in. × 19 mm

Test No.	Filling Electrodes (AWS)		Tensile Strength WM (2 round bar samples)		Tensile Strength ISO Transverse (2 samples)	
	Vertical Down	Vertical Up	YS (MPa)	UTS (MPa)	UTS (MPa)	Fracture Position
1	E10018		769-768	810-813	785-756	BM
2	E10018				757-756	HAZ

Table 26. Mechanical Characterization of Weld Joints GMAW 56 in. × 19 mm

Test No.	Wire (AWS)	Tensile Strength WM (2 round bar samples)		Tensile Strength ISO Transverse (2 samples)	
		YS (MPa)	UTS (MPa)	UTS (MPa)	Fracture Position
3	ER 100 S-G	722-724	798-796	800-813	HAZ

Table 27. Metal-Cored Wire Alloy Variation Trials - Resultant Weld Metal Chemistry

	Weld Metal Chemical Composition (wt%) 82.5%Ar, 12.5%Co$_2$,5%He shielding gas)																	
Weld No.	**C**	**Mn**	**Si**	**Ni**	**Mo**	**Cr**	**P**	**S**	**Cu**	**Nb**	**V**	**Al**	**Ti**	**B**	**O**	**N**	**CE_{IIW}**	**CET**	**P_{cm}**
Solid Wire Pipe Weld	0.085	1.71	0.54	0.87	0.30	0.03	0.010	0.008	0.13	0.008	0.005	<0.005	0.04	0.0005	0.0258	0.0062	0.504	0.316	0.23
Solid Wire Plate Weld	0.076	1.62	0.53	0.85	0.32	0.08	0.009	0.008	0.14	0.009	0.014	<0.005	0.04	<0.0005	0.0210	0.0088	0.495	0.302	0.22
MC Control 1	0.094	1.66	0.51	0.77	0.30	0.07	0.013	0.009	0.06	0.007	0.009	0.029	0.02	<0.0005	0.0537	0.0043	0.502	0.316	0.23
MC Control 2	0.094	1.72	0.50	0.78	0.30	0.08	0.010	0.009	0.09	0.008	0.013	0.020	0.03	<0.0005	0.0473	0.0075	0.517	0.324	0.24
Ni Low	0.091	1.67	0.48	0.08	0.29	0.08	0.010	0.009	0.09	0.008	0.012	0.020	0.02	<0.0005	0.0514	0.0069	0.457	0.298	0.22
Ni High	0.090	1.77	0.52	1.28	0.31	0.09	0.010	0.009	0.10	0.009	0.014	0.020	0.02	<0.0005	0.0462	0.0072	0.560	0.340	0.25
Mo Low	0.098	1.74	0.51	0.81	0.19	0.08	0.010	0.009	0.09	0.008	0.012	0.020	0.02	<0.0005	0.0448	0.0077	0.504	0.320	0.24
Mo High	0.094	1.71	0.51	0.82	0.42	0.08	0.010	0.009	0.09	0.008	0.012	0.020	0.02	<0.0005	0.0459	0.0074	0.542	0.336	0.25
Cr Medium	0.089	1.75	0.53	0.88	0.32	0.32	0.009	0.009	0.10	0.009	0.013	0.020	0.03	<0.0005	0.0437	0.0083	0.577	0.339	0.25
Cr High	0.088	1.71	0.51	0.84	0.32	0.53	0.009	0.009	0.10	0.010	0.014	0.020	0.03	<0.0005	0.0474	0.0093	0.608	0.344	0.26
C Low	0.057	1.70	0.51	0.83	0.29	0.08	0.009	0.009	0.10	0.009	0.012	0.020	0.02	<0.0005	0.0560	0.0089	0.479	0.286	0.20
C High	0.120	1.71	0.52	0.81	0.31	0.08	0.010	0.009	0.09	0.008	0.011	0.020	0.02	<0.0005	0.0443	0.0083	0.545	0.351	0.26
C High, Mo Low	0.110	1.69	0.50	0.80	0.09	0.08	0.010	0.009	0.10	0.008	0.012	0.019	0.02	<0.0005	0.0443	0.0076	0.488	0.317	0.24
C Low, Si Low, Ni High, Mo Low	0.067	1.72	0.28	1.32	0.20	0.08	0.009	0.009	0.10	0.010	0.014	0.018	0.04	<0.0005	0.0545	0.0077	0.507	0.301	0.21

CE_{IIW} = C+Mn/6(Cr+Mo+V)/5+(Ni+Cu)/15
CET = C+(Mn+Mo)/10+(Cr+Cu)/20+Ni/40
P_{cm} = C+Si/30+(Mn+Cu+Cr)/20+Ni/60+Mo/15+V/10+5B
N.B. when B levels stated as <0.0005, a value of 0.0004 was used in the P_{cm} calculation

Table 28. Metal-Cored Wire Alloy Variation Trials – TS and Harness Results

		All Weld Metal Strip Tensile								Weld Metal Hardness (vertical traverse on weld centerline: 15 indents)		
Weld No	Plate No.	Specimen Original Gauge Area Dimensions (mm)	$R_{p0.2}$ (MPa)	Change in $R_{p0.2}$ wrt MC Control 2 Average	$R_{t0.5}$ (MPa)	R_m (MPa)	Change in R_m wrt MC Control 2 Average	$R_{p0.2}/R_m$	A (%)	Weld Metal Average HV10	Weld Metal Max HV10	Standard Deviation of WM HV10 Values
Solid Wire (Pipe)		4.04 x 8.23	841	-27	838	888	-30	0.95	20.5	N/A	N/A	N/A
Solid Wire (Plate)	12	4.03 x 8.17	909	41	825	942	24	0.96	20	293	312	10.14
MC Control 1		4.03 x 8.10	848	-20	757	893	-25	0.95	12.5	285	304	10.81
MC Control 2 Test1	1	4.03 x 8.25	876	Avg. 868 Std. Dev. 4.95	764	906	Avg. 918 Std. Dev. 8.61	0.97	16.5	287	309	10.74
MC Control 2 Test 2	1	4.02 x 8.20	868		873	913		0.95	21			
MC Control 2 Test 3	1a	4.00 x 8.22	865		746	926		0.93	18			
MC Control 2 Test 4	1a	4.00 x 8.17	863		856	926		0.93	16.5			
Ni Low	2	4.04 x 8.19	793	-75	808	841	-77	0.94	18	270	289	9.92
Ni High	3	4.04 x 8.05	958	90	790	997	79	0.96	14.5	321	351	13.92
Mo Low	4	4.01 x 8.07	885	17	865	932	14	0.95	16.5	308	325	11.24
Mo High	5	4.01 x 8.29	908	40	859	955	37	0.95	17	310	339	15.07
Cr Medium	6	3.99 x 8.14	933	65	838	991	73	0.94	17	320	342	15.52
Cr High	7	4.02 x 8.10	1009	141	785	1043	125	0.97	14.5	333	354	13.74
C Low	8	4.03 x 8.14	822	-46	793	857	-61	0.96	18.5	280	294	11.52
C High	9	4.07 x 8.14	944	76	925	1002	84	0.94	18	322	348	19.20
C High, Mo Low	10	4.01 x8.27	913	45	800	955	37	0.96	15.5	310	348	16.94
Ni High, C Low, Mo Low	11	4.01 x 8.20	846	-22	843	879	-39	0.96	14	285	306	13.68

NB Standard deviation calculated using biased (n) method i.e., STDEVP = ((n;x^2)/^2)^1/2)

Table 29. Metal-Cored Wire Alloy Variation Trials – Impact Toughness Results

	Charpy Impact Toughness (J)											
Process Type	**WM CL Cv @ -20°C**	**WM CL Cv @ -20°C**	**WM CL Cv @ -20°C**	**WM CL Avg. @ -20°C**	**WM CL Cv @ -40°C**	**WM CL Cv @ -40°C**	**WM CL Cv @ -40°C**	**WM CL Avg. @ -40°C**	**WM CL Cv @ -60°C**	**WM CL Cv @ -60°C**	**WM CL Cv @ -60°C**	**WM CL Avg. @ -60°C**
Solid Wire (Pipe)	164	158	220	181	180	252	198	210	96	100	124	107
Solid Wire (Plate)	210	176	180	189	108	120	128	119	80	90	52	74
MC Control 1					84	72	64	73				
MC Control 2	82	84	74	80	70	58	60	63	50	56	44	50
Ni Low	76	82	80	79	70	66	64	67	52	44	54	50
Ni High	58	64	58	60	50	52	44	49	42	36	30	36
Mo Low	78	72	72	74	48	60	62	57	50	46	46	47
Mo High	62	70	68	67	48	48	60	52	38	50	44	44
Cr Medium	68	64	66	66	60	52	46	53	36	46	30	37
Cr High	54	66	62	61	46	44	38	43	30	38	30	33
C Low	72	64	68	68	52	56	54	54	40	38	44	41
C High	64	74	64	67	58	62	54	58	32	40	46	39
C High, Mo Low	68	66	64	66	62	68	62	64	50	52	50	51

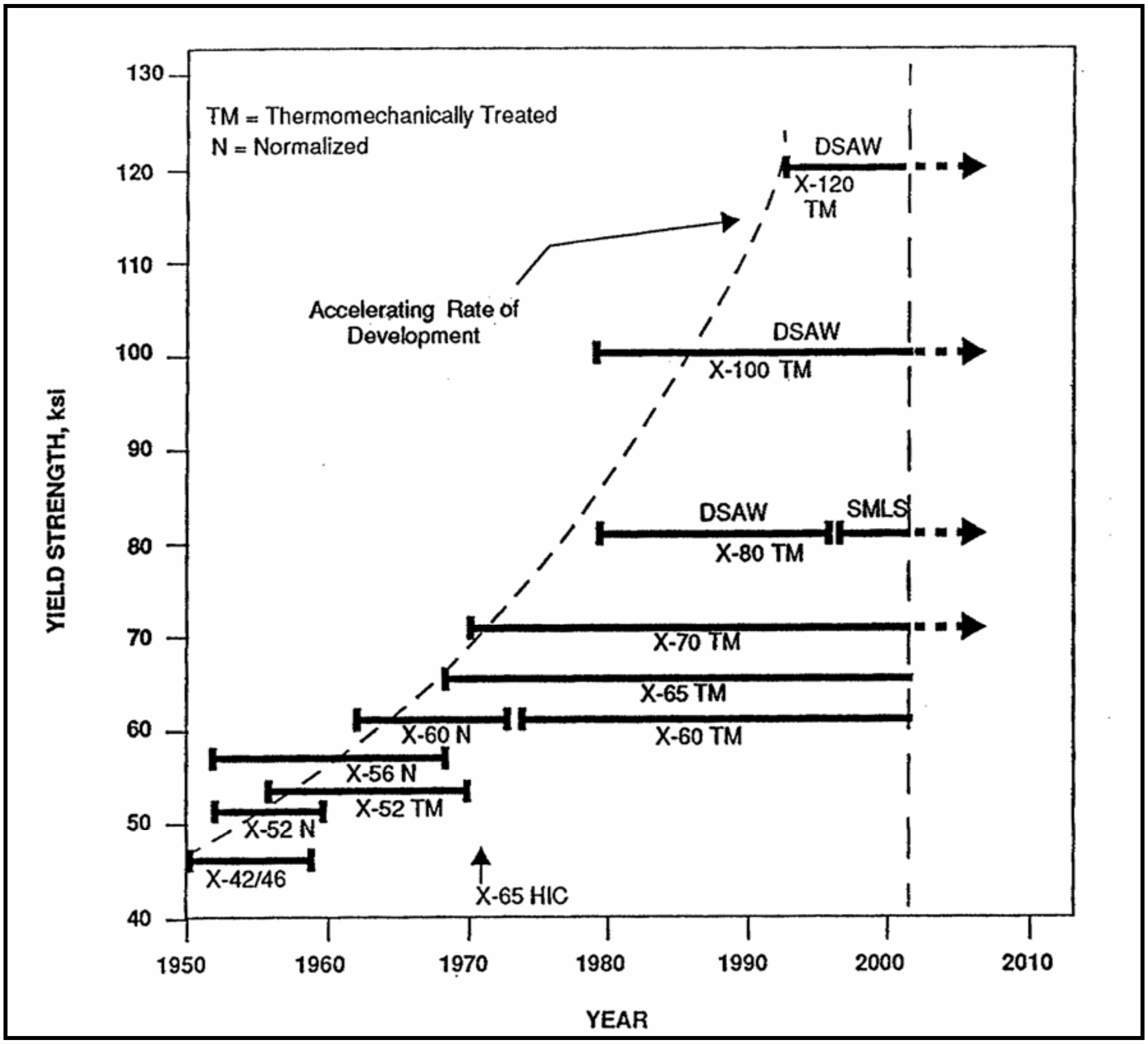


Figure 1. Progression of Line Pipe Steel Development

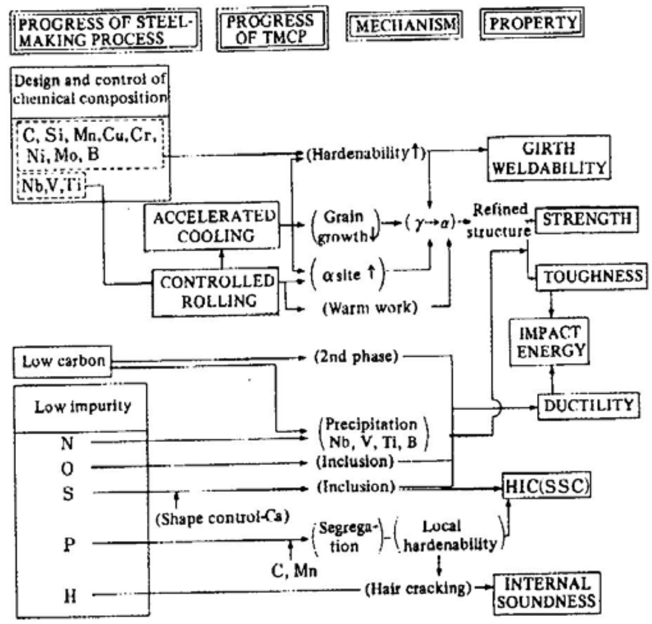


Figure 2. Primary Relationships Among Metallurgical Factors and Properties of Line Pipe Steels

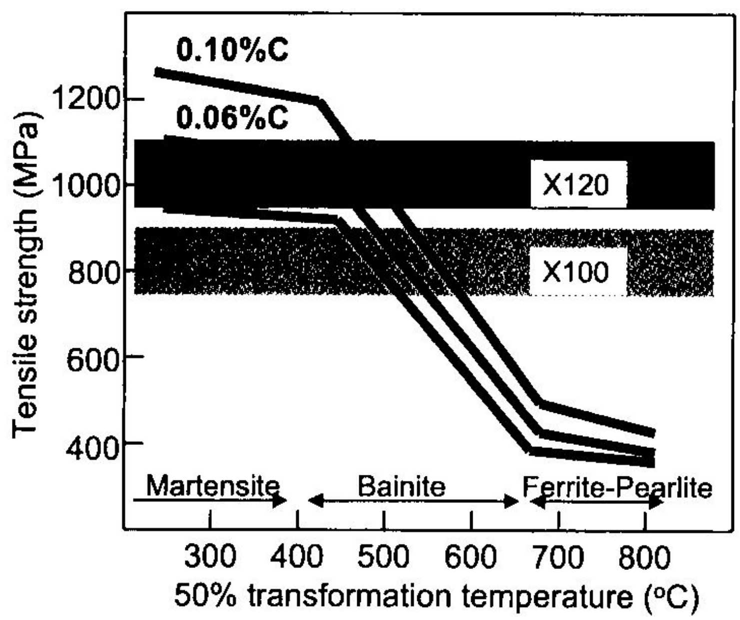
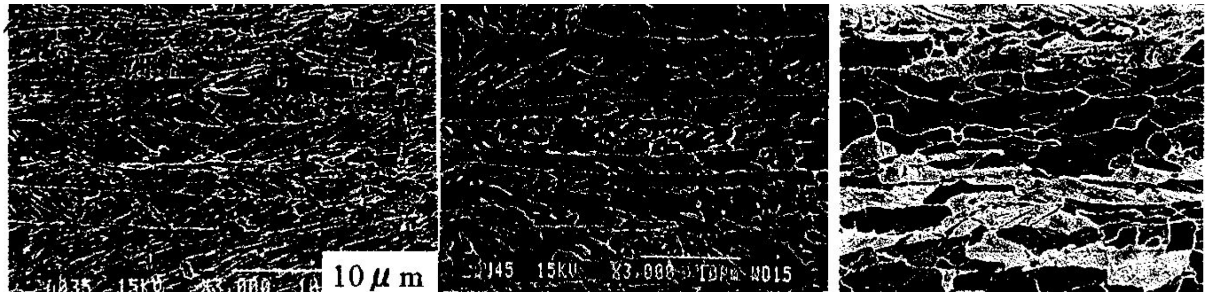


