Qualification of ERW/HFI Manufactured Pipe For Wet, Sour Crude and Gas Services

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ABSTRACT

API 5L pipe manufactured with the Electric Resistance Weld (ERW) or High Frequency Induction (HFIW) welding processes offers considerable cost saving to the end user in place of similar seamless or Submerged Arc Welded (SAW) pipe. Historically, such pipe has never been fully trusted for full application by the oil and gas industry due to catastrophic failures in the field. No universally recognized industry standard exists for qualification of manufacturers of ERW/HFI pipe, and there is no robust standard for promoting a high level of quality and reliability of such a product. Saudi Aramco learned first hand the impact of such lack of product reliability with 10 field failures during hydrostatic testing of a newly constructed pipeline. The experience resulted in significant project delay and cost over run.

As a result of this experience, Saudi Aramco eventually developed an extremely comprehensive qualification and manufacturing specification for such pipe. The specification incorporates a statistically proven qualification procedure and a rigorous manufacturing process control regimen to maintain extremely high quality and mechanical properties of the ERW/HFI weld seam. At the same time, Saudi Aramco developed a proprietary computer program for the collection, manipulation, and reporting of qualification and production test data. Currently four such pipe manufacturers in the world are approved to manufacture pipe in accordance with the new specifications. Because of the greatly increased reliability of pipe produced to the new specification, Saudi Aramco has been able to consider the use of ERW/HFI manufactured pipe in applications which were considered more critical. As projects begin to utilize this new approach Saudi Aramco will be able to realize as much as $100/ton savings in the future.

1. INTRODUCTION

Electric Resistance Welded (ERW) pipe and High Frequency Induction Welded (HFIW) pipe are manufactured in accordance with API 5L. Both ERW and HFIW are commonly referenced as ERW. Both have been an attractive alternative to seamless pipe and Submerged Arc Welded (SAW) pipe due to lower production costs and greater availability. This is especially true for crude oil flow lines and trunk lines up to 26 inches in diameter. Saudi Aramco has used ERW pipe for many such applications within pipeline projects. However, in 1997 one such project experienced a significant number of ERW pipe failures during field hydro testing before final commissioning as shown in figures 1 and 2. This experience indicated that it was necessary for Saudi Aramco to improve the current requirements for ERW/HFIW line pipe. After several years of work with various pipe mills, and participation in a Joint Industry Project managed by The Welding Institute (TWI), a very detailed specification rationale was developed. The new specifications are now imposed on all new orders of ERW line pipe. So far three separate pipe companies have successfully qualified, using the new rationale, and the improvement in pipe quality and reliability has been extremely good. Although the current price of line pipe fluctuates, Saudi Aramco has realized a significant cost saving, through project and stock purchases, and drastically reduced the risk of failure during service. This improved performance has enabled Saudi Aramco to begin safely expanding ERW usage to some services previously restricted to seamless or SAW pipes.

2. HISTORICAL PERSPECTIVE

Earlier produced ERW piping was characterized in the 1980's by its susceptibility to grooving corrosion along the weld seam. These types of failures were also experienced by Saudi Aramco in water services such as water injection or fire water as shown in figures 3 and 4. In general, grooving corrosion was attributed to excessive sulfur content along the weld seam and inadequate normalizing practice of the weld seam. Grooving corrosion in water service is no longer a concern due to lower sulfur levels in the steel and improved normalizing practice. However, some failures have still been experienced which are related to lack of process control during the edge preparation, welding process, and normalizing process as shown in figures 5 and 6. The arrows indicate areas in the failed weld seam with lack-of-fusion and/or oxides commonly referred to as penetrators. The degree of process variation experienced was either due to momentary equipment failures or was endemic generally to the manufacturing practice of the specific pipe mill. There is no internationally recognized standard or code which adequately controls the qualification and manufacturing at individual ERW pipe mills. Therefore, the overall effectiveness of the manufacturing process control depends chiefly upon the dedication, experience, and determination of the individual pipe mill in question. TWI has, on several occasions, attempted to further characterize ERW pipe for sour service applications, but has found that significant variations in product quality still exist throughout the industry. Therefore, it has been incumbent upon the end user to devise a rationale to control the usage of ERW pipe thereby reducing any risk of catastrophic and costly failures during service. The recent developmental work done by Saudi Aramco, in partnership with TWI and several Saudi Aramco approved suppliers, has resulted in a qualification and process control rationale which can be specified in general without being specifically designed for each individual pipe mill.

3. NEW PERFORMANCE MANDATE

During the mid-to-late 1990's Saudi Aramco required much greater reliability in its line pipe for sour crude production. Saudi Aramco also began to plan for producing of high pressure (greater than 1000 psi), wet, sour, gas in support of a Kingdom developmental directive, and to support corporation requirements for pipeline safety. In order to benefit from the cost effective nature of ERW/HFI pipe usage the quality and reliability of ERW pipe needed to be greatly improved. This included expanding the use of ERW pipe into high pressure, wet, sour, Khuff gas production which was previously limited to seamless or SAW pipe for service over 1000 psi.

4. IMPROVED PIPE SPECIFICATIONS

Saudi Aramco specifications for ERW line pipe are now based upon ISO 3183 rather than API 5L. The manufacturing process must be controlled within the requirements of Saudi Aramco defined Continuous Electronic Process Control (CEPC), levels 2 or 3, as listed below.

CEPC level 2 – Continuous monitoring and recording of heat input variables (voltage, current, line speed) and seam annealing variables (annealing temperature and line speed) with alarm and automatic pipe marking for upset conditions outside of the qualified process limits (See Figures 7 - 10).

CEPC level 3 – Continuous monitoring and recording of heat input variables (voltage, current, line speed) and seam annealing variables (annealing temperature and line speed) with alarm and automatic pipe marking for upset conditions outside of the qualified process limits (See Figures 7 - 10). In addition, squeeze roll force, related to distortion angle shall be monitored and recorded.

Company specification for High Frequency Welded Line Pipe, Class A
For non-hydrocarbon service

Company specification for High Frequency Welded Line Pipe, Class B
For liquid hydrocarbon and sweet dry gas service

Company specification for High Frequency Welded Line Pipe, Class C
For wet, sour gas with a MAOP of 1000 psi or less

Above ground piping restrictions do not currently permit ERW pipe for the following services:

1. ASME B31.3 plant piping
2. Any offshore piping
3. Khuff Gas or any other wet, sour gas service with a maximum allowable operating pressure above 1000 psig in any pipeline location Classes described by the Loss Prevention and Safety Dept.
4. Corrosive or sour gas, in pipeline Class 2, 3, or 4 locations or within 500 meters of plants and permanently manned facilities.

