

How good do piping system welds *really need to be?*



Using fracture mechanics to determine the required inspection level

By Walter J. Sperko, P.E.

Anyone who fabricates pressure piping (or almost any construction) by welding knows that various codes and customer specifications limit the extent of cracking, incomplete penetration, incomplete fusion, undercut, reinforcement, porosity, and slag permitted in a weld.

Codes and customers also specify the method of detection of such defects—visual inspection is always required, and sometimes it is supplemented by radiographic, ultrasonic, magnetic particle, or liquid penetrant examination.

Where do these requirements and criteria originate? How do they relate to the design?

The inspection requirements and acceptance criteria found in the American Society of Mechanical Engineers (ASME) piping codes were established based on the combined opinion of many distinguished engineers who sat on various committees many years ago.

There is no real engineering basis for the flaws that are permitted in today's piping codes; the acceptance criteria in the codes



are more weld quality control standards than anything. In fact, nobody could have established engineering-based criteria as recently as 20 years ago, because the tools that are available today were not available then.

Today, an engineer can determine how good a weld *really* needs to be by using fracture mechanics analysis. Fracture mechanics traditionally has been a fairly esoteric discipline, but because of the need to put this tool to use in the structural steel, nuclear, petrochemical, and chemical processes industries, it has been simplified and made more user-friendly.

Fracture mechanics allows an engineer to consider the size of a flaw at any location, the stress across the flaw, and the fracture resistance (i.e., the toughness). Before discussing the available tools, however, it is important to review a few case studies to see how a couple of flawed piping joints behaved under some severe conditions.

Flawed Pipe Joint Failures

Piping Leaks. In 1994, this writer was asked to help resolve a dispute between an engineer who designed a piping system and the owner of the system. The steel piping system distributed hot water at 400 degrees Fahrenheit and 600 pounds per square inch (psi) to provide space and hot water heating on a local government-owned campus of buildings.

The original underground piping system was found to be leaking shortly after its first year of operation in the 1960s, and it has leaked chronically in various locations ever since. The leaking superheated water provided an attractive Yellowstone-like campus environment—complete with smoldering geysers—for the residents and the employees.

The replacement piping system also started leaking within one year of installation. The essential problem with the system was lack of control over the water chemistry, which caused corrosion fatigue throughout the system but attacked the piping preferentially at the welds.



Figure 1

This photo was taken looking down into a valve pit of the piping system. The leaking steam is typical of all the steam leaks.

Figure 1 shows a view looking downward into a valve pit of the piping system. The leaking steam is obvious and typical of all the steam leaks.

Catastrophic failure never occurred, although the size of the leaks increased over time. Regular repairs were made because the rate at which make-up water could be put into the system was limited, and, when a leak occurred inside a building, the heat from the leaking steam eventually became unbearable.

Fracture mechanics analysis can explain this behavior by showing that, although the stress was high and the flaws were large, steel is very tough at 400 degrees Fahrenheit, and catastrophic failure will not occur.

Incomplete Penetration. The second case study was on a chilled water system in a 60-story office building. Although radiography of the system was not part of the contract or code requirements, the customer radiographed many welds and found incomplete penetration, which he believed to be unacceptable.

A demonstration was conducted in September 1992 to show that circumferential pipe butt welds can have significant weld imperfections and still be entirely suitable for typical chilled water system service conditions. The entire

process was videotaped for future presentation to a jury because few jurors could be expected to understand fracture mechanics.

The demonstration assembly was two 10-foot lengths of 24-inch American Society for Testing and Materials (ASTM) A53 Grade B seamless standard weight ($\frac{3}{8}$ -inch-thick) pipe with caps welded on one end of each piece (see **Figure 2**). These lengths were welded together so that a “bad weld” existed in the middle of the assembly (see **Figure 3**).

The objective was to create a weld with incomplete penetration about 25 percent of the wall thickness in depth around the entire circumference of the pipe.