Figure 3. Typical Microstructure Transformed from Deformed Austenite of Low-C, High-Strength Steel (TS = 1000 MPa)



(a) LB (b) DUB (c) DP

Figure 4. Effect of Chemical Composition on Tensile Strength

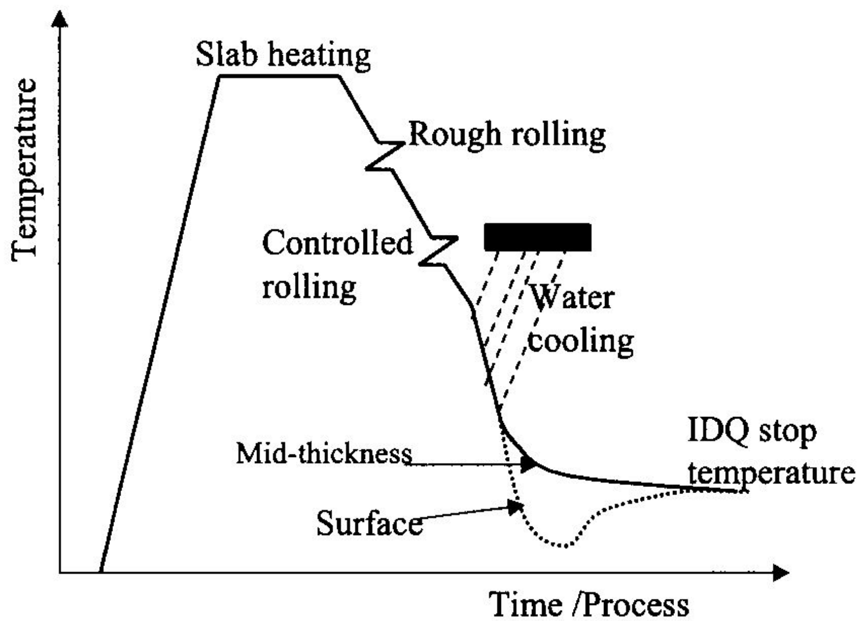


Figure 5. Schematic Illustration of IDQ Process

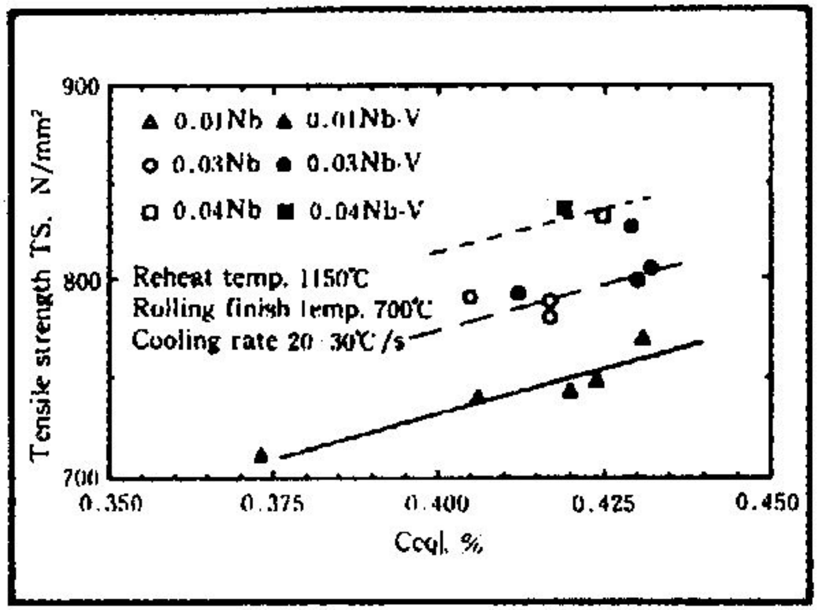


Figure 6. **Relationship Between Transformation Temperature and Strength for Varying Nb Levels**

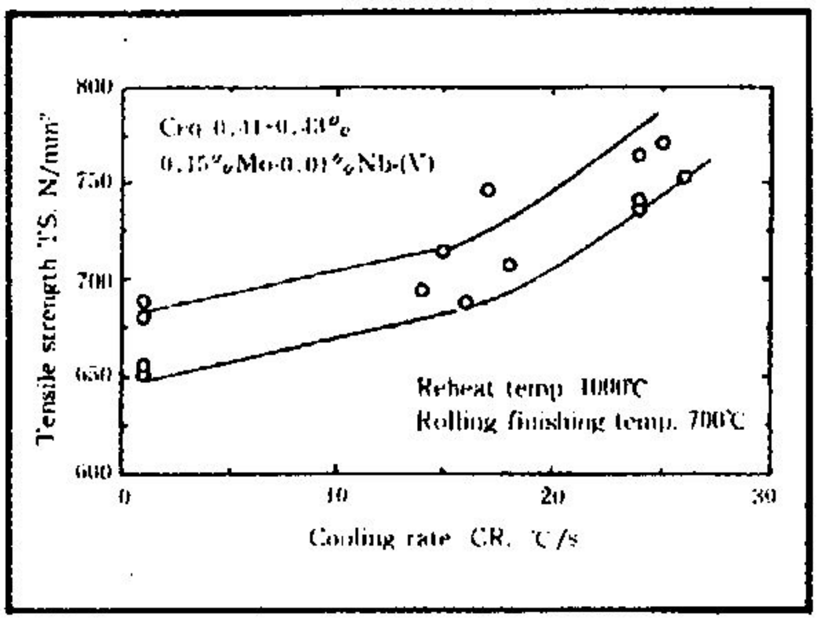


Figure 7. **Effect of Cooling Rate on TS (Ceq 0.41-0.43%, Mo-Nb Steel)**

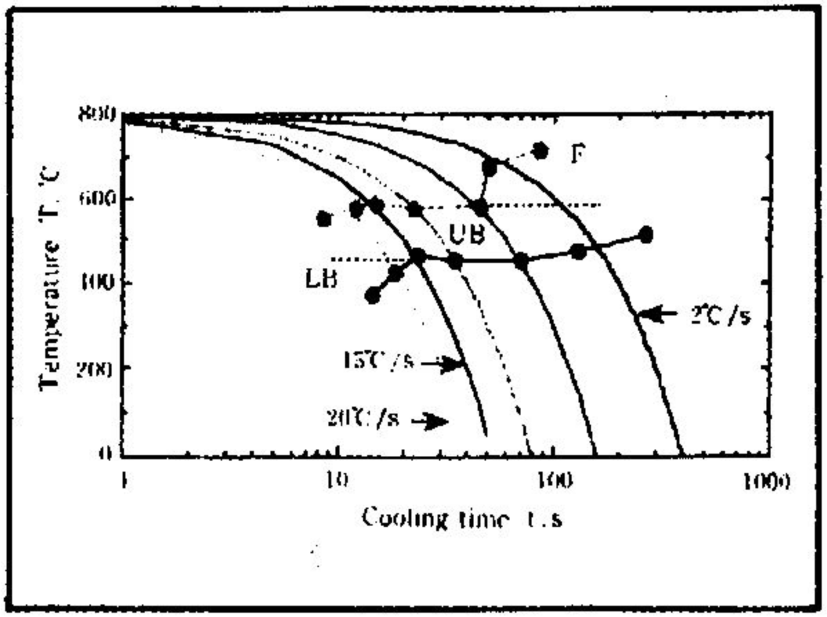


Figure 8. **Continuous Cooling Transformation Behavior after Deformation**

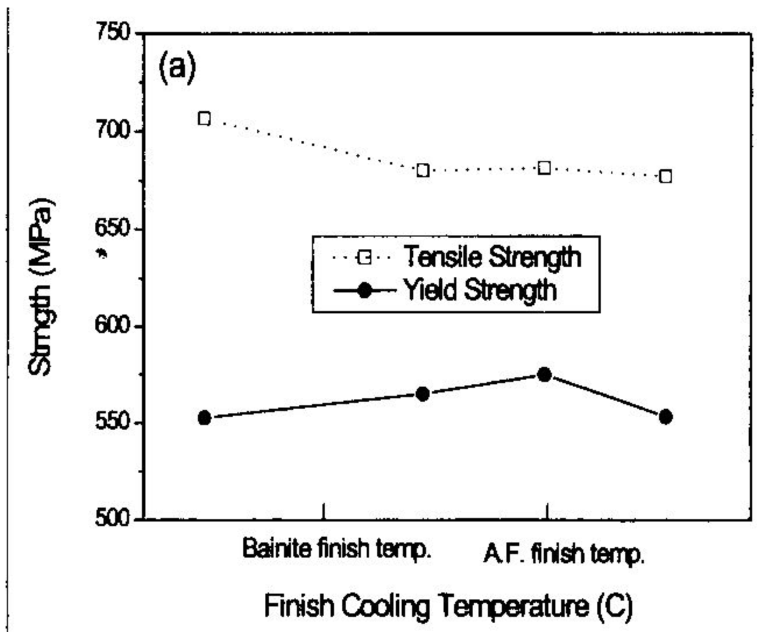


Figure 9. **Changes of Strength with Finish Cooling Temperature in API-X80 Grade 1.6Mn-0.25Mo-Nb-V Steel Produced by Accelerated Cooling**

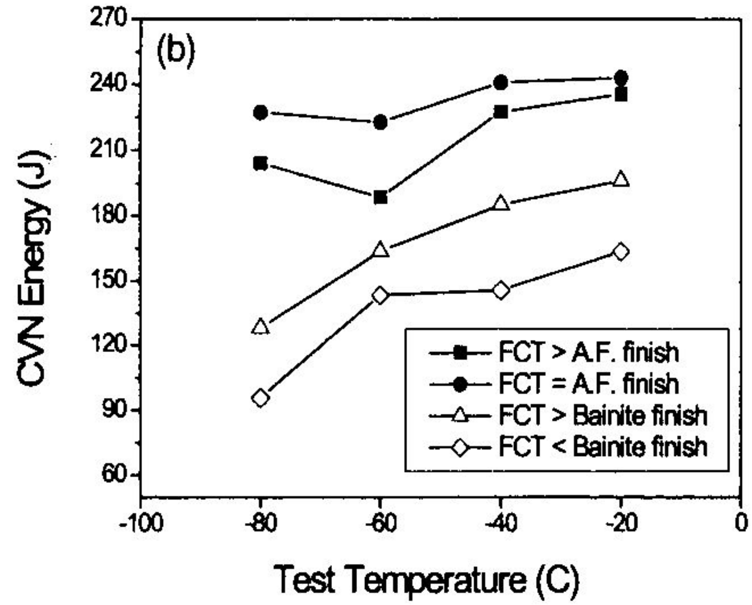


Figure 10. **Changes of CVN Energy with Finish Cooling Temperature in API-X80 Grade 1.6Mn-0.25Mo-Nb-V Steel Produced by Accelerated Cooling**

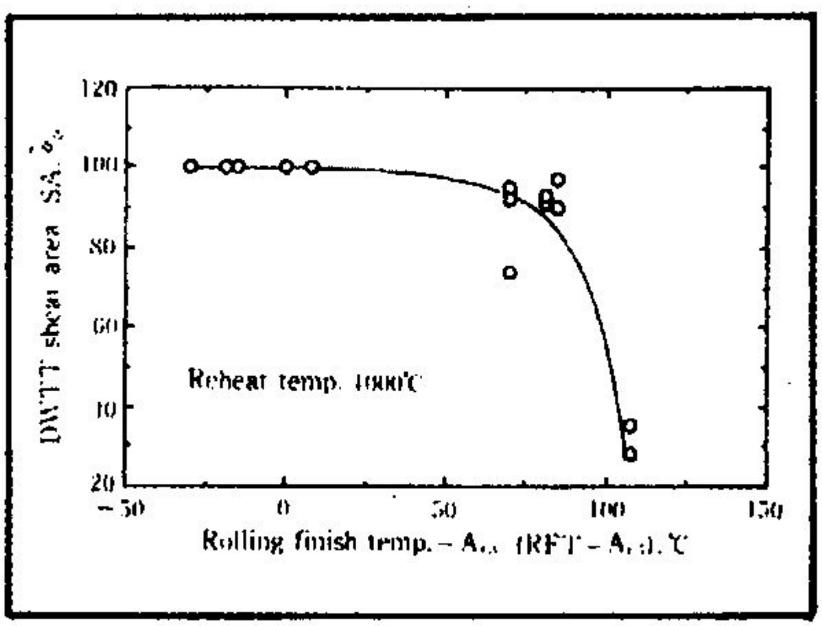


Figure 11. **Effect of Rolling Finish Temperature on Shear Area of DWTT at -40°C**

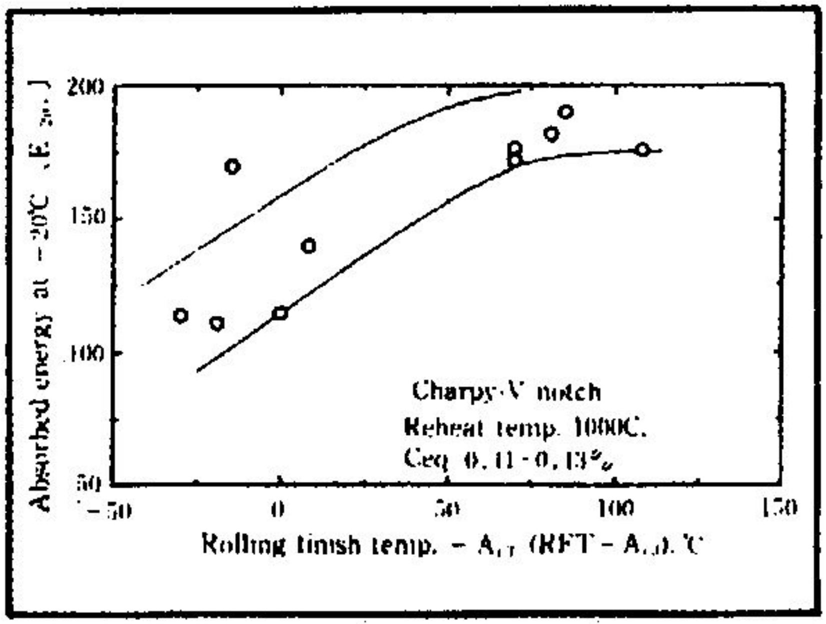


Figure 12. Effect of Rolling Finish Temperature on Absorbed Energy of Charpy Test