These restrictions had been increased to the above list after the major field hydro test failure described earlier. However, since the new specifications have resulted in greatly improved pipe quality the previous restrictions may be drastically reduced as experience grows. The main restrictions which will remain in effect will be in plant piping and pipelines in Class 3 and 4 locations to preclude the possibility of catastrophic failure in populated areas. If high quality ERW pipe can, in time, be shown to exhibit similar integrity and mechanical properties to seamless pipe it may be possible to reduce the restrictions further.

5. QUALIFICATION HIGHLIGHTS

The basic requirement is that each ERW/HFIW pipe manufacturer must qualify each combination of Diameter/Wall-Thickness/Strength-Grade. Major steps required for first time qualification are:

A. Submit a complete Manufacturing Procedure

This is based upon ISO 3183-2, Annex B.1 and also requires the strip mill to be identified. This includes a general description of manufacturing from steel making through pipe manufacture. It also includes the pipe mill Inspection and Test Plan (ITP) reflecting the requirements of Saudi Aramco specification 01-SAMSS-332 or -333. Each Manufacturing Procedure Qualification is reviewed by Saudi Aramco within five days from start of the order. Acceptance of any order is contingent upon approval by Saudi Aramco. The basic procedure qualification report includes:

1. All quality control testing sets required by company specifications

	Class B	Class C
Lot Size	100	50
Flattening Test	4 / Coil	4 / Coil
Hardness (Hv)	4 (sets of 3) 3 / Coil for qualification	4 (sets of 3) 3 / Coil for qualification
HAZ Width	4	4
Centerline FL - HAZ distance	4	4
Microstructure	4	1
CVN	3 sets of 3	3 sets of 3 (6 for qualification)
Grain Size	4	1
Metal flow angle	4 (4 / set)	3 / shift
Root Bend	N / A	3 / Coil
HIC	1 / heat (1st 3 / steel mill / PO)	1 / heat (1st 3 / steel mill / PO)
SSC (80% of SMYS, 90% for information purpose only)	N / A	6 / heat

2. Results from Hydrogen Induced Cracking testing (company specification); one test from the first three heats, per steel mill, applied to pipe purchase order.
3. Welding qualification as described in company specification, Annex B.3
4. Procedure describing process control method (CEPC). Control can be through CEPC, or traditional Statistical Process Control (SPC) with AQL (Average Quality Level) = 0.65, or a combination of both.

   a. Class A - Normal quality controls activity required by ISO 3183-1 (considered CEPC level 1)
   b. Class B - Normal quality controls activity required by ISO 3183-2, plus CEPC level 2.
   c. Class C - Normal quality controls activity required by ISO 3183-3, plus CEPC level 3, along with satisfactory track record of previous production to Class B.
5. Post-production control report for a previous order which normally includes typical SPC charts as in shown in figures 14 and 15.

B. Select the appropriate method for process control

Verifiable control of essential and process variables is required for all pipe produced. Slit strip shall not be used unless the Manufacturing Procedure documents the absence of harmful segregation and non-homogeneous structure in the slab and strip.

Essential welding variables are:

1. Pipe strength grade
2. Nominal diameter
3. Specified nominal wall thickness ± 1.0 mm
4. Operation within qualified process limits (See Figure 7, 10 and 11)
5. Contact tip/roller alloy composition (ERW only)
6. Induction coil configuration (HFIW only)
7. Impeder configuration (HFIW only)

Essential process variables are:

1. Heat Input Factor (function of wall thickness, voltage, current, temperature, and line speed) (See Figures 7 and 10)
2. Metal Flow Factor (distortion angle ÷ girth reduction at squeeze roll) (See Figures 7 - 10)
3. Seam annealing temperature (See Figure 11)
4. Seam anneal width at I.D. surface (See Figure 12)

C. Qualify supplier specific welding conditions by test on at least five coils (at least one pipe each)

Supplier qualifies their nominal welding and normalizing conditions, as shown in Figure 7 - 11, and the limits within which acceptable pipe can be manufactured. The results observed during qualification calculations in the software identify the expected variation during regular production. Calculated standard deviation, during qualification, can not be greater than 3.0 for acceptable manufacturing process control. Results also include hardness tests required by NACE MR0175 (2002), as shown in figure 13, and flattening tests modified to identify the point at which splitting begins in the weld seam as shown in figures 16 – 18.

D. Submit test results for Saudi Aramco approval

For first time qualification, results can be developed on any non-Aramco customer order without affecting production. Follow-on qualification, for a different Diameter/Wall-Thickness/Strength-Grade combination, can be done on the current order. Saudi Aramco must report approval status back to the pipe mill within five days after submittal.

E. Begin producing ordered pipe within qualified boundaries at nominal conditions

Pipe mill can continue producing pipe, after first time qualification, as soon as qualification samples are gathered. Risk to producer is that five days production is possible before obtaining Saudi Aramco approval.

F. Main process control features identify unacceptable production lots
   1. Sampling in accordance with ANSI/ASQC Z1.4, AQL = 0.65, represents the minimum quality level desired and maximum risk by Saudi Aramco.
   2. SPC charting, in accordance with ISO 8258, for reporting of lot process control throughout production, as shown in figures 14 and 15, for metal flow angle, weld seam normalizing width, flattening, and hardness.
   3. CEPC of voltage, current, line speed, and normalizing temperature to identify offsets during production for automatic rejection.
   4. Rationale for retesting of rejected lots of 100 pipes evaluates whether the difference between means and standard deviations of the lot and retesting is statistically significant (t-distribution and ?^{2} tests).

6. CONCLUSIONS

- The new ERW/HFIW pipe specifications developed by Saudi Aramco have provided a reliable framework for pipe manufacturers to produce high quality, reliable pipe. The specifications allow each pipe mill to choose their own discrete process conditions to which to qualify.
- This new qualification rationale will adequately restrict qualification to only those pipe mills which can exhibit adequate process control and traceability.
- ERW/HFIW pipe manufactured to the new specifications exhibit much better mechanical properties and a much more reliable weld seam than previously purchased pipe.
- Pipe manufactured to this new qualification rationale can exhibit mechanical properties, and reliability very similar to seamless pipe.
- The subject qualification rationale will be presented to API and ASME for adoption as an internationally recognized process for qualification of ERW/HFIW pipe manufacturers.