This weld condition was verified by both radiographic and ultrasonic inspection. Both inspections indicated incomplete penetration in the root, and ultrasonic inspection measured it as being between $\frac{1}{8}$ and $\frac{3}{16}$ inch deep.

The next step was to pressurize the assembly until it failed and observe whether the assembly failed at the imperfect weld or elsewhere.

Engineering theory says that the stress in the pipe caused by pressure is twice as high in the circumferential or

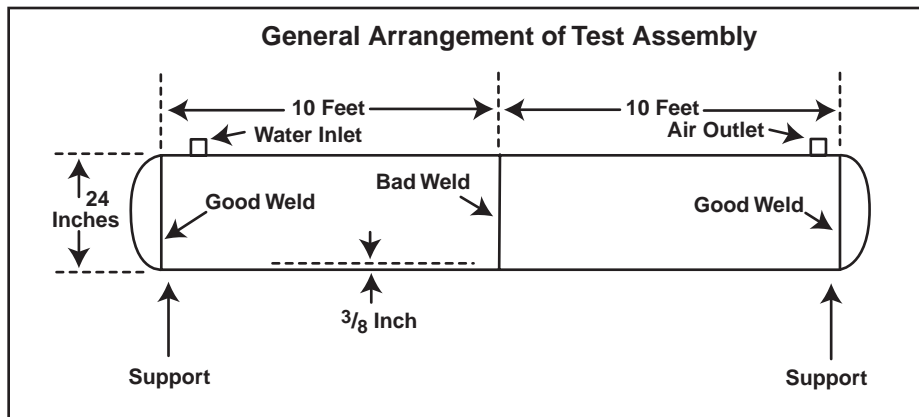


Figure 2

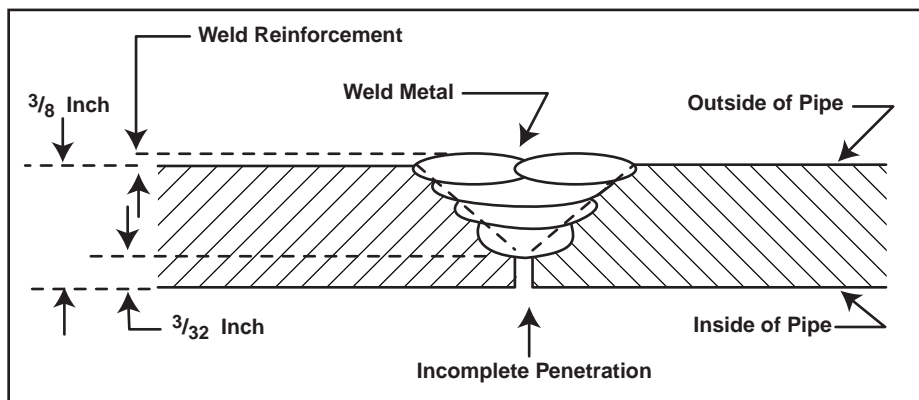


Figure 3

“hoop” direction as it is in the axial direction. This means that, theoretically, the pipe will split down its length when overpressurized rather than across the imperfect circumferential weld—provided the imperfection is not too large.

Fracture mechanics predicted that the incomplete penetration could be as deep as 40 percent of the pipe wall thickness, and failure would still occur in the hoop direction rather than across the bad circumferential weld.

Piping in operation has both pressure stress and bending stress caused by the weight of the pipe and its contents as it hangs between supports. Bending stresses also result from thermal growth of a pipe that is heated or cooled while in service. These bending stresses change only the axial stresses; they do not change the circumferential stress.

In this demonstration, a small amount of bending stress was added to the pressure stress by supporting the 20-foot assembly at each end. This resulted in a bending stress of about 1,000 PSI in

the middle of the assembly, across the bad weld (see **Figure 4**).

This stress was compressive at the top of the pipe. It pushed the imperfect weld together, and the stress was tensile at the bottom of the pipe, where it combined with the pressure stresses to pull the weld apart.

To make the local stress across the bad weld as high as possible, the pipe was rotated so that the deepest incomplete penetration in the bad weld was located at the bottom of the pipe during the test.