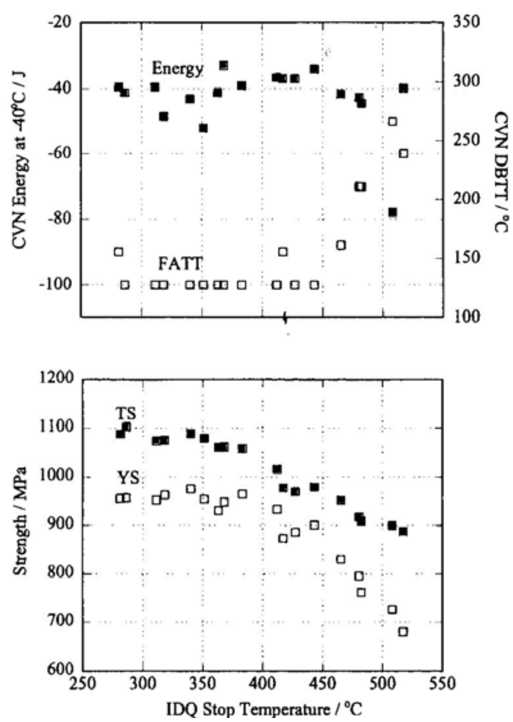


Figure 13. Effect of IDQ Stop Temperature on Strength and Toughness

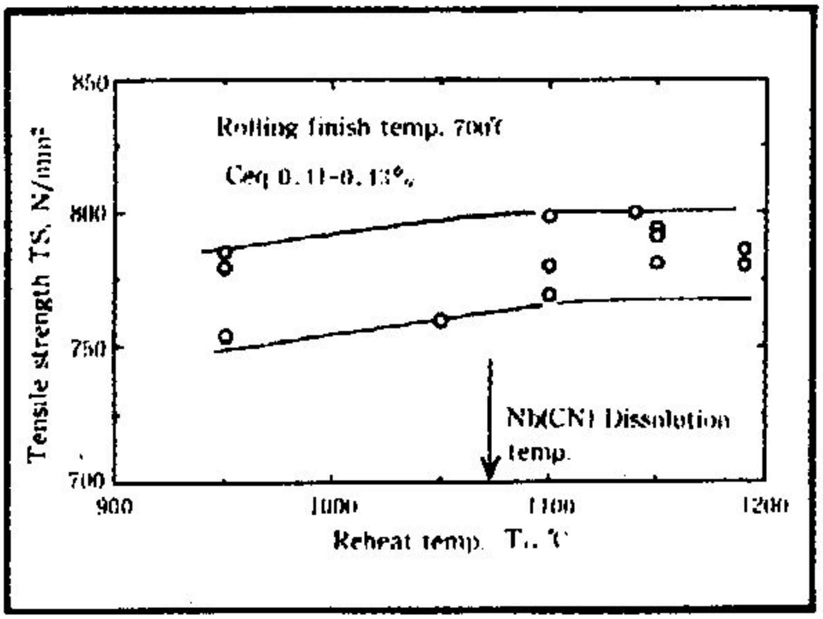


Figure 14. Relationship Between Slab Reheat Temperature and TS

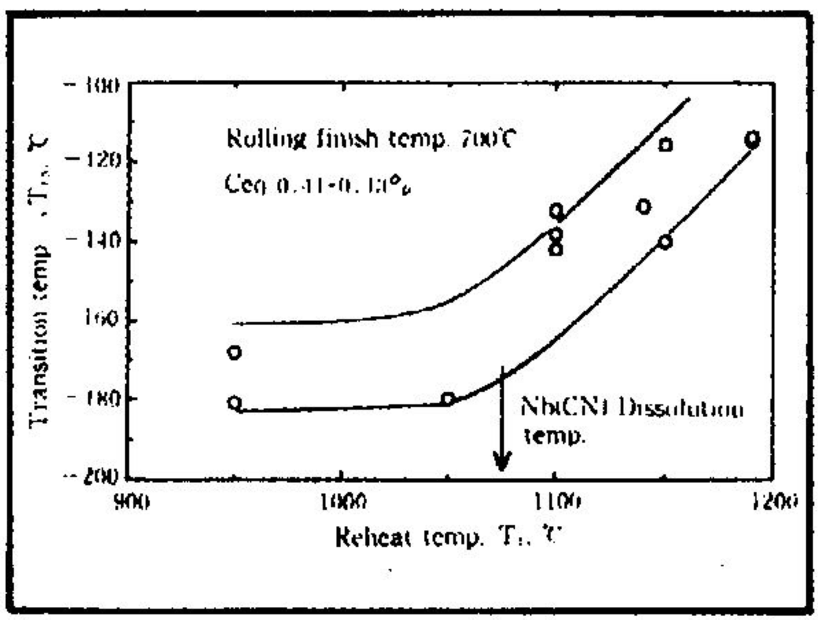


Figure 15. Relationship Between Slab Reheat Temperature and Toughness

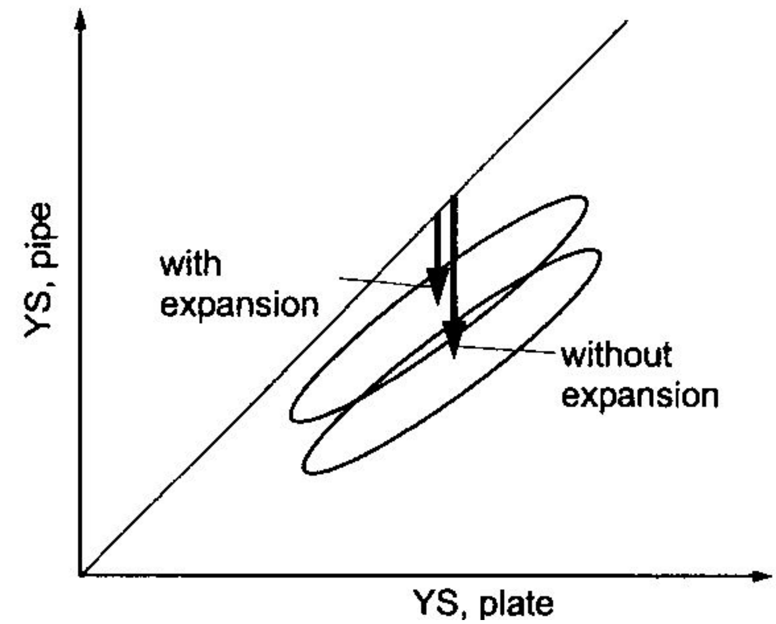


Figure 16. Plate-Pipe Correlation of YS with and without Pipe-Expansion

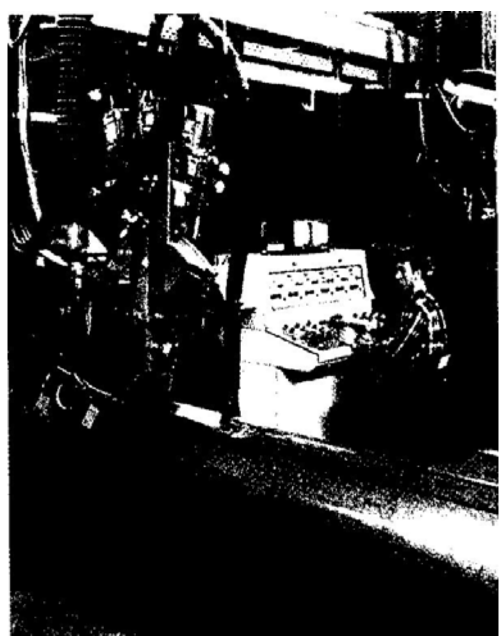


Figure 17. Welding Equipment of Pipe Mill EBK

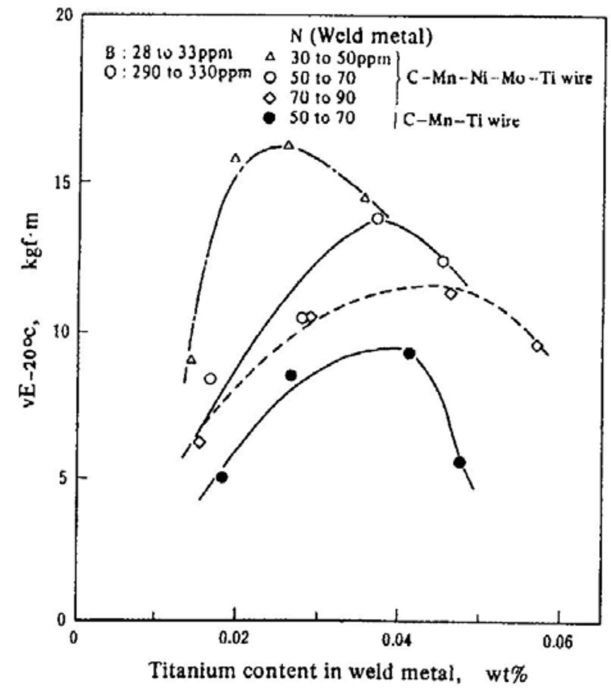


Figure 18. Effect of Ti and N on CVN Toughness in Weld Metal

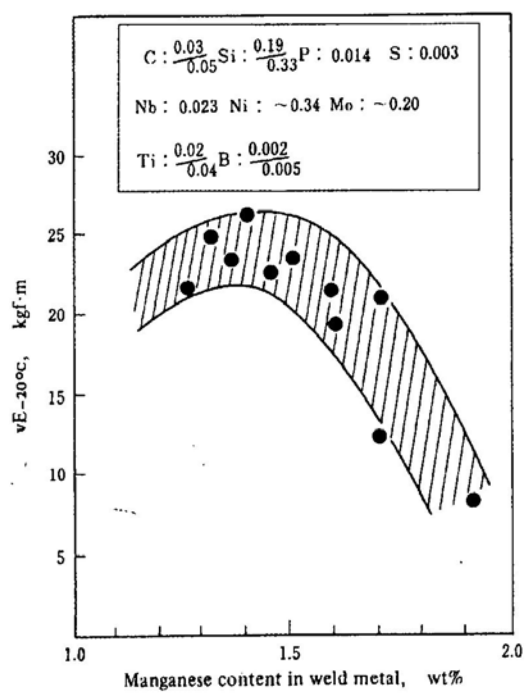


Figure 19. Effect of Mn Content on CVN Toughness in Weld Metal

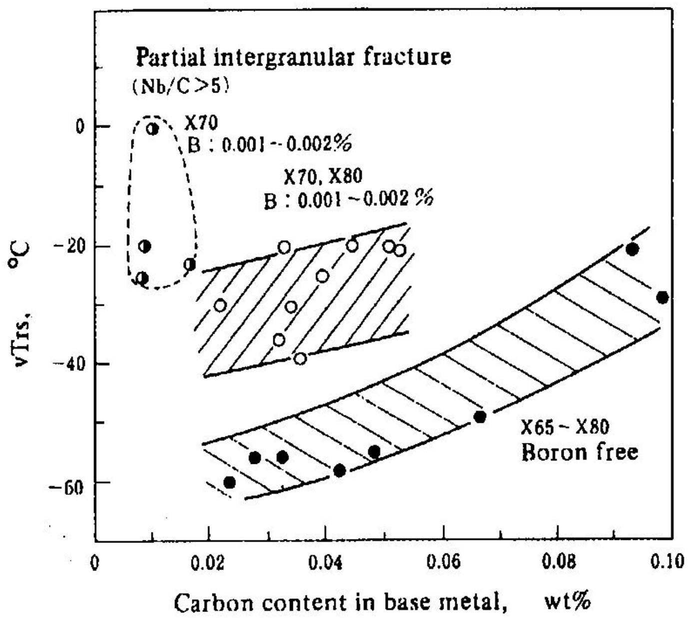


Figure 20. **Effect of C and B Content on HAZ Toughness**

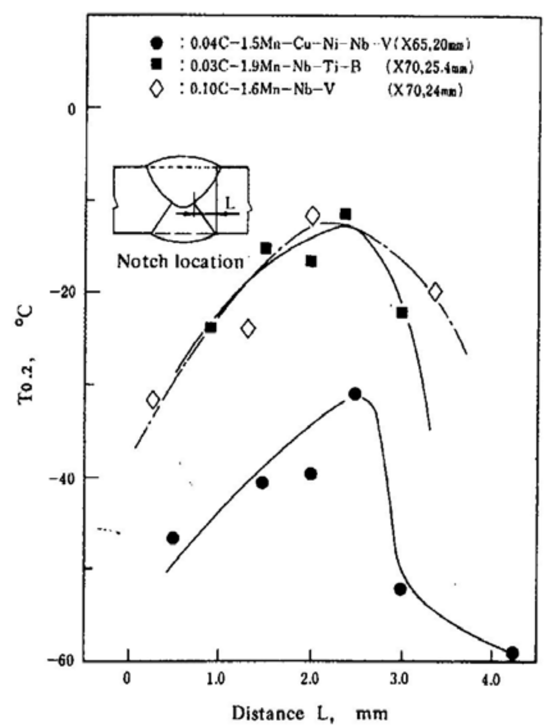


Figure 21. Effect of Notch Location on CTOD Properties of HAZ

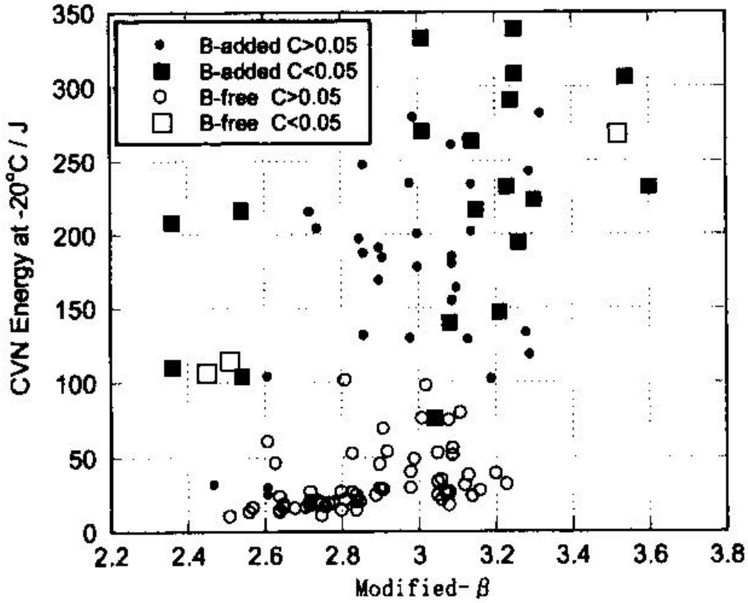


Figure 22. **Effect of Hardenability Index, β on CVN Energy at -20°C of Simulated HAZ**