Figure 1 - API 5L X65 20 inch OD and 0.312 inch wall thickness which failed during field hydro-test

Figure 2 - API 5L X65 20 inch OD and 0.312 inch wall thickness which failed during field hydro-test

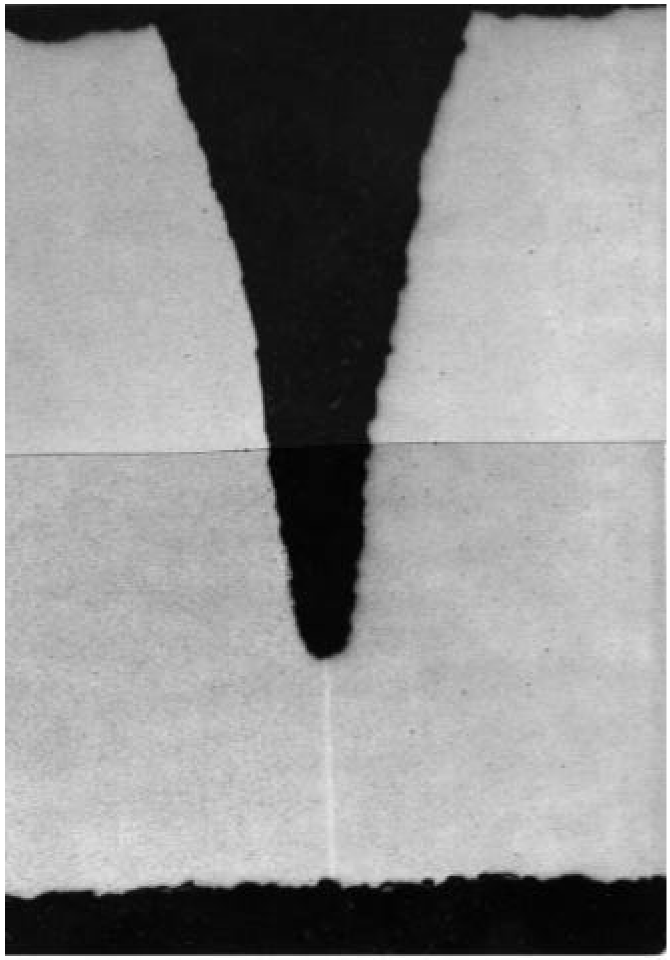


Figure 3 - API 5L Gr B 12 inch OD and 0.375 inch WT, produced prior to 1981, which failed due to grooving corrosion of the ERW weld seam

Figure 4 - API 5L Gr B 12 inch OD and 0.375 inch WT, produced prior to 1981, exhibiting varying degrees of grooving corrosion.

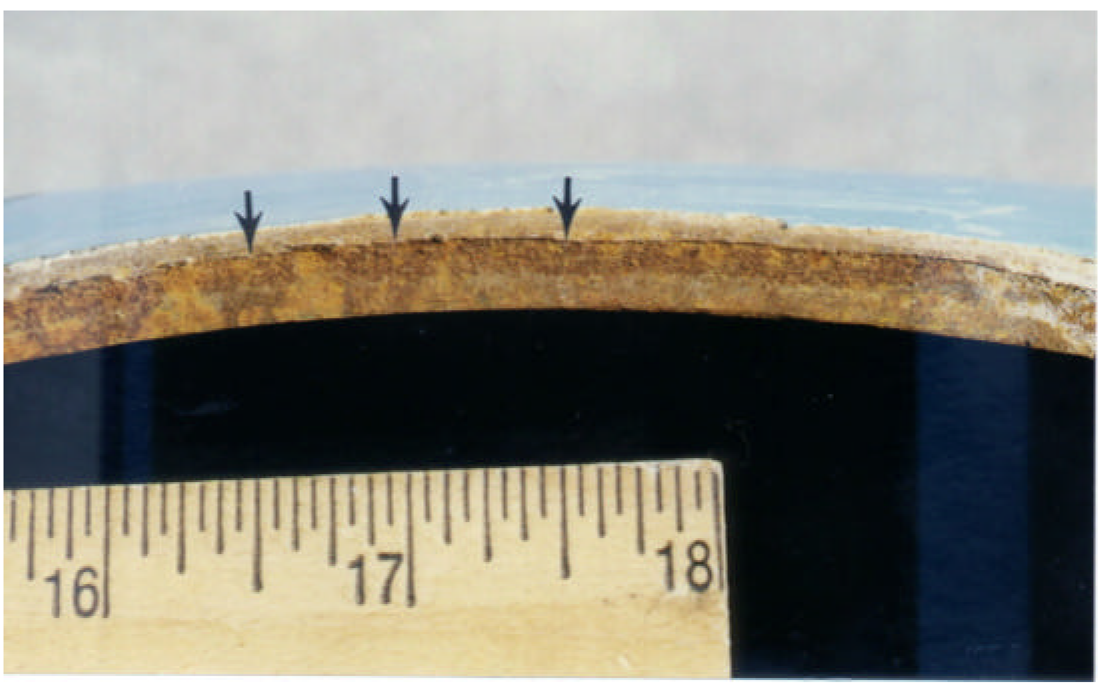


Figure 5 - API 5L X65 20 inch OD and 0.312 inch wall thickness which failed during field hydro-test