According to the design rules of ASME B31.1, Power Piping, and B31.9, Building Services Piping, 24-inch A53 Grade B seamless pipe with a 0.375-inch nominal wall thickness may be used at a maximum pressure of about 400 PSI. Using the code safety factor of 4, the pipe should withstand at least 1,600 PSI before failure occurs.

Based on the actual tensile strength of the pipe, failure was predicted to occur between 2,000 and 2,250 PSI, depending on the exact wall thickness

of the pipe. The water temperature during testing was about 60 degrees F.

The test assembly was pressurized until it failed. The burst pressure was 2,250 PSI, and failure occurred in the axial (hoop stress) direction as predicted by fracture mechanics (see **Figure 5**). The failure was quite dramatic, shooting water more than 100 feet into the air.

Gross plastic deformation of the pipe was obvious during the test, mostly in the form of swelling. The diameter of the pipe near the weld grew from 24 to 26½ inches. The wall of the pipe at the point of failure was less than ⅜ inch thick.

Do these results mean that weld quality in circumferential butt welds in piping is unimportant? Absolutely not.

The stresses in piping systems are complex. It is possible for a piping system to have high stresses at some welds and low stresses at others.

Are Extra Examinations Cost-Effective?

Weld quality is a serious concern when stresses are high and less of a concern when stresses are low. This observation currently is not taken into account by ASME codes and rarely by engineers when the extent of nondestructive examination or the acceptance criteria are established.

Because welds that meet radiographic or ultrasonic examination requirements cost anywhere from 25 to 200 percent more than do welds that are not required to be so examined, radiographic or ultrasonic examination of welds that are not highly stressed wastes time and money unless special circumstances justify the added cost.

Why do these extra inspections cost more? In addition to the direct additional cost of performing radiographic or ultrasonic examination, some factors that contribute to increased cost of making “reduced-flaw” welds are:

1. Fewer welders available who have the necessary skill do the work.
2. More time used by welder to prepare ends and preclean.
3. More time used by welder to get perfect fit-up and alignment.

4. More time used by welder to make and prepare tack welds.

5. More time used by welder to make root pass. (Sometimes, two welders are needed.)

6. More time used by welder to get perfect layers of weld metal, including cleaning between layers and contouring previous layers of weld.

7. More time spent on preparing the cover pass for examination.

8. Additional supervision and/or inspection personnel to verify that the welders are doing the job so that the examinations pass.

Additional examinations increase a fabricator's or contractor's labor costs for which they should be compensated. A customer who wants welds that have been demonstrated to contain fewer flaws should so specify—and be willing to pay for what it takes to make such welds.

In fact, the B31 Code Sections typically specify something comparable to that found in B31.1, paragraph 136.1:

The degree of examination and the acceptance standards beyond the requirements of this code shall be a matter of prior agreement between the manufacturer, fabricator, or erector and the owner.

The codes make the engineer responsible for specifying the extent and the acceptance criteria for any nondestructive examination, beyond that required by code, that he believes are necessary to ensure the integrity of any piping system, and he is obligated to do that before the system is fabricated and installed.

Uses for Fracture Mechanics

The stress level at any weld determines the quality of weld needed, and that, in turn, determines the extent of inspection justified. The tool that is available to assist the engineer in making the correct decision about the extent of inspection required and the acceptance criteria is fracture mechanics.