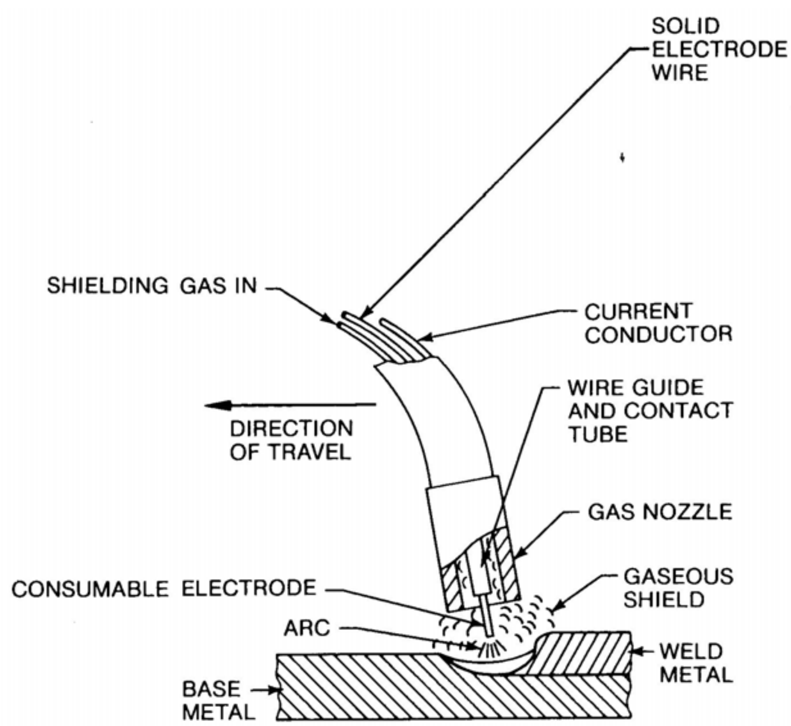


Figure 23. **GMAW Process**

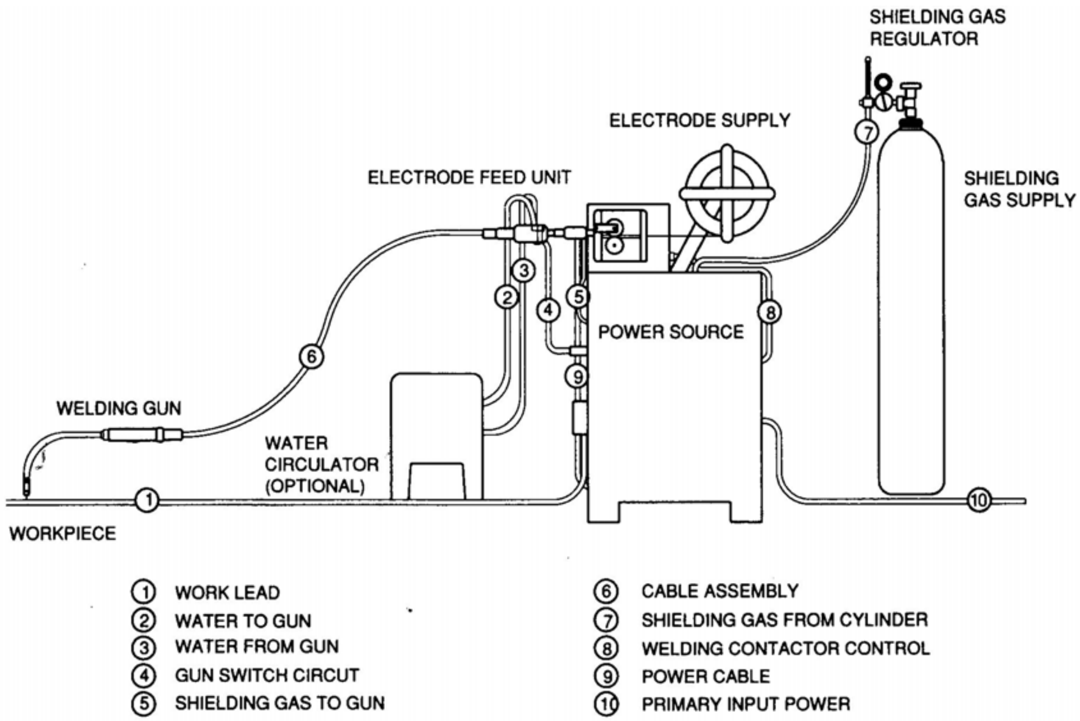


Figure 24. Schematic Diagram of GMAW Equipment

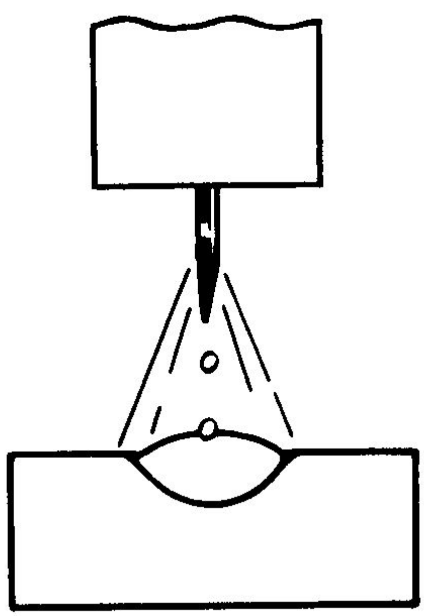


Figure 25. Axial Spray Transfer

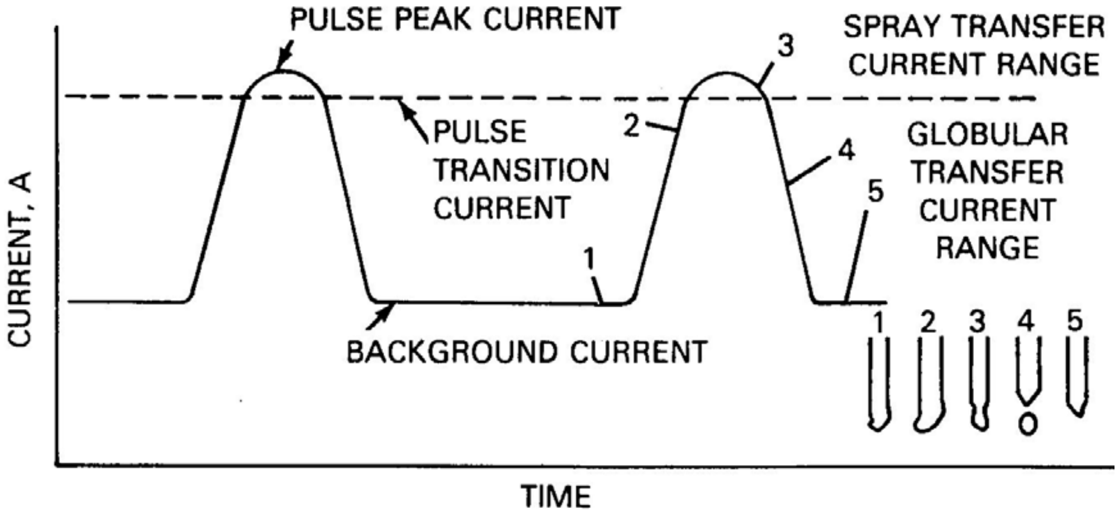


Figure 26. Pulsed-Spray Arc Welding Current Characteristic

Figure 27. External Welding Carriage

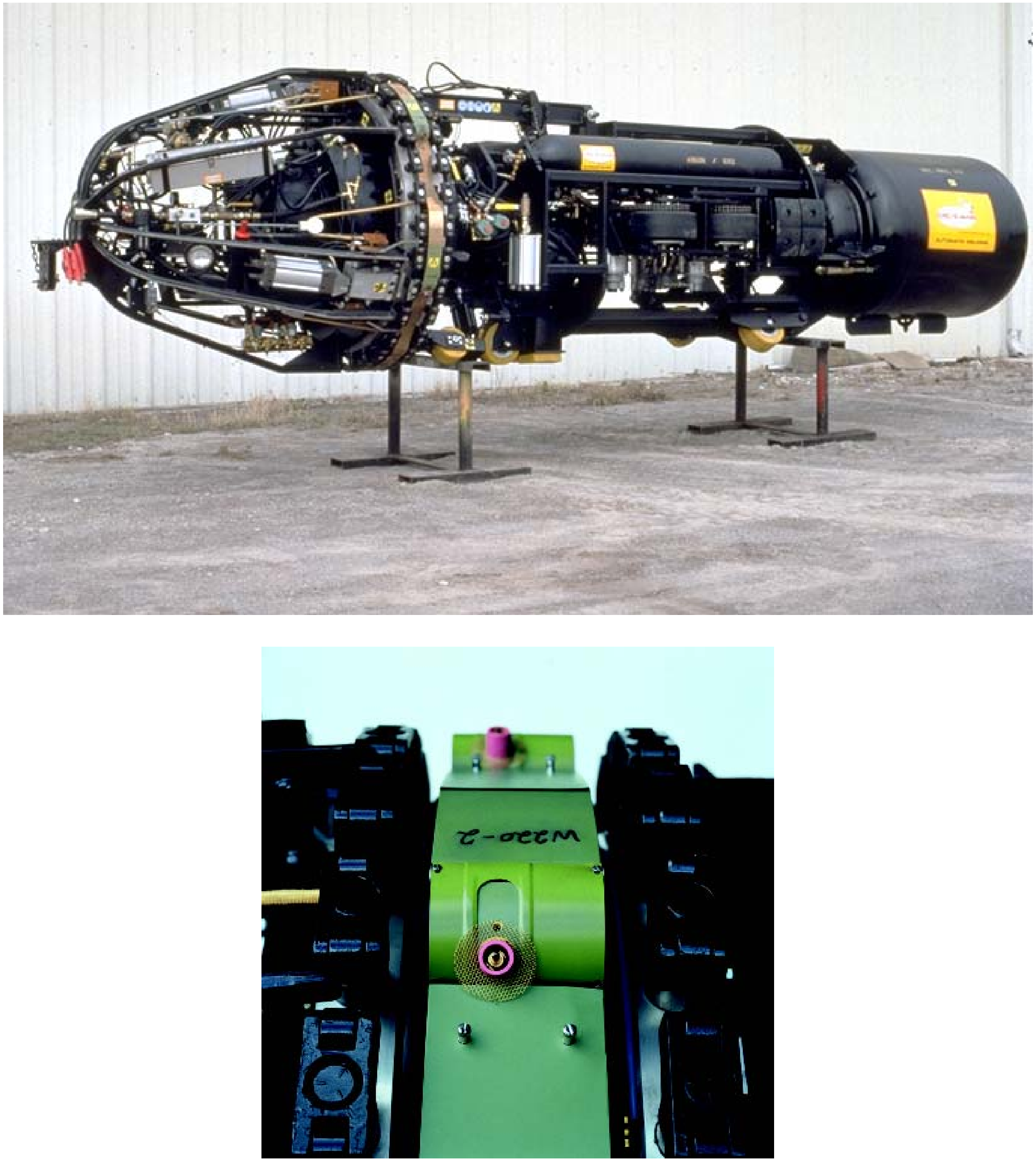


Figure 28. Internal Welding Machine

Figure 29. **Welding Shelters or “Shacks”**

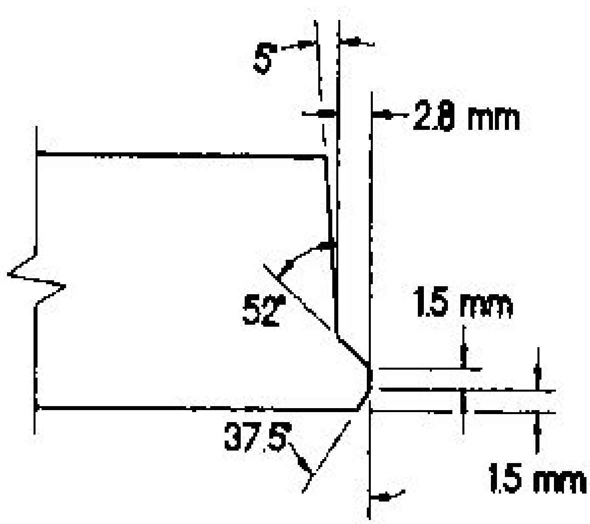


Figure 30. **Typical Joint Design**

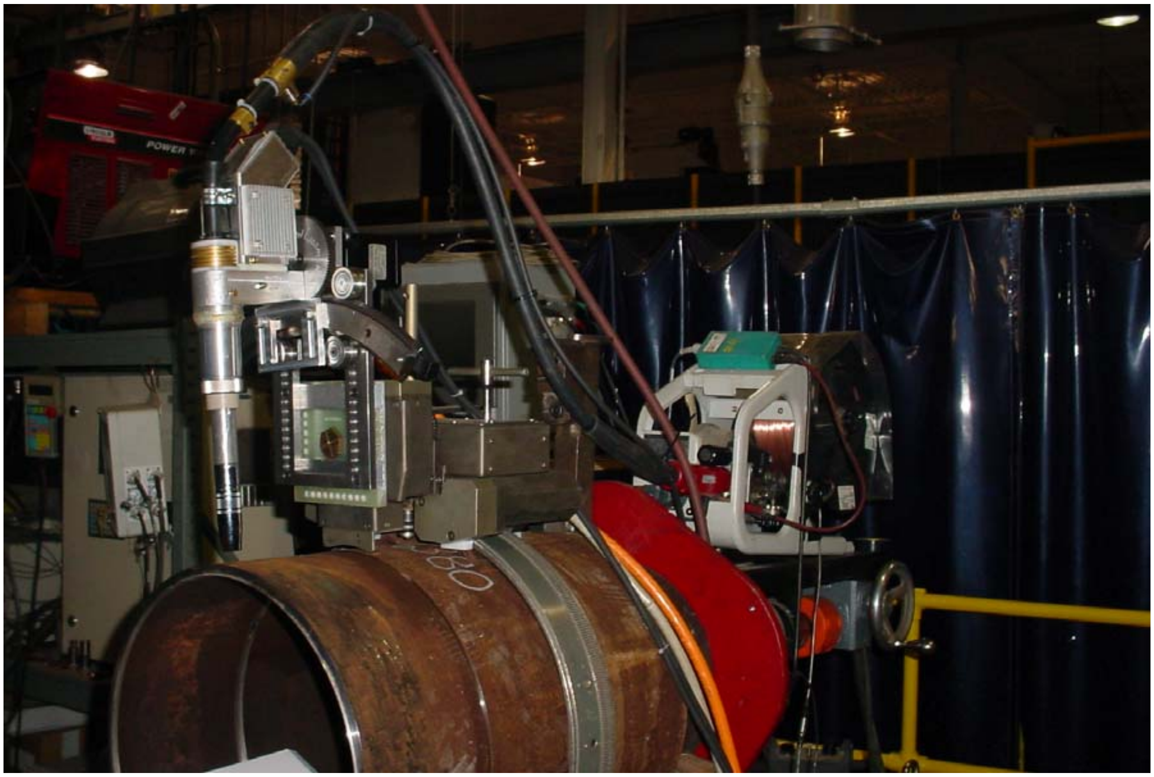


Figure 31. “Spin Arc” RE-GMAW Torch Mounted to a Serimer-Dasa STX Tractor