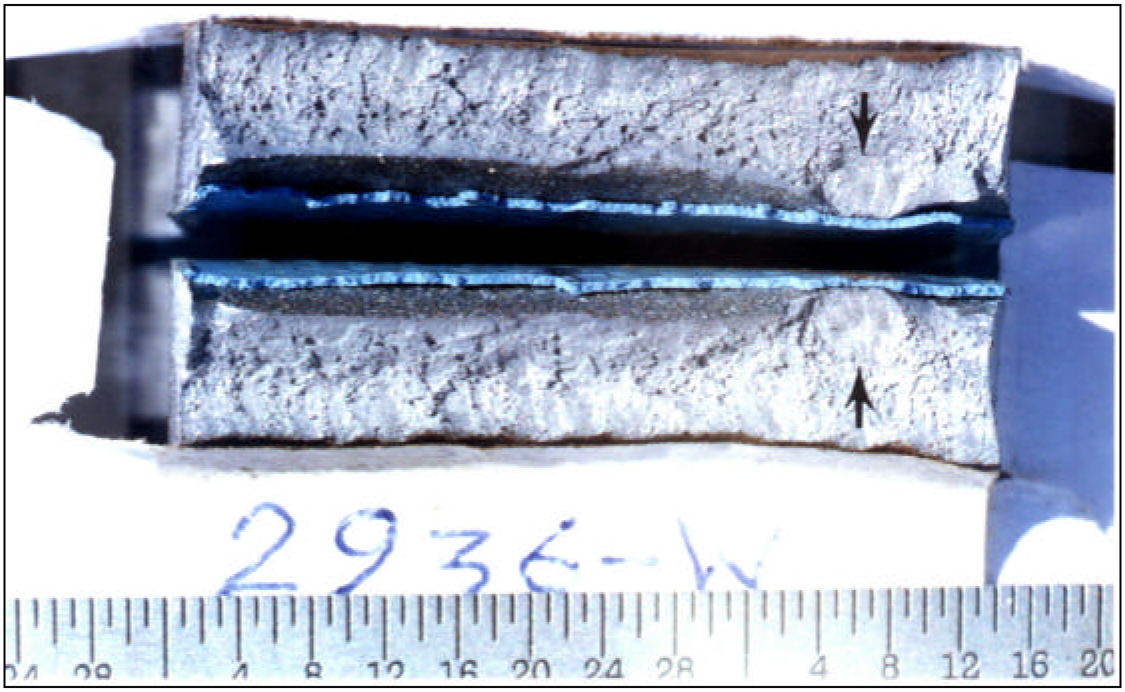


Figure 6 - API 5L X65 20 inch OD and 0.312 inch wall thickness which failed during field hydro-test

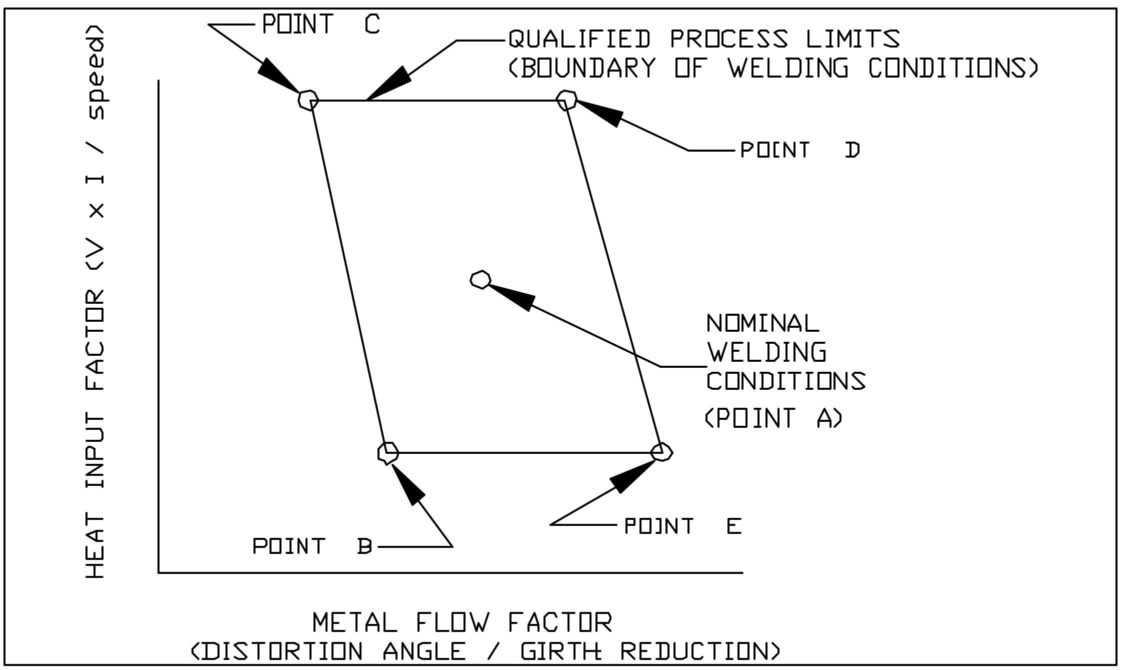


Figure 7 – General qualification boundary for ERW welding conditions

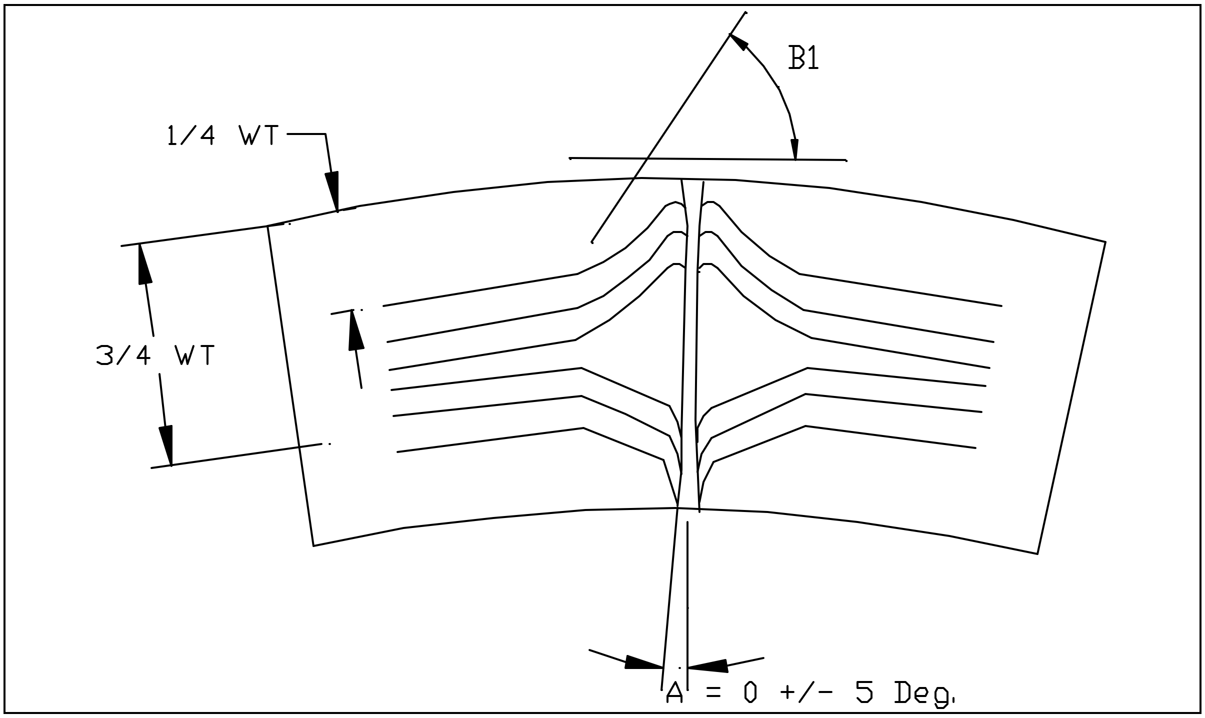


Figure 8 - Metal distortion angle measurement location

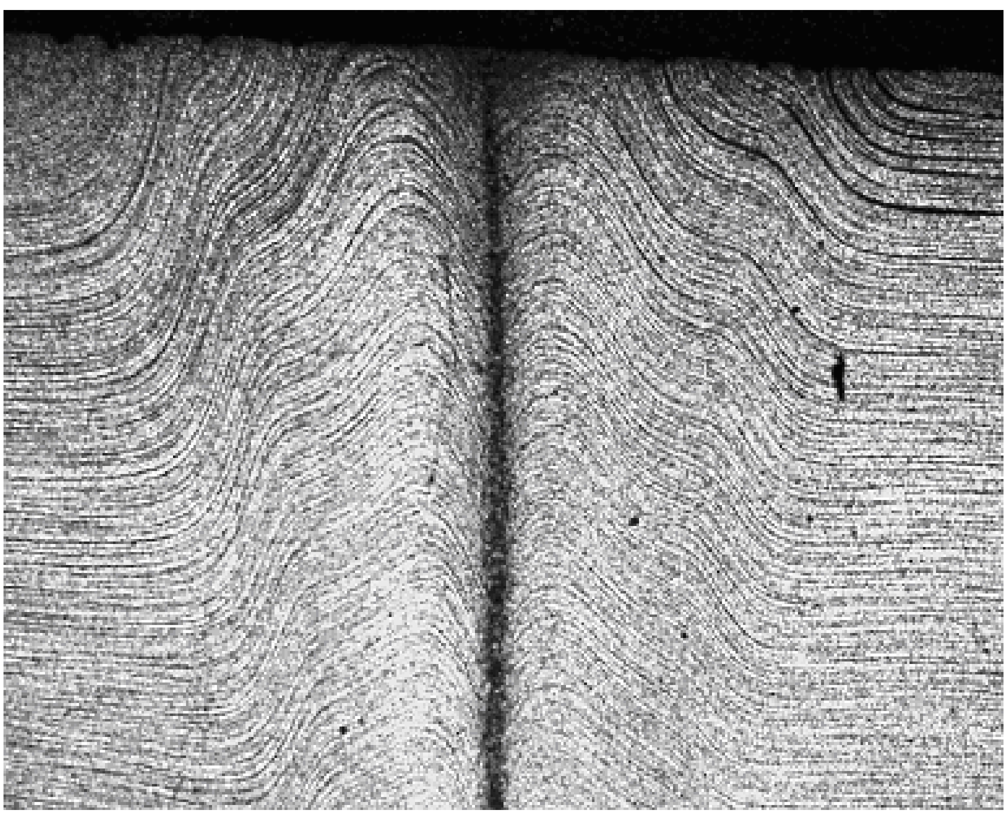


Figure 9 - Typical metal flow pattern for ERW weld seam at OD surface (Picral etch)

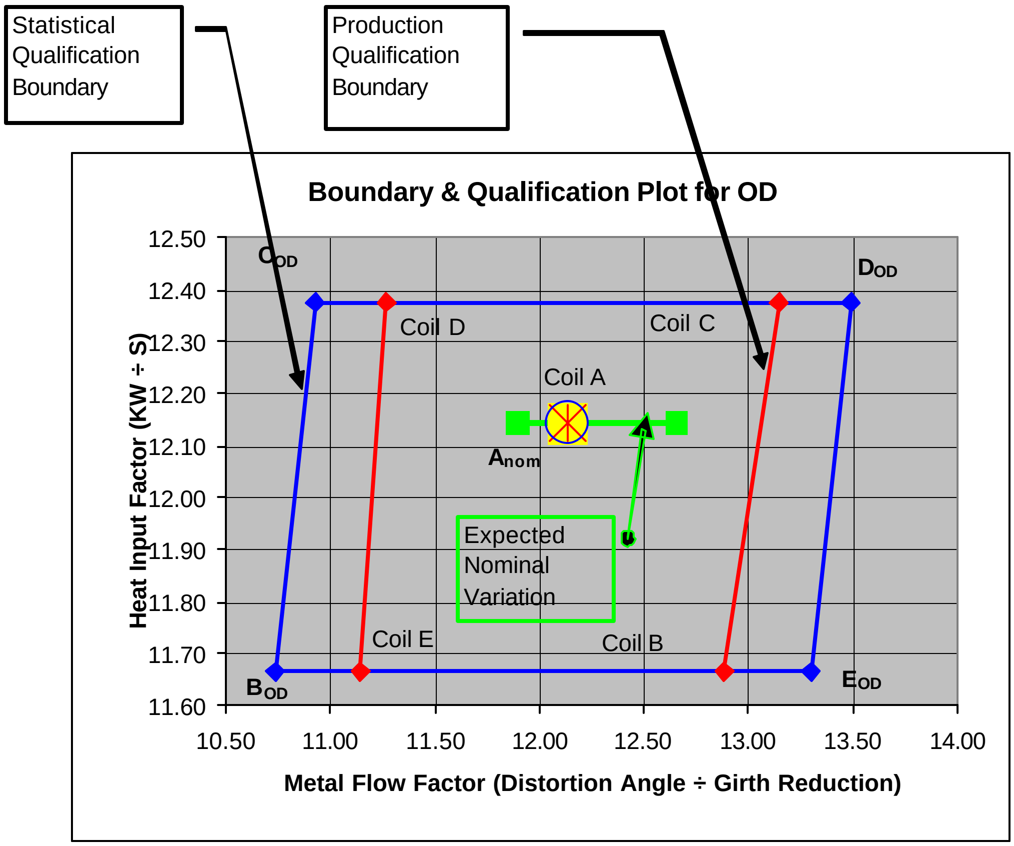


Figure 10 - Qualification boundary chart produced by software using actual production data