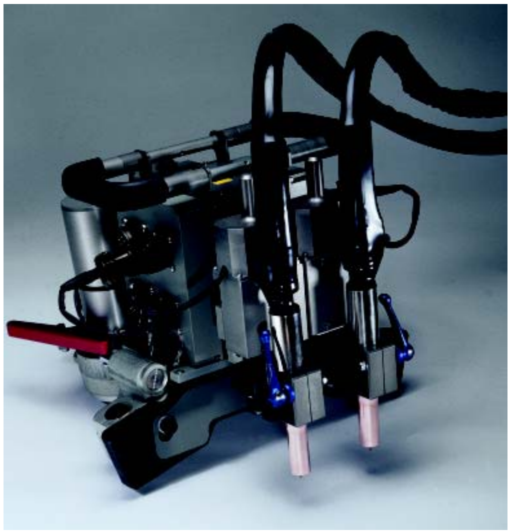


Figure 32. CRC-Evans P500 Dual Torch Welding Head

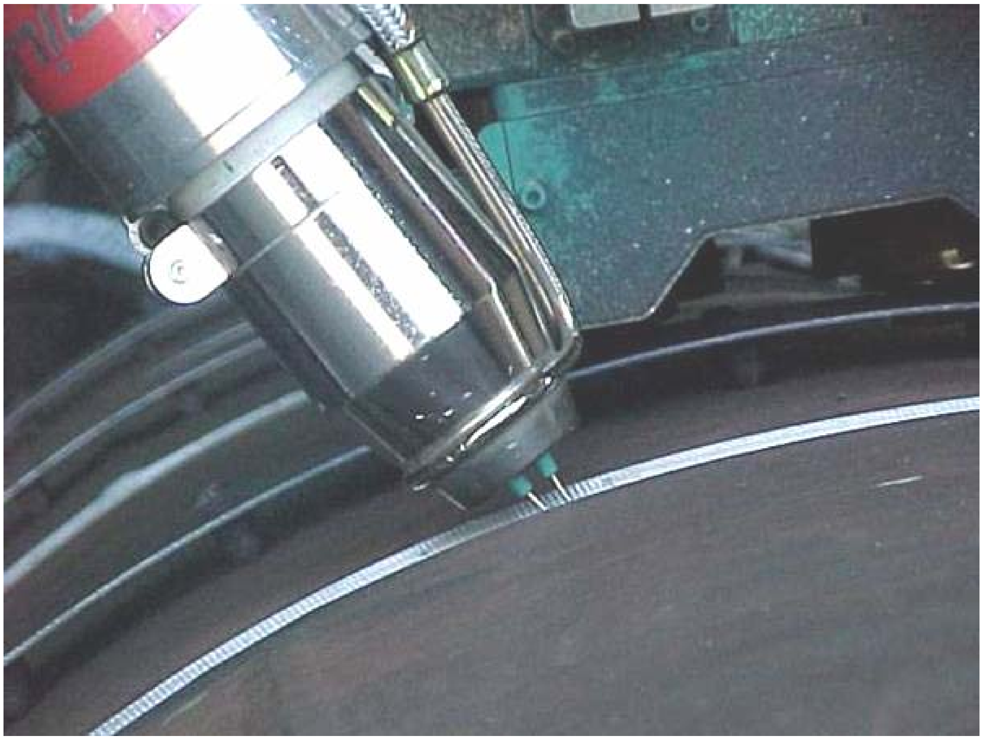


Figure 33. **Tandem GMAW**

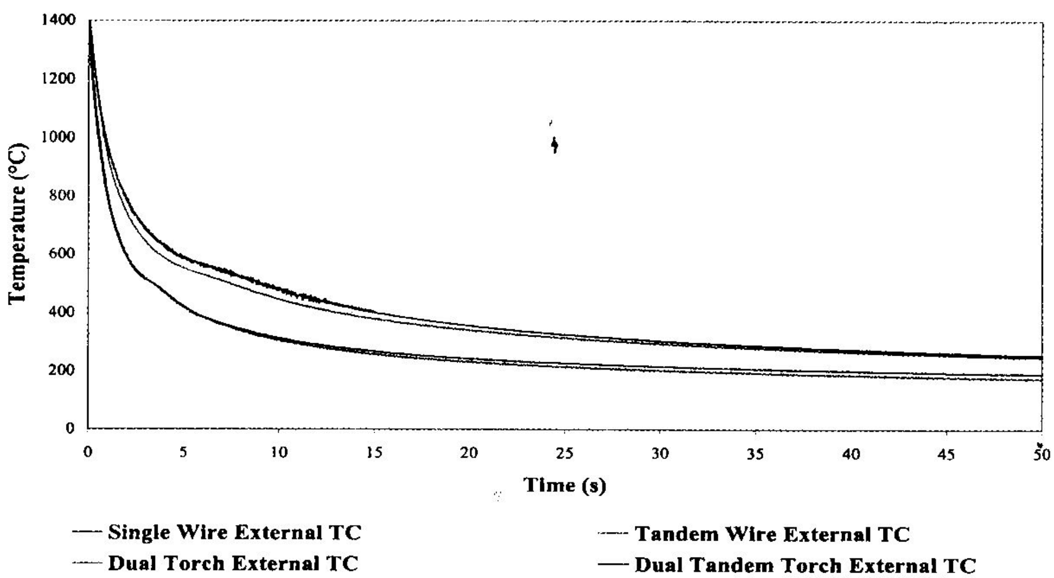


Figure 34. **Cooling Curves for an External Plunged Thermocouple with Various GMAW Pipeline Welding Systems**

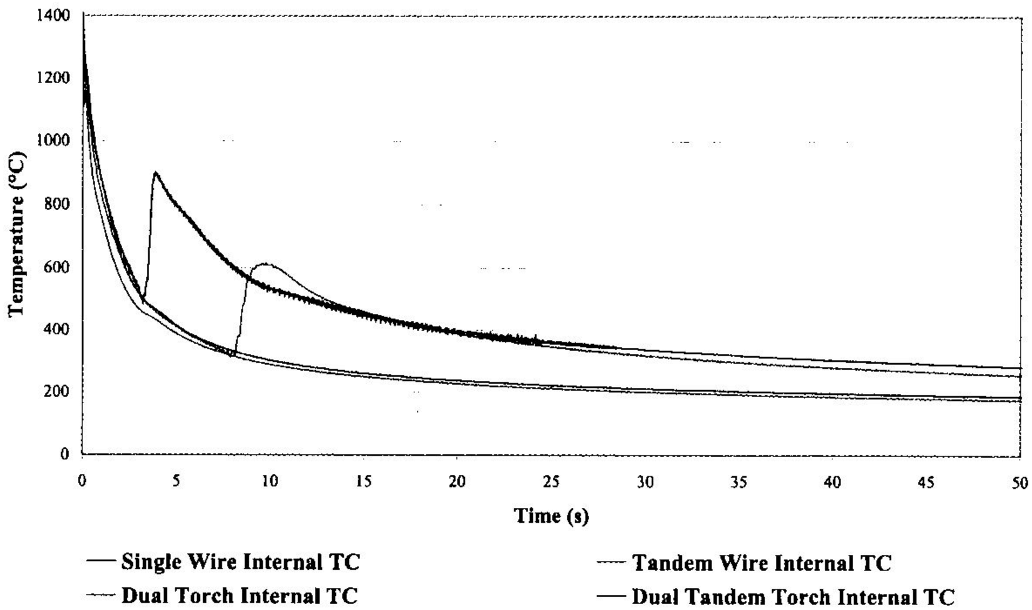


Figure 35. **Cooling Curves for an Internal Thermocouple with Various GMAW Pipline Welding Systems**

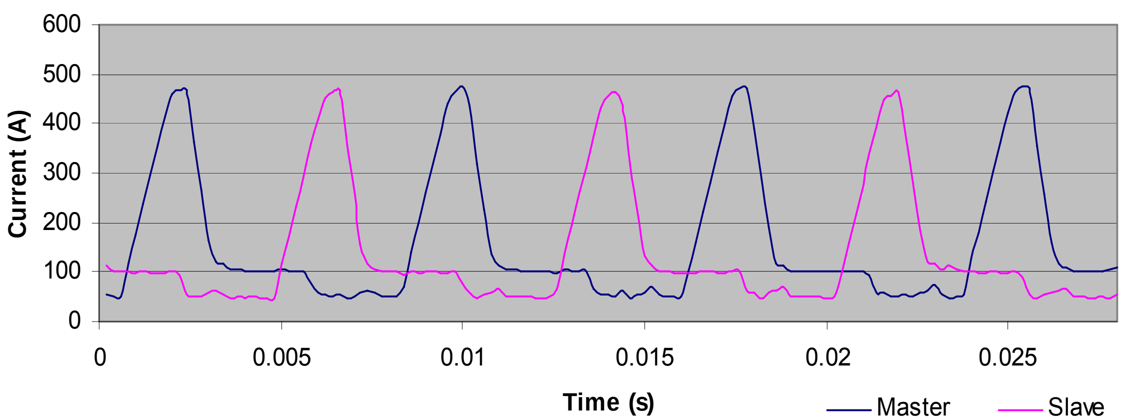


Figure 36. **Tandem GMAW-P Waveforms with Synchronized Power Sources**

Figure 37. Automated Tandem GMAW for Al Panels (courtesy of Cloos, U.K.)