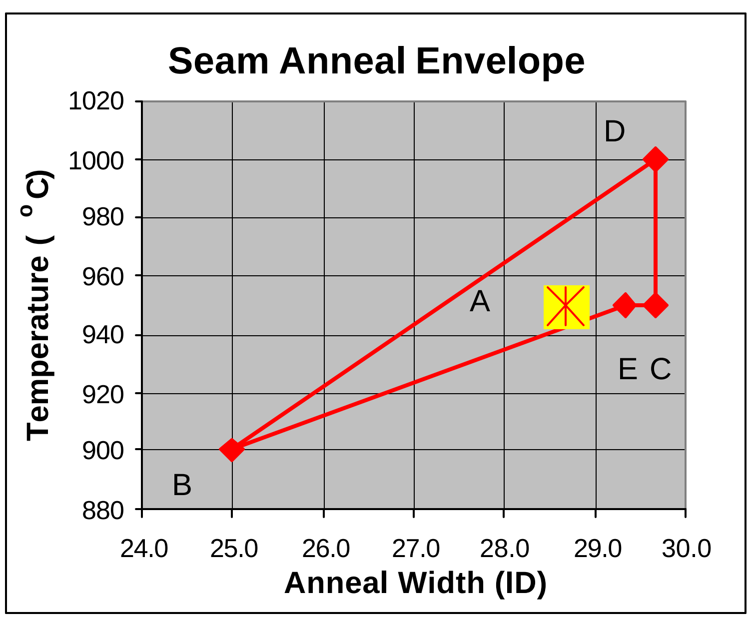


Figure 11 - Qualification boundary chart produced by software using actual production data

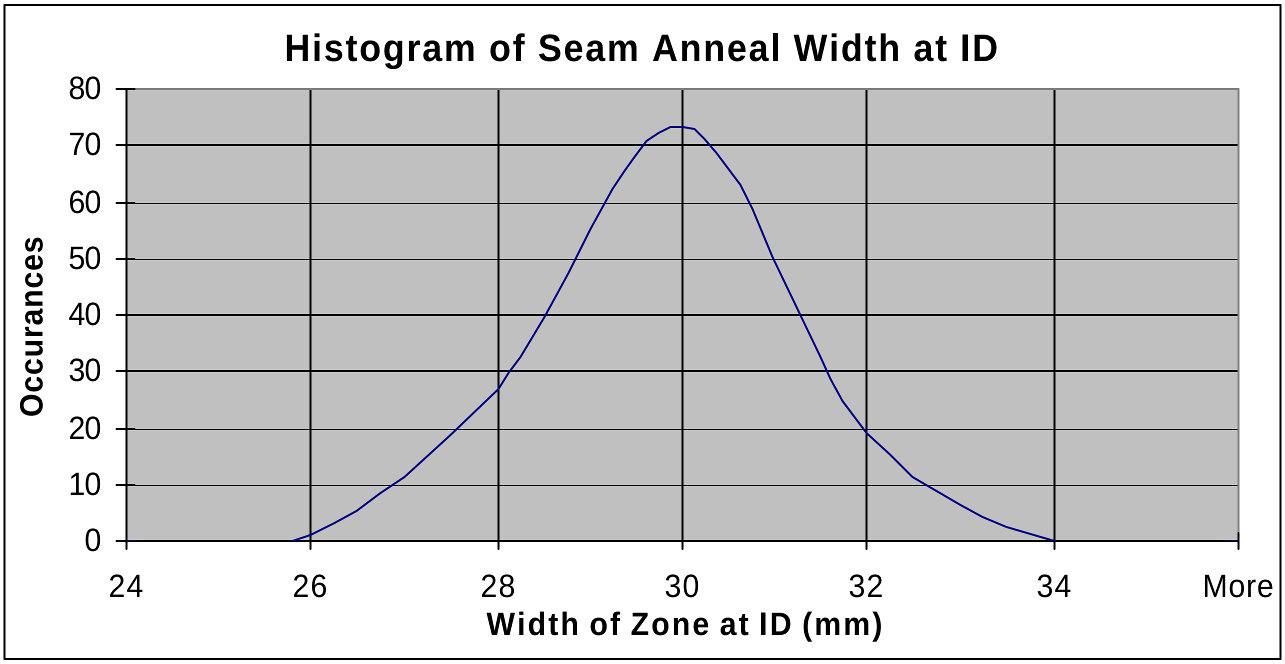
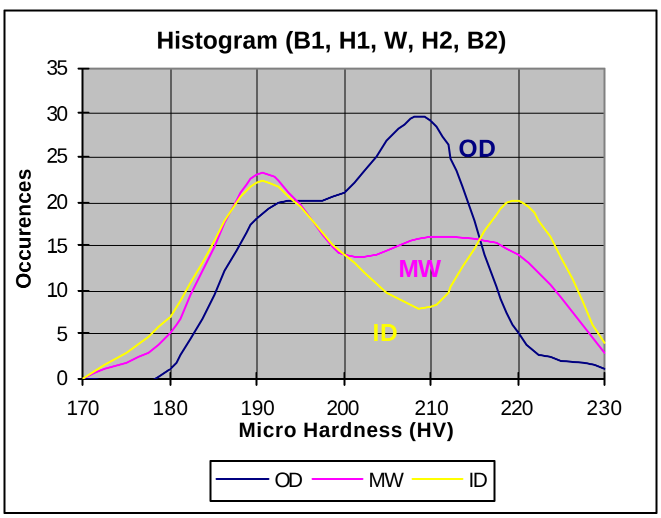


Figure 12 - Results from metallurgical evaluation during real production



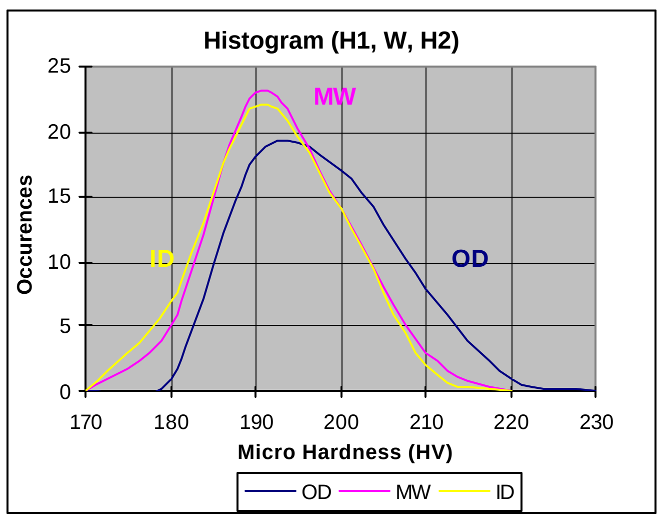


Figure 13 - Micro-hardness variation measured on regular production samples
Base metal (B1 & B2), HAZ (H1 & H2), Weld metal (W)