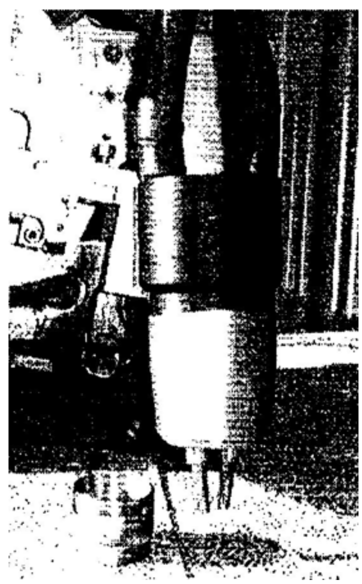


Figure 38. Lightweight Tandem GMAW Torch on Pipeline Welding Bug

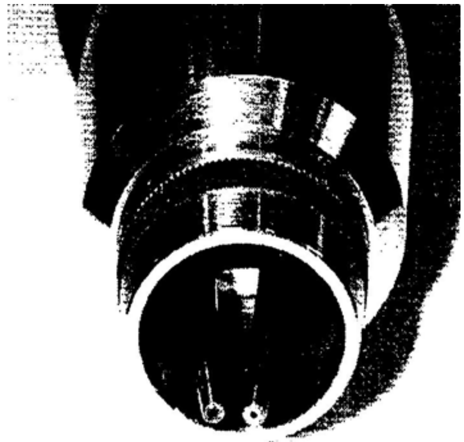


Figure 39. Cranfield Tandem GMAW Torch

Figure 40. Spacing of CAPs Dual-Tandem Welding Torches

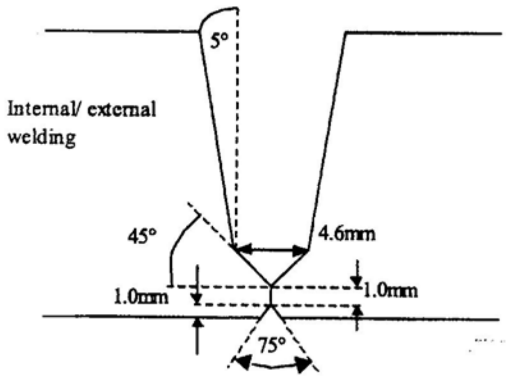


Figure 41. Narrow Gap Bevel Geometry

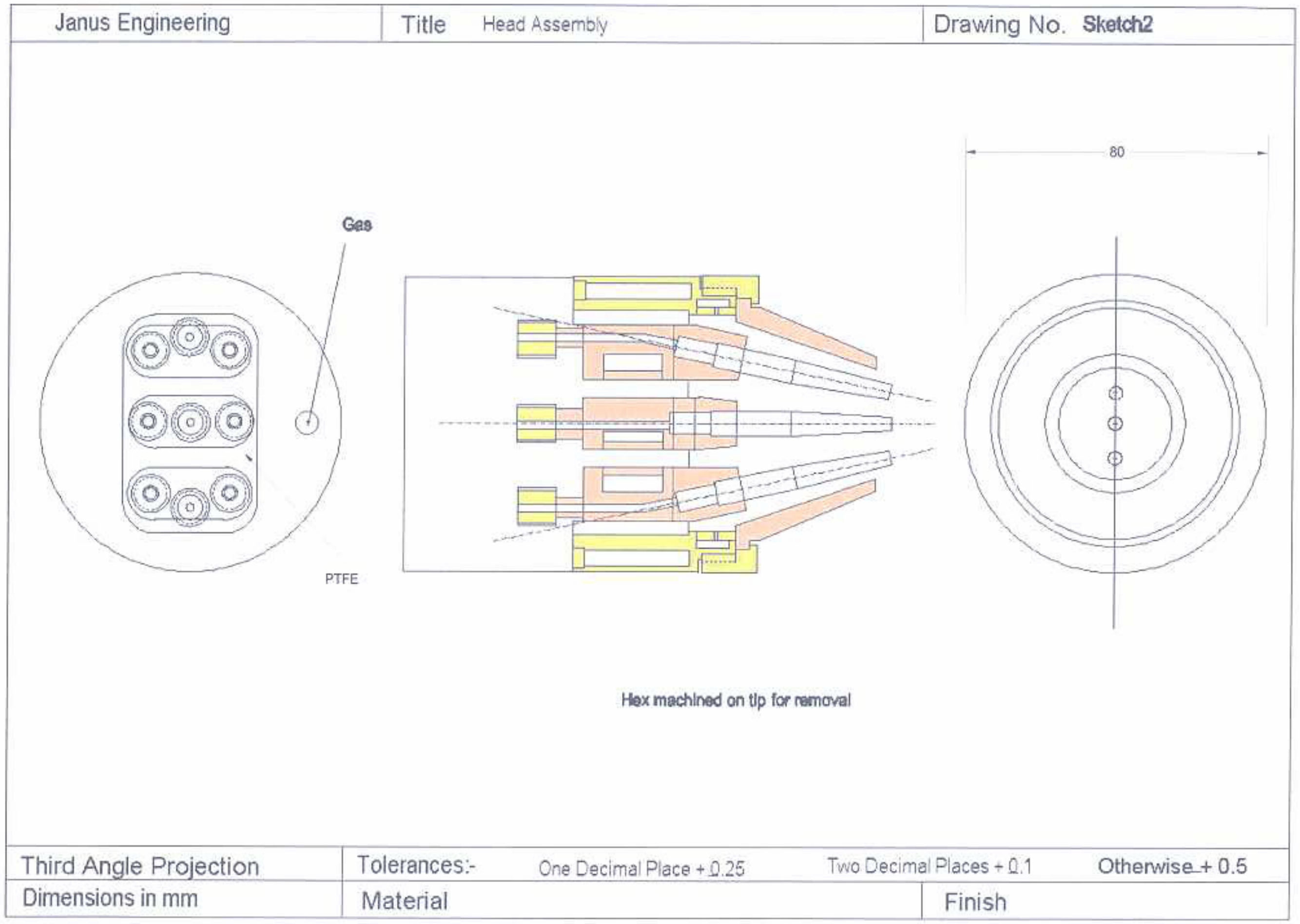


Figure 42. Head Assembly

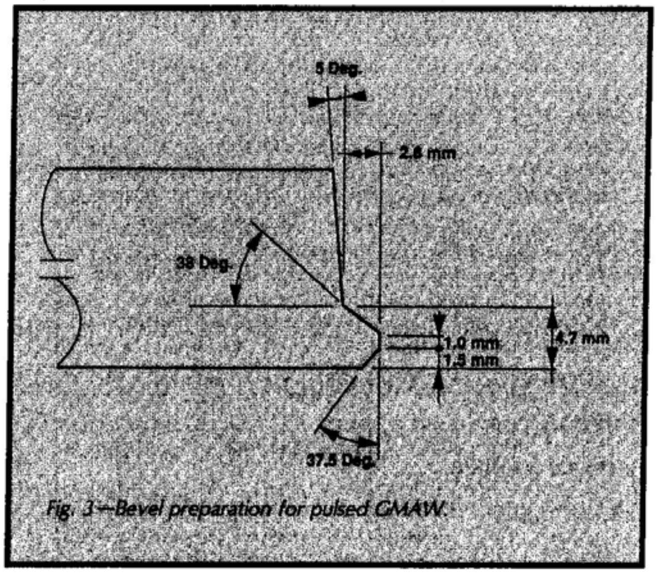


Figure 43. Bevel Preparation for GMAW-P

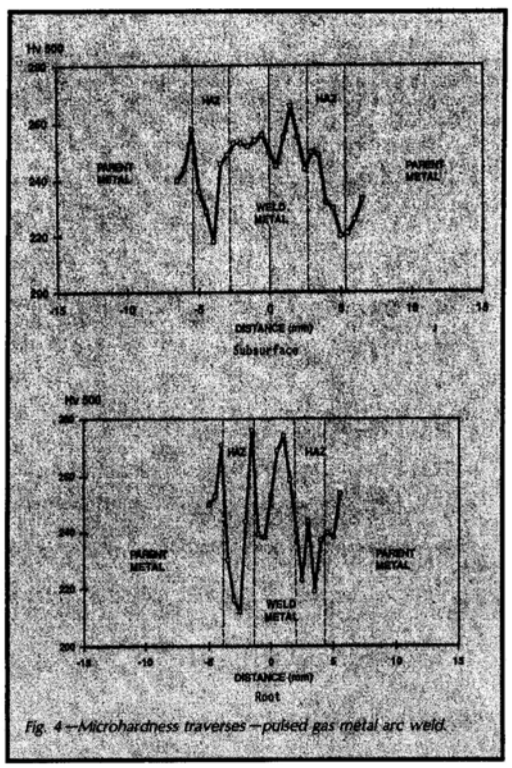


Figure 44. Microhardness Traverses – GMAW-P

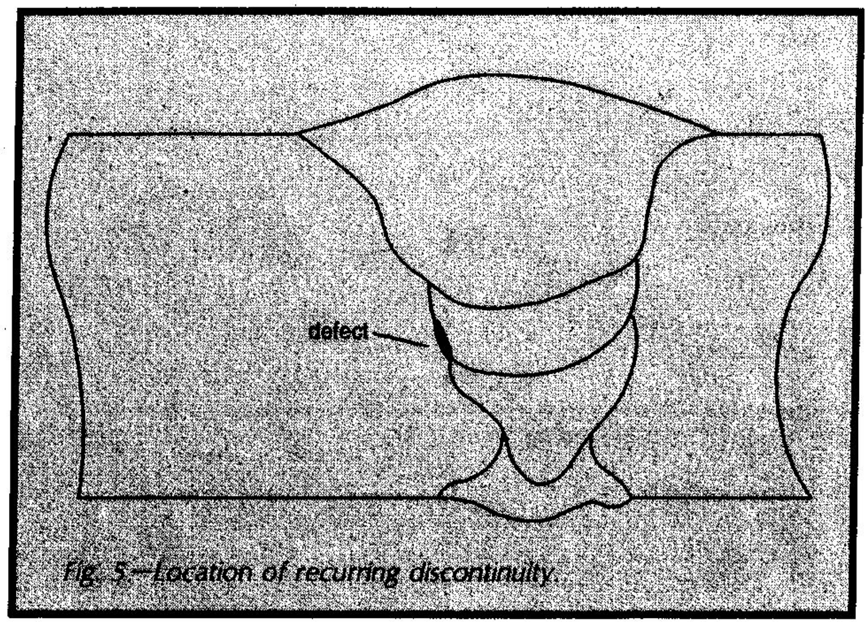


Figure 45. Location of Recurring Discontinuity

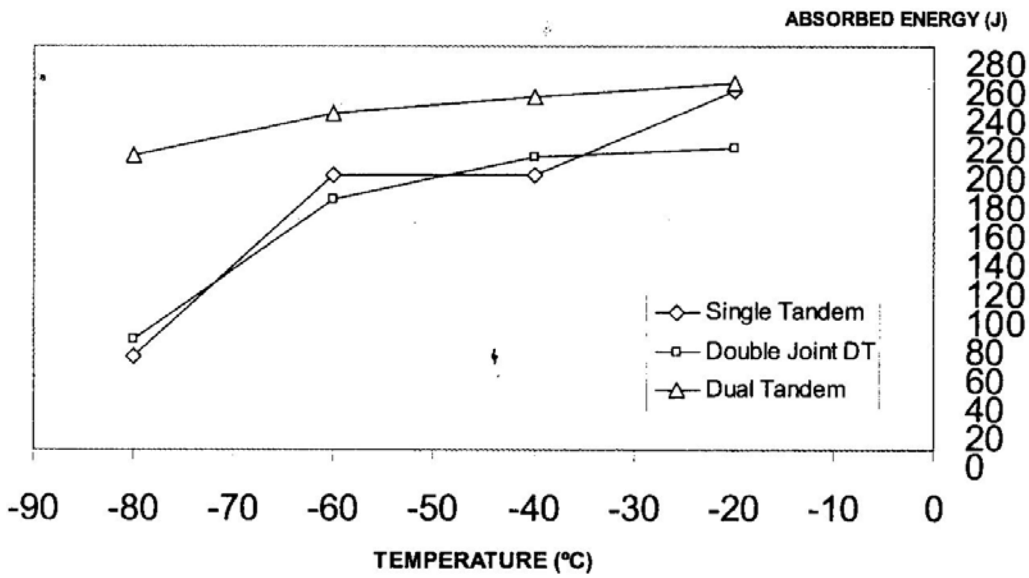


Figure 46. Average Charpy Impact Values for Weld Metal Root

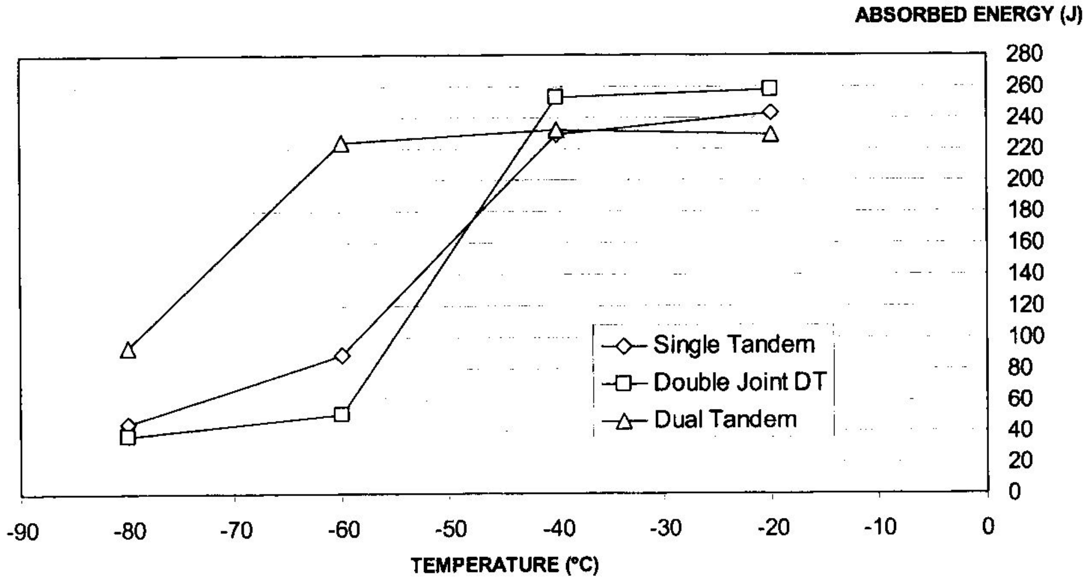


Figure 47. **Average Charpy Impact Values for Fusion Line Root**

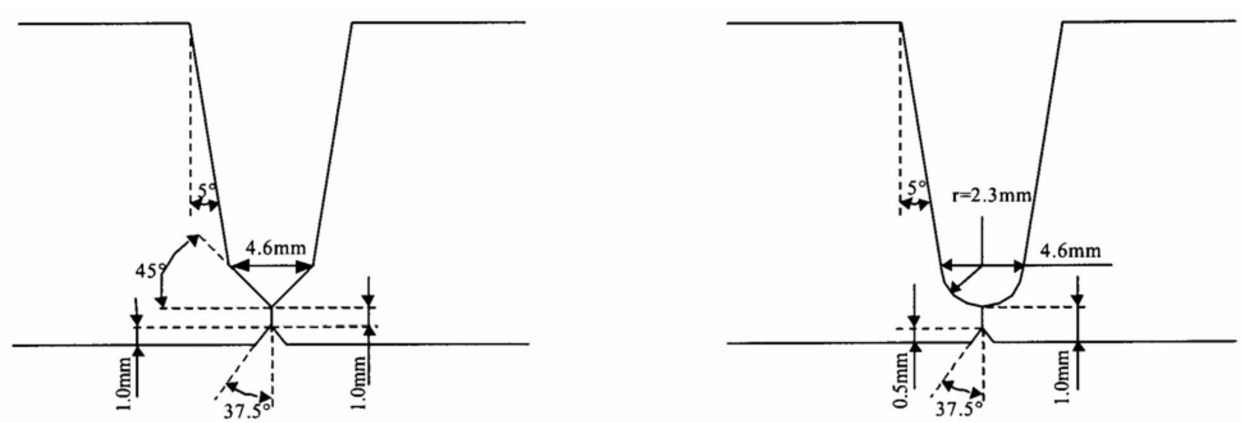


Figure 48. **Narrow-Gap Preparations for Internal/External Welding and All-External Welding**

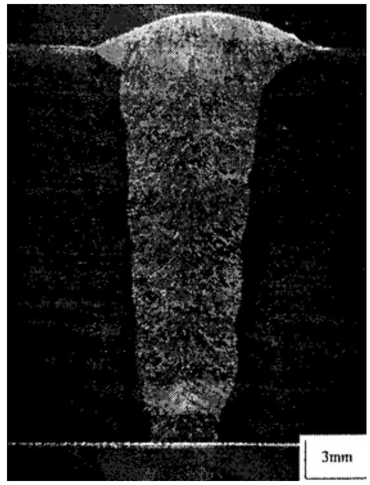


Figure 49. Typical All-External Mechanized Weld Macrosection

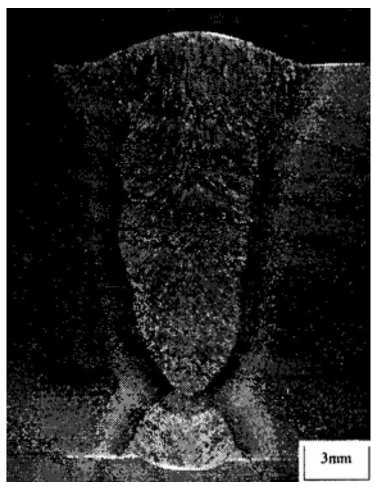
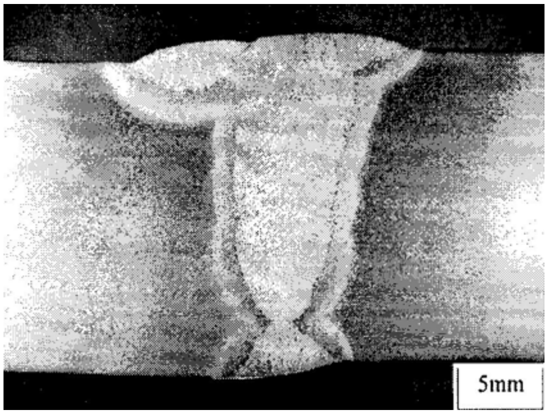
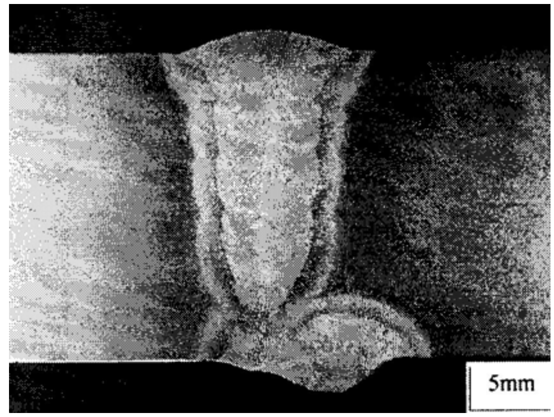


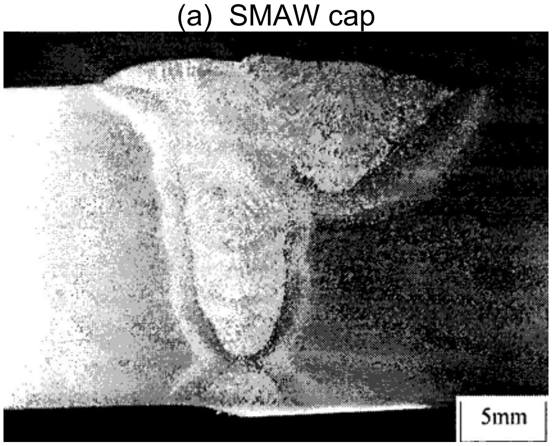
Figure 50. Typical Internal/External Mechanized Weld Macrosection