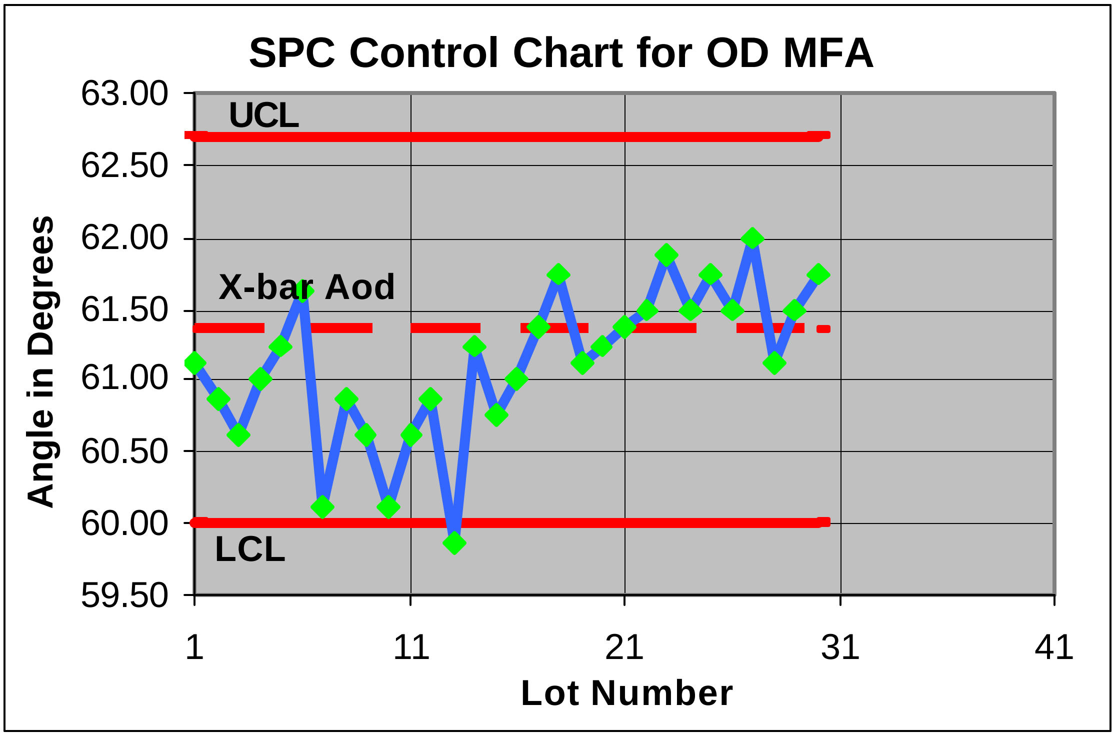


Figure 14 - Typical SPC control chart developed during production

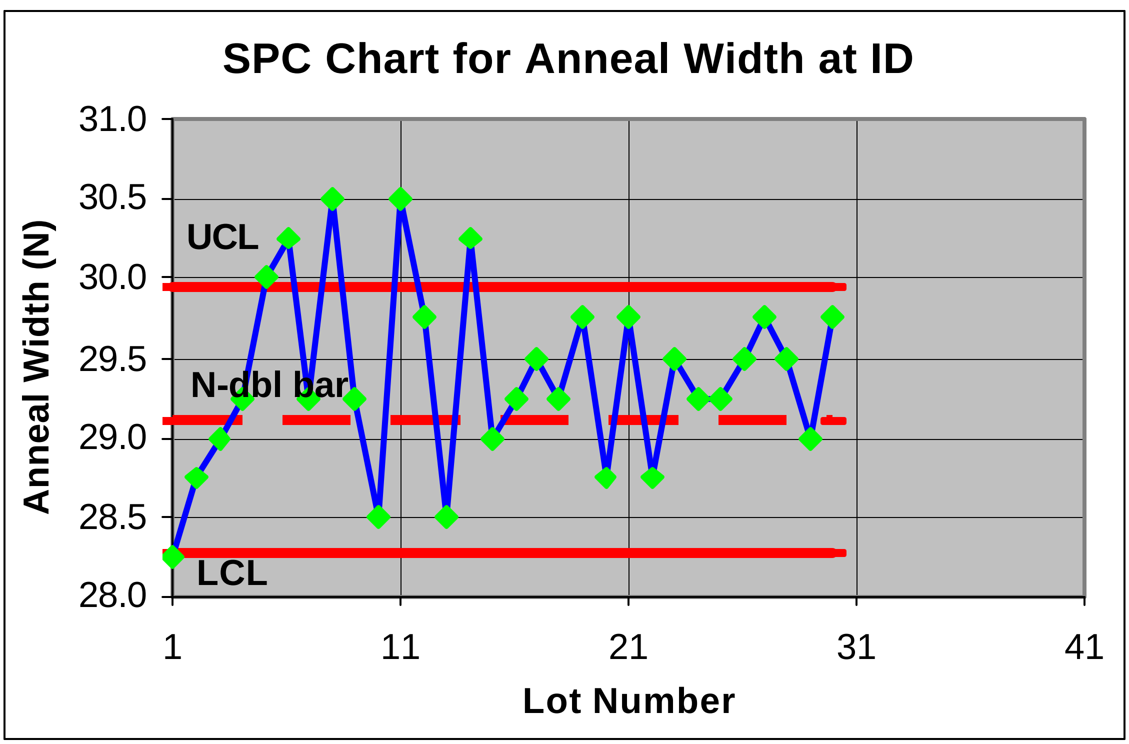


Figure 15 - Typical SPC control chart developed during production

Figure 16 - Typical API flattening test showing split failures in the ERW weld seam
API 5L X60 8 inch OD 0.322 inch WT