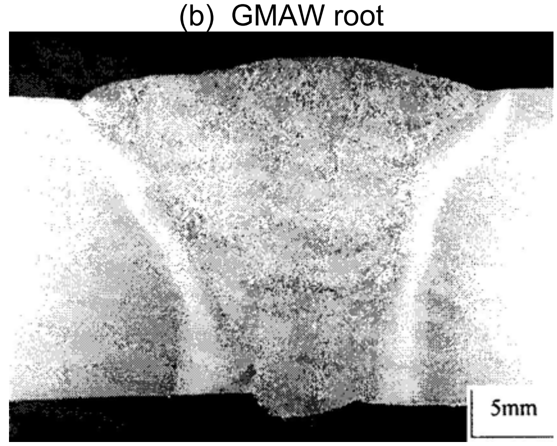
(a) SMAW cap



(b) GMAW root



(c) FCAW cap



(d) SMAW/FCAW full-penetration repair

Figure 51. Repair Procedure Macros

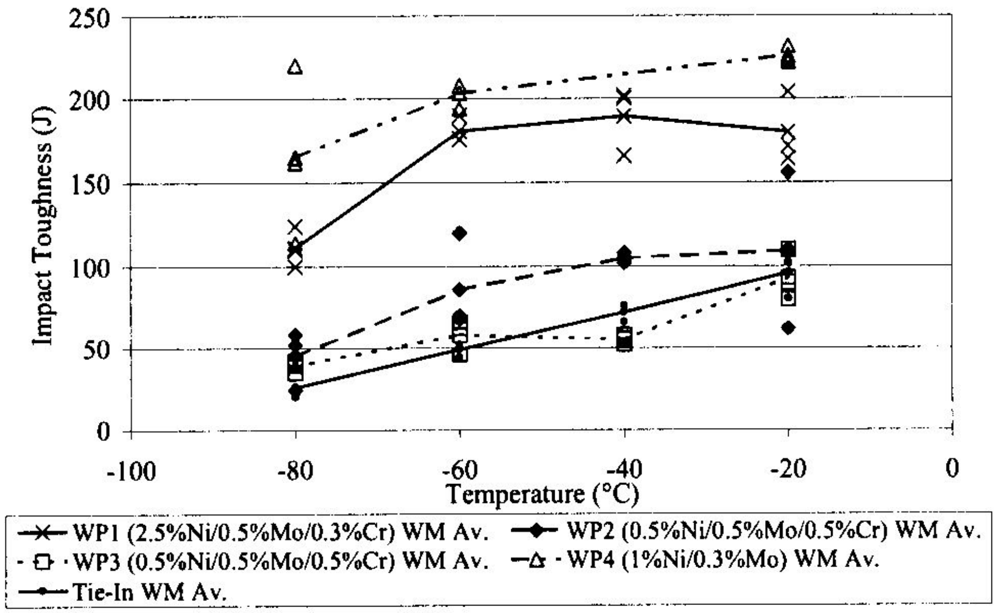


Figure 52. Weld Metal Impact Toughness

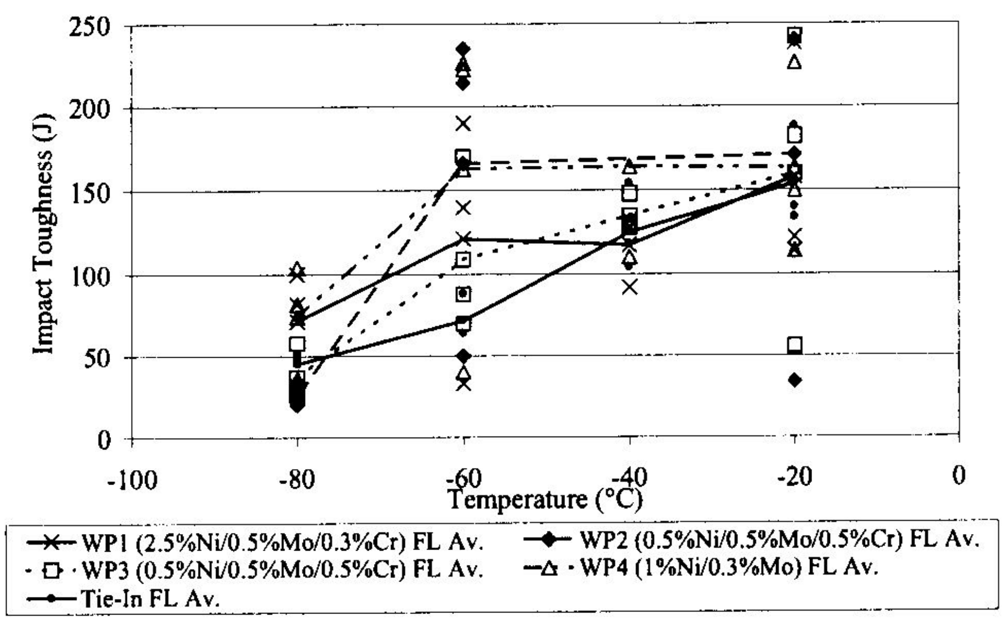
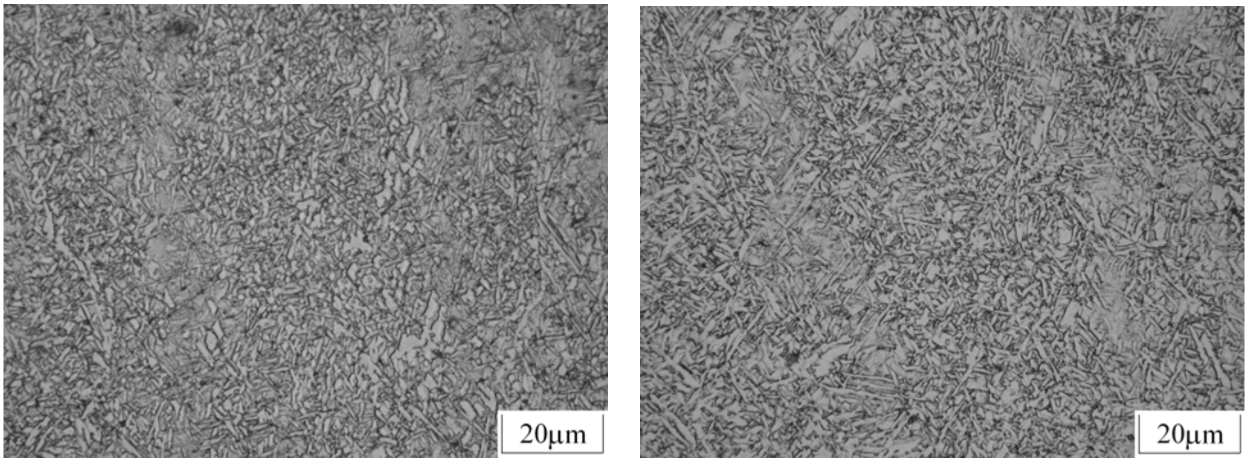
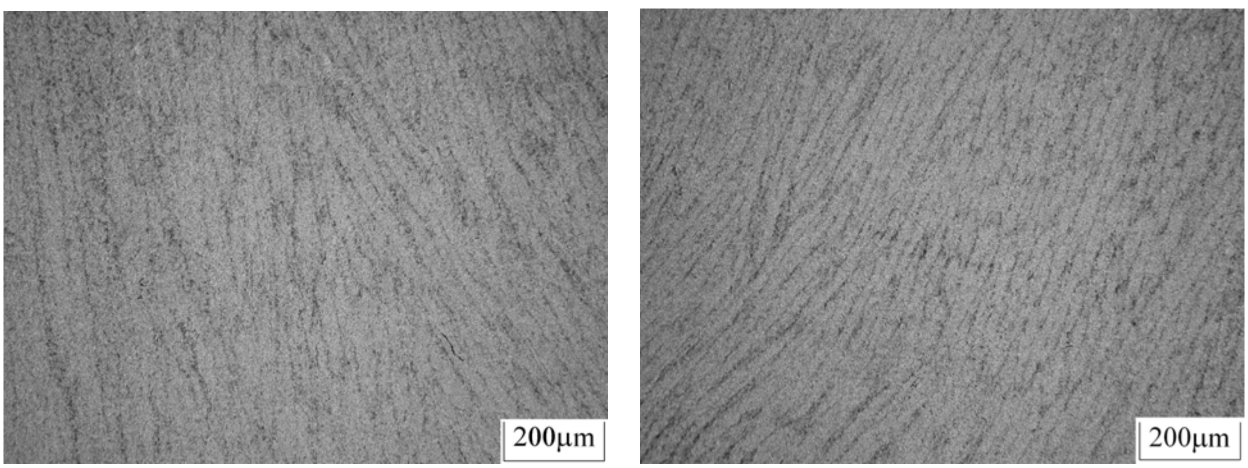


Figure 53. Fusion Line Impact Toughness



(a) (b)

Figure 54. Comparison of (a) Metal-Cored and (b) Solid Wire Cap Pass Microstructures (0.9Ni-0.3Mo)



(a) (b)

Figure 55. Dark Field Micrographs Showing Prior Austenite Grain Size in Cap Pass (a) 0.9Ni 0.3Mo Metal-Cored Wire Control (b) 0.9Ni 0.3Mo Solid Wire

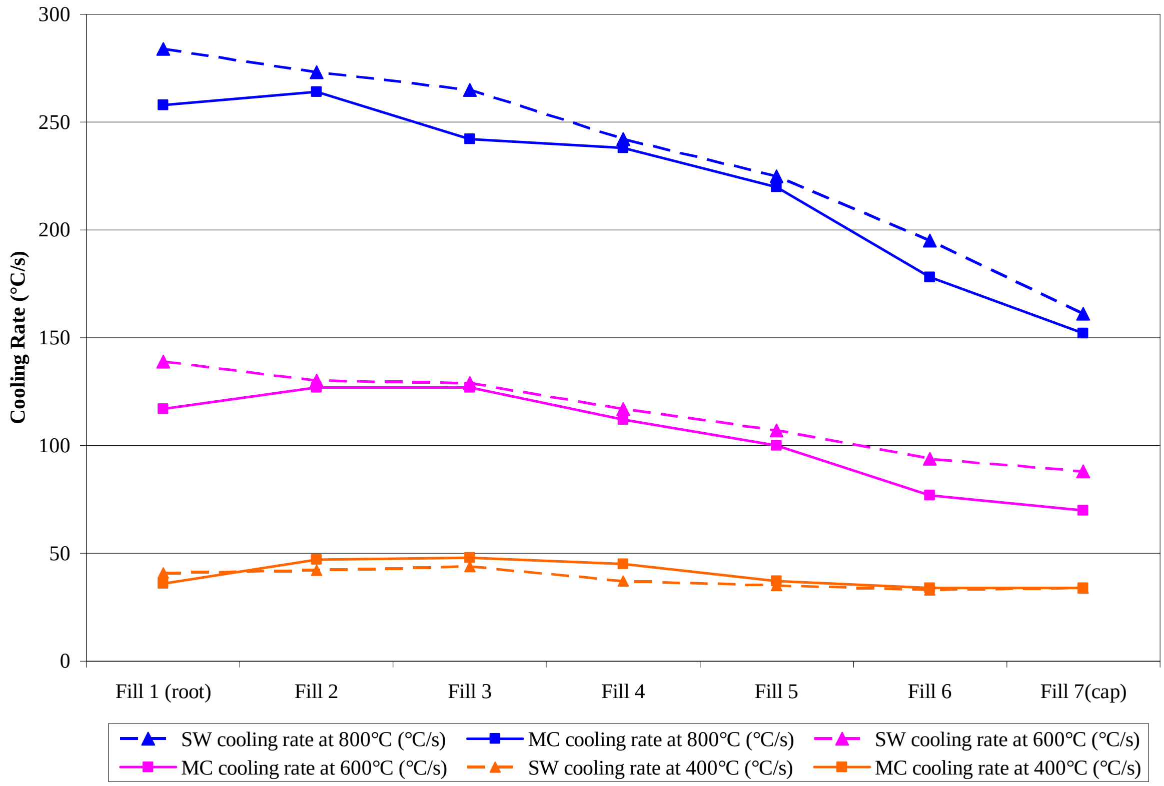


Figure 56. **Metal-Cored and Solid Wire Cooling Rate Comparison** (Baseline composition: 0.9Ni-0.3Mo)

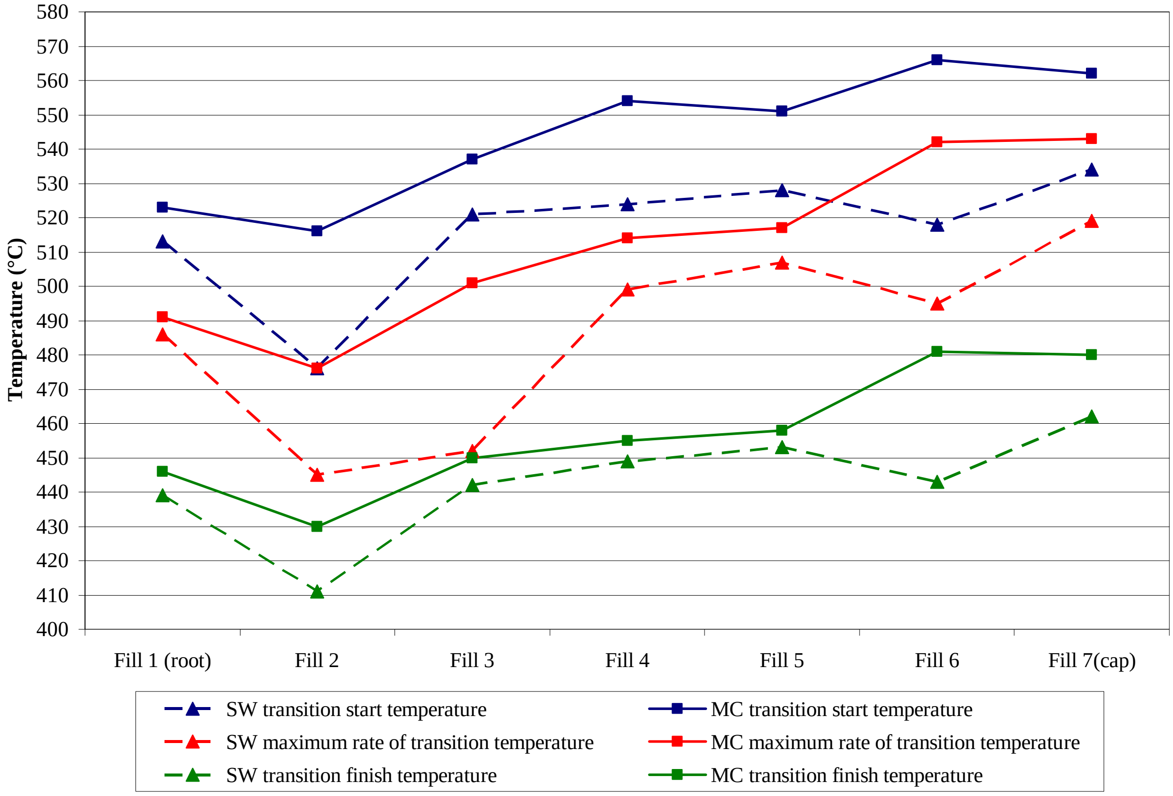


Figure 57. Metal-Cored and Solid Wire Transition Start, Finish, and Maximum Rate Temperature Comparison (Baseline composition: 0.9Ni-0.3Mo)