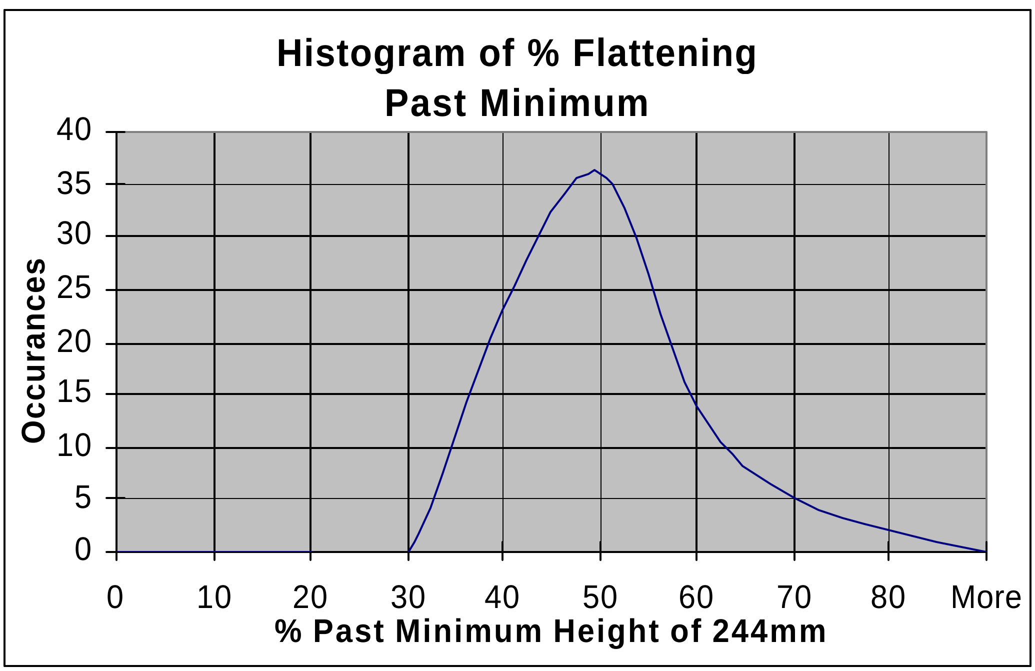


Figure 17 - Actual performance of production flattening tests continuing beyond minimum flattening height until splitting failure occurs (See Figures 16 & 18).

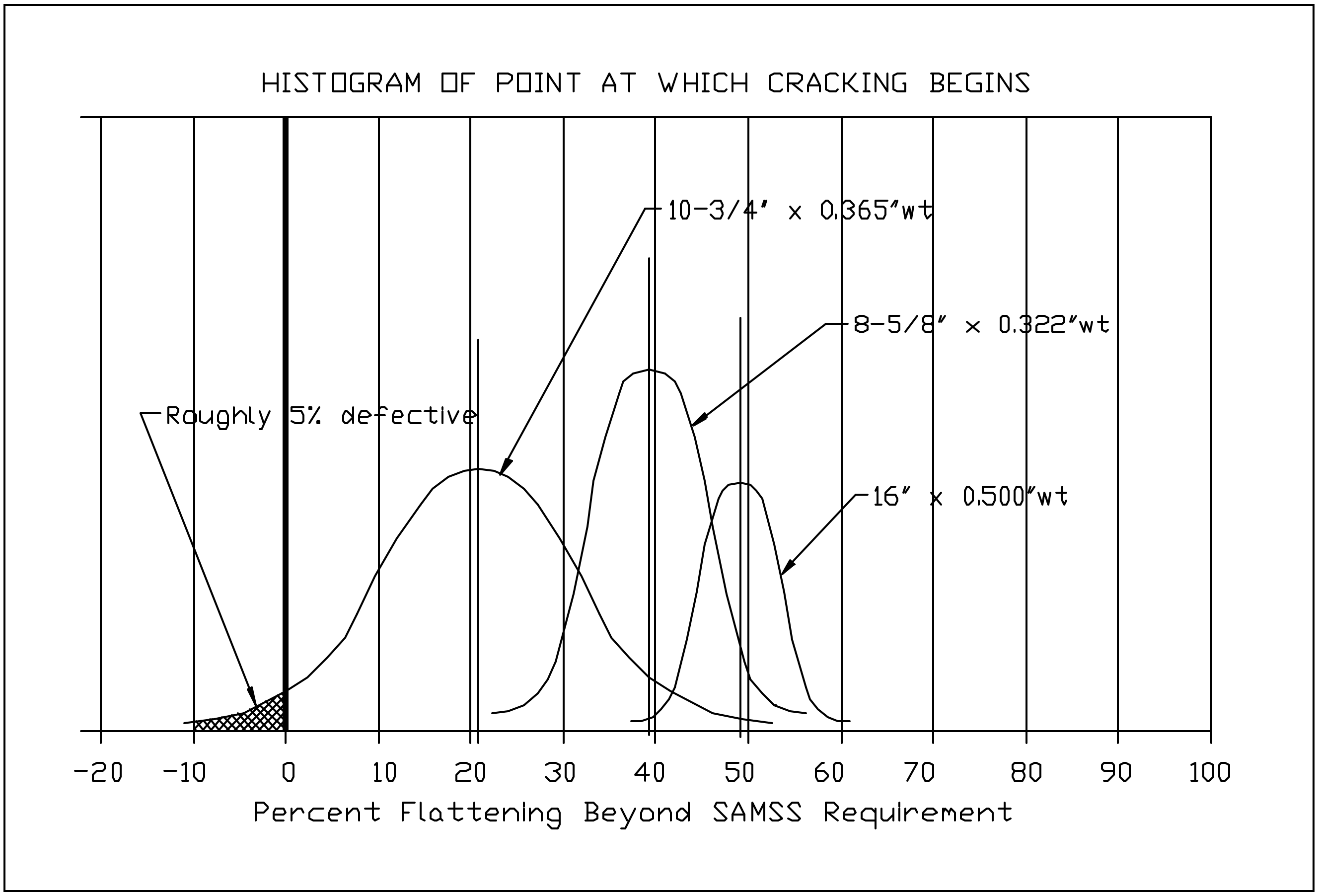


Figure 18 - Chart showing actual production performance of three pipe sizes during flattening test. Pipe mill must maintain a standard deviation of 3.0 maximum during qualification so that the production average of flattening tests will exceed 20% beyond the minimum flattening height.