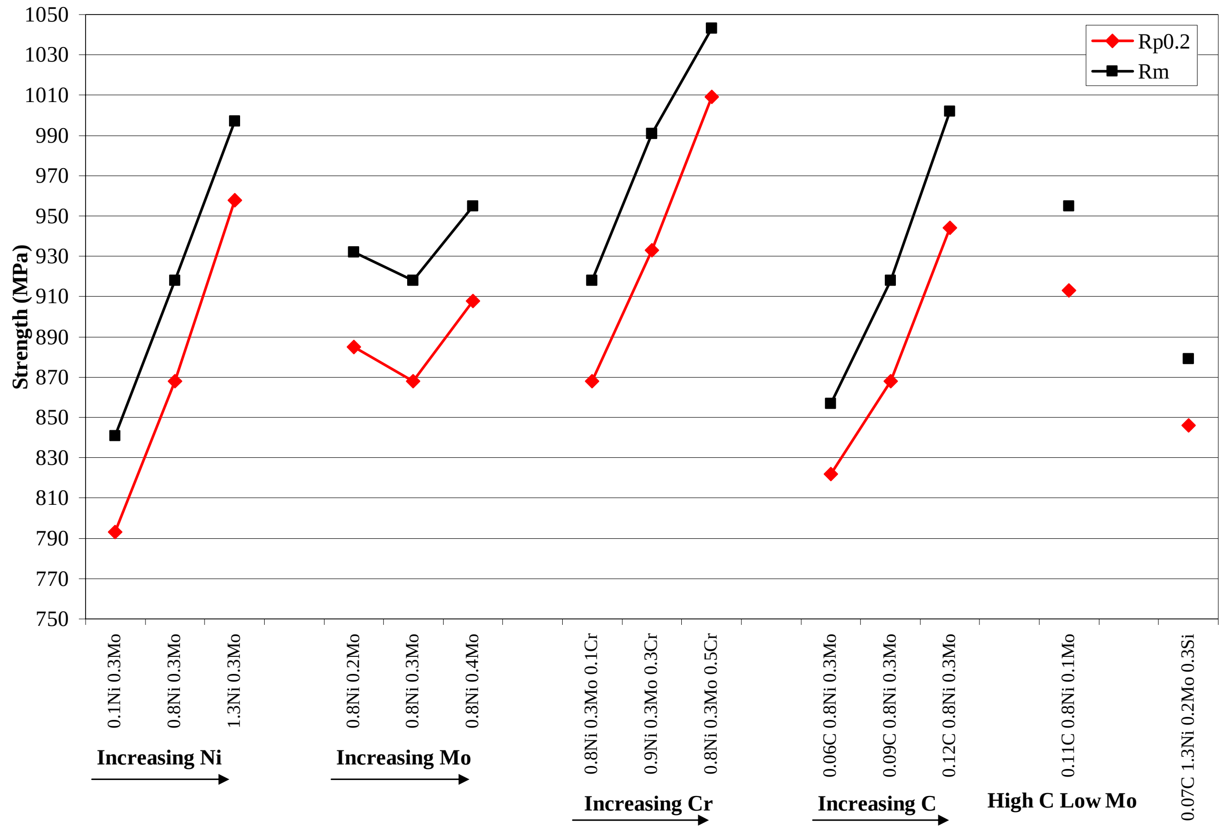


Figure 58. Metal-Cored Wire Alloy Effects on Strength

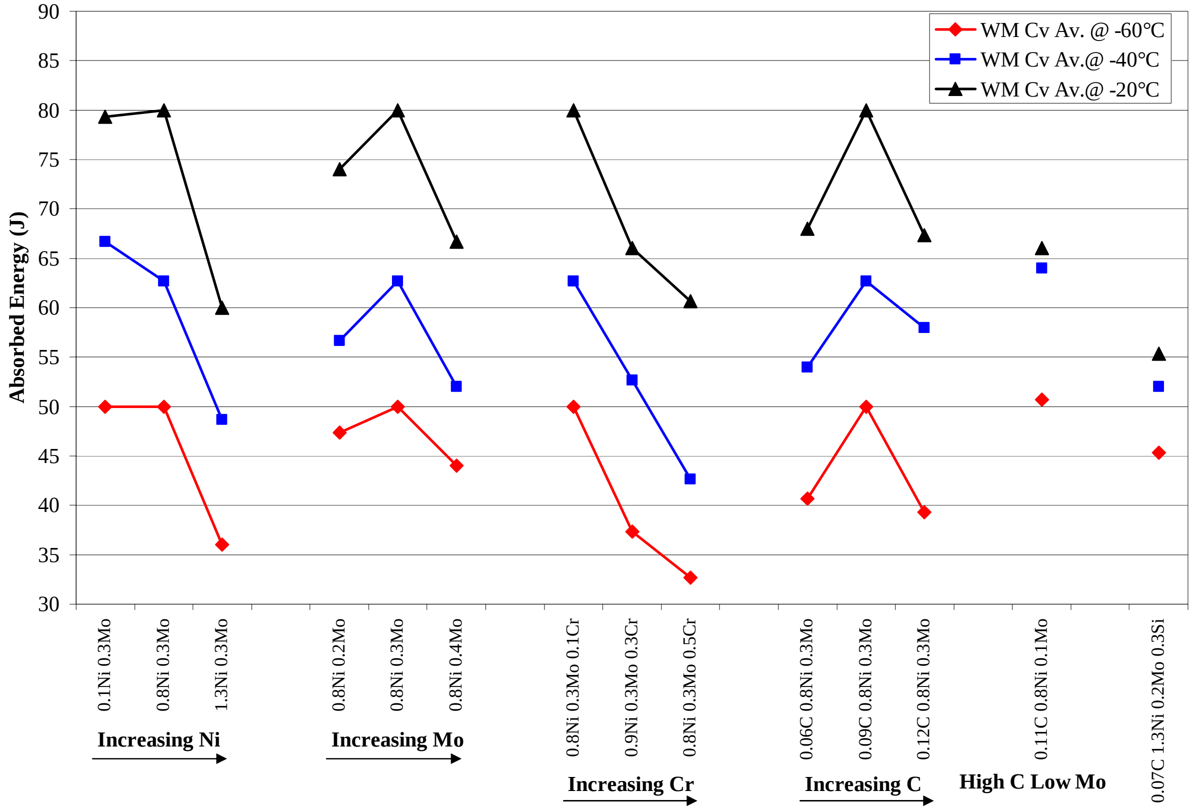


Figure 59. Metal-Cored Wire Alloy Effects on Impact Toughness

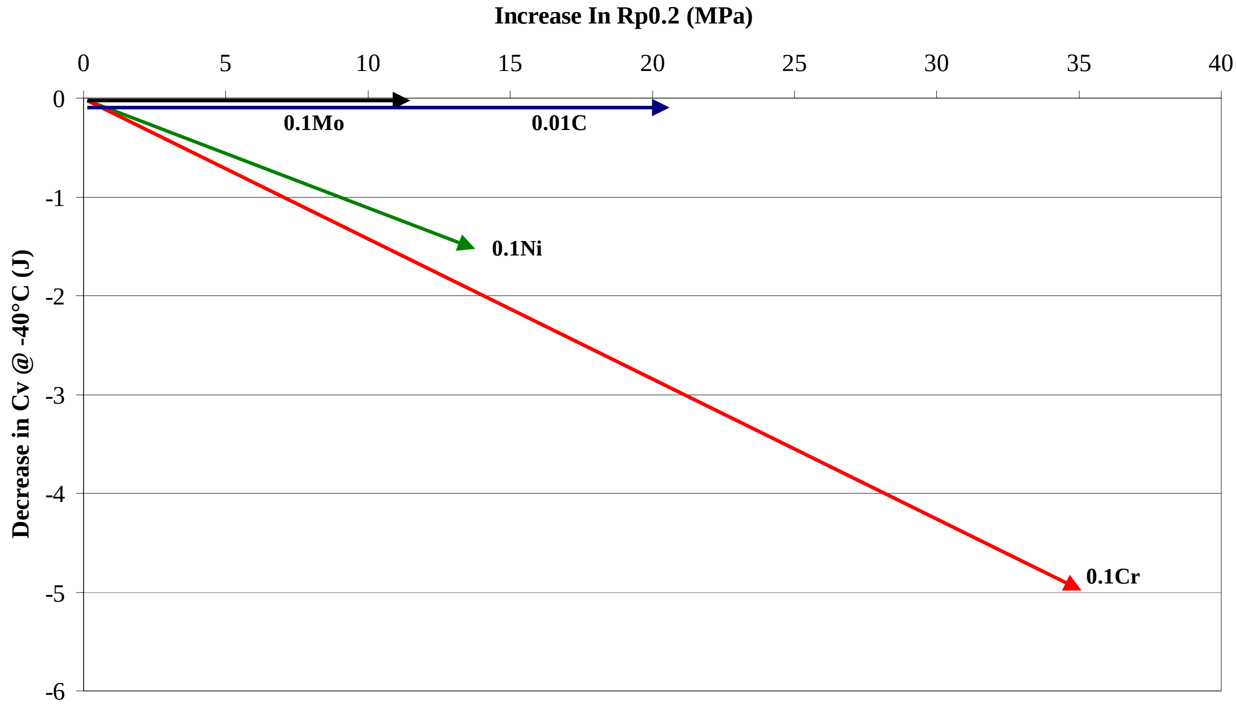
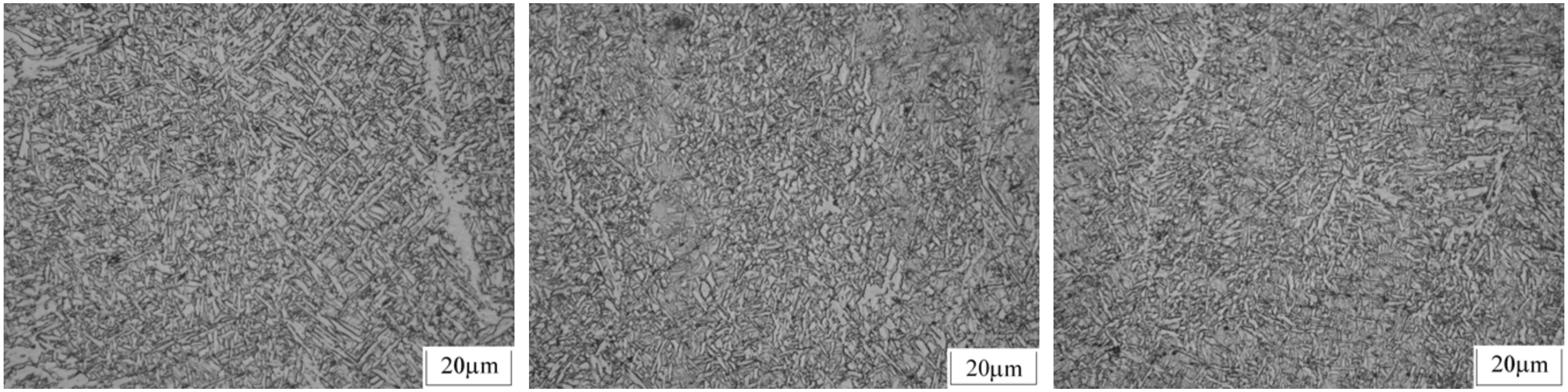
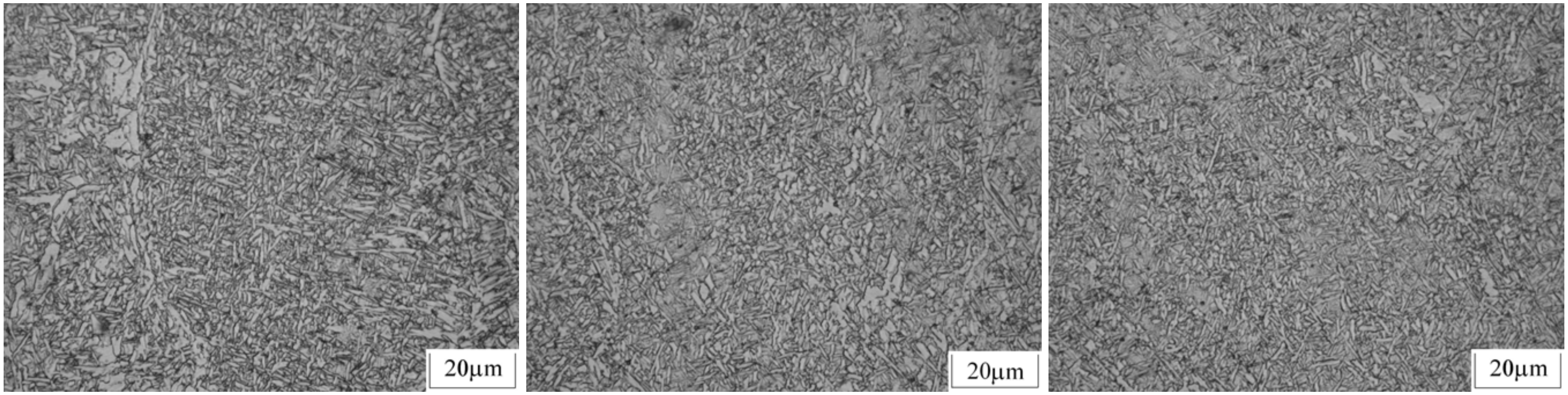


Figure 60. Influence of a Specified Weight Percentage Alloy Addition on Strength and Toughness



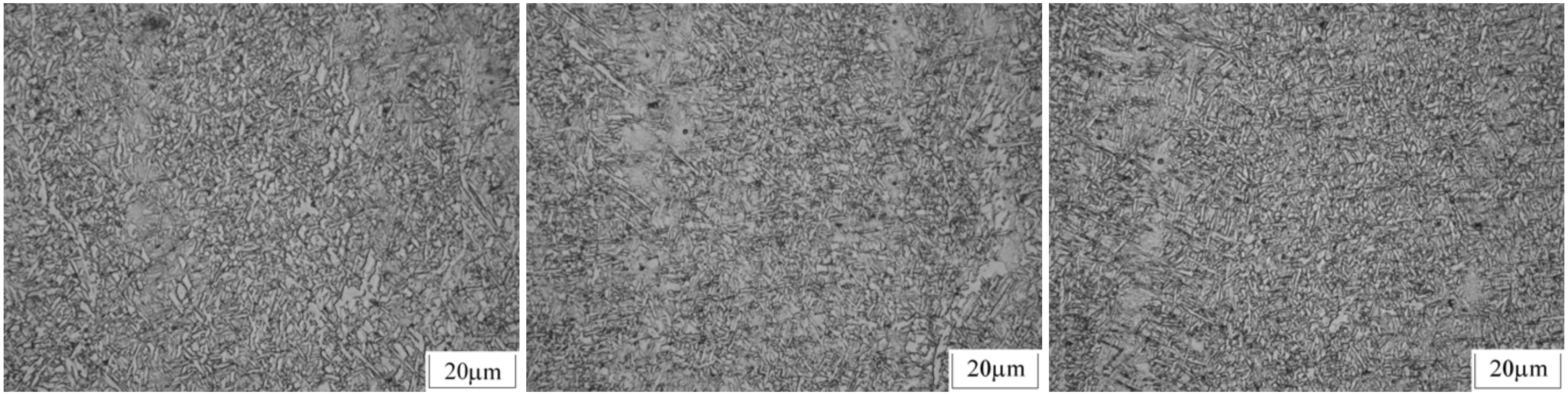
0.1 Ni | 0.8 Ni | 1.3 Ni

Figure 61. Metal-Cored Wire Cap Pass Microstructures – Effect of Increasing Ni



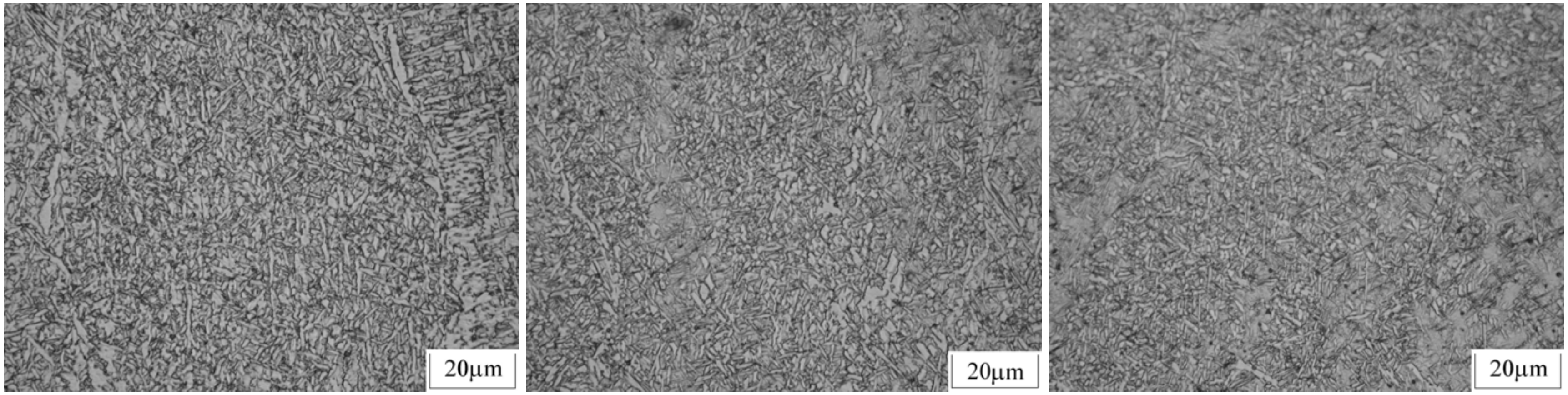
0.2 Mo 0.3 Mo 0.4 Mo

Figure 62. Metal-Cored Wire Cap Pass Microstructures – Effect of Increasing Mo



0.1 Cr 0.3 Cr 0.5 Cr

Figure 63. Metal-Cored Wire Cap Pass Microstructures – Effect of Increasing Cr



0.06 C 0.09 C 0.12 C

Figure 64. Metal-Cored Wire Cap Pass Microstructures – Effect of Increasing C

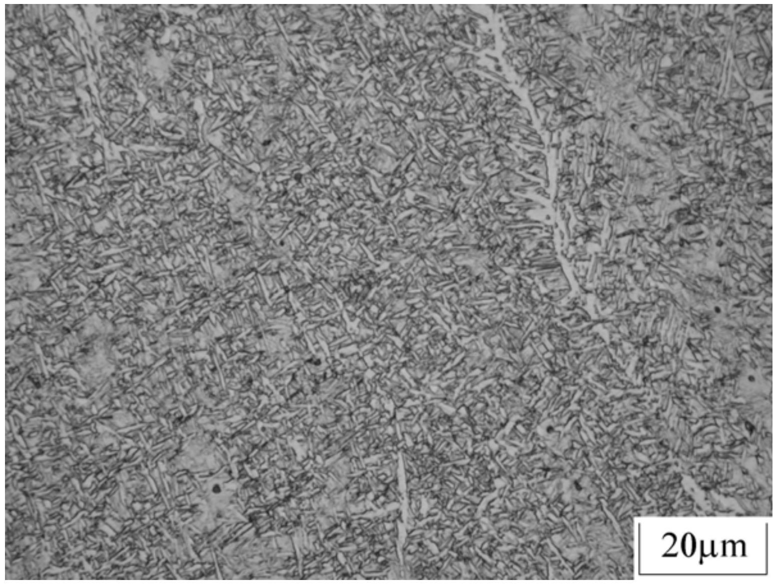


Figure 65. Metal-Cored Wire Cap Pass Microstructures - Multiple Alloy Variant Effects (0.11C-1.7Mn-0.5Si-0.8Ni-0.1Mo)

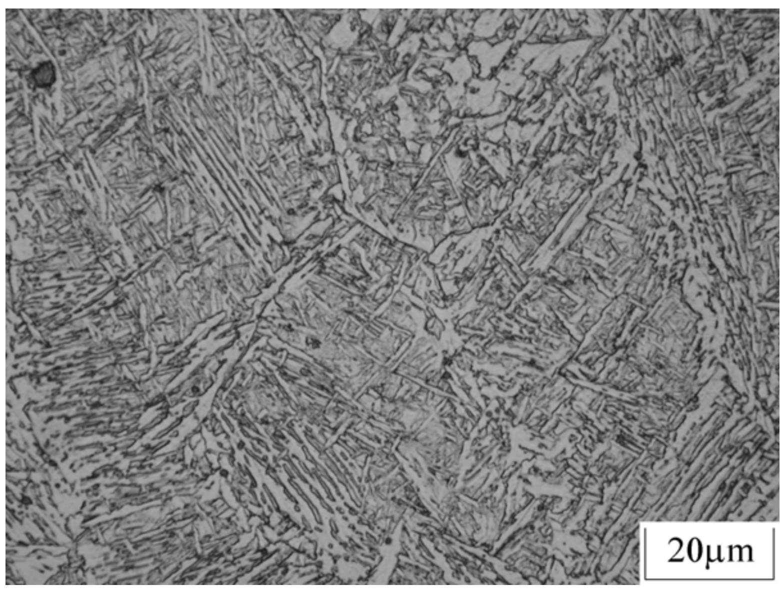


Figure 66. Metal-Cored Wire Cap Pass Microstructures - Multiple Alloy Variant Effects (0.07C-1.7Mn-0.3Si-1.3Ni-0.2Mo)