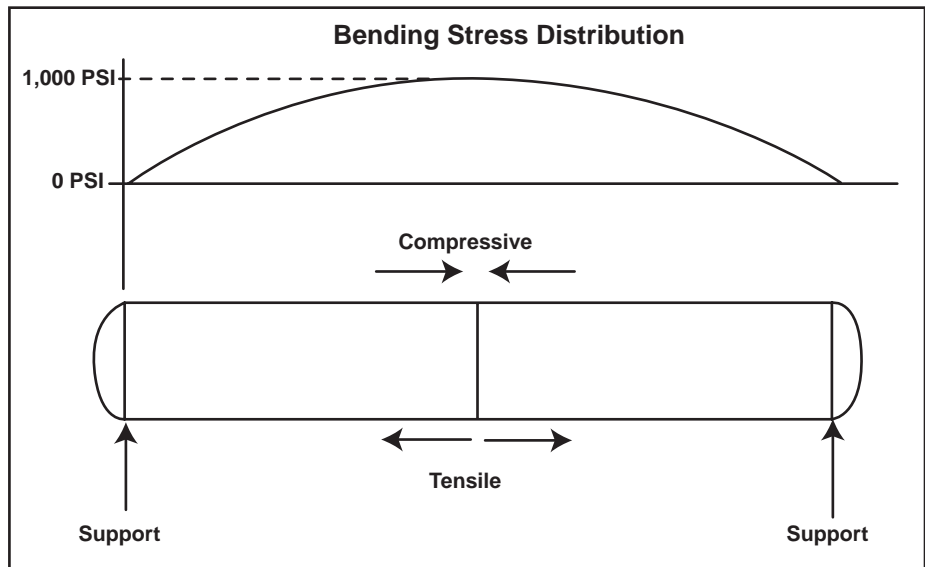


Figure 4

In this example, a little bending stress was added to the pressure stress by supporting the 20-foot assembly at each end.

Unfortunately, few engineers who are involved in commercial or industrial piping recognize that this technology is available to them, and even fewer use it in establishing the extent of nondestructive examination to be applied.

Fracture mechanics recognizes the connection between the size of any flaw, the stress across the flaw, and the toughness of the material. Because no weld—or base metal, for that matter—is perfect, there is always some tolerance for flaws.

The reason that more piping systems do not fail catastrophically is that the stress is sufficiently low and/or the toughness of the material is sufficiently high. Most piping failures show up as leakage—as was clearly the case in the 400-degrees-F, 600-PSI system described earlier.

What the Codes Say

The codes recognize that every weld has flaws, and the codes permit them to some extent in all new construction. For example:

1. ASME B31.1 and ASME Section III permit some slag inclusions, porosity, and undercut.
2. ASME B31.3 and B31.9 permit



Figure 5

This NPS 24 standard-weight seamless pipe contains a bad circumferential weld. However, as indicated by the arrow, the failure was not near the weld (under the white tape).

not only slag, porosity, and undercut, but also 1½ inches of incomplete penetration in any 6 inches of weld length for normal fluid service.

3. American Petroleum Institute

Relating Service Conditions to Examinations

Service Condition	Weld Type			
	Longitudinal Groove	Circumferential Groove	Branch Groove	Fillet
Hoop stress > 80% of the allowable	RT or UT	N/A	N/A	N/A
Hoop stress > 50% and ≤ 80% of the allowable	MT or PT	N/A	N/A	N/A
Sustained stresses due to combined pressure, dead weight, or other non-self-limiting loads > 80% of the nonintensified allowable	N/A	RT or UT	VT fit-up and Backgouge by owner	MT or PT
Dynamic loads that will exceed 80% of the allowable stress	RT or UT	RT or UT	VT fit-up and Backgouge by owner	MT or PT
Toxic service (when specified by the owner)	RT or UT	RT or UT	VT fit-up and Backgouge by owner	MT or PT
Welds subject to more than 7,000 thermal cycles and the calculated stress range at the weld is > 80% of the allowable	N/A	RT or UT	VT fit-up and Backgouge by owner	MT or PT
Sustained stress caused by pressure + dead weight and any other non-self-limiting loads > 50% but not > 80% of the nonintensified allowable stress at temperature	N/A	Visual examination at fit-up by owner's or independent inspector engaged by owner	Visual examination at fit-up by owner's or independent inspector engaged by owner	N/A
Sustained stress caused by pressure + dead weight and any other non-self-limiting loads > 25% but not > 50% of the nonintensified allowable stress at temperature	N/A	Visual examination at fit-up by independent inspector engaged by contractor	Visual examination at fit-up by independent inspector engaged by contractor	N/A
Sustained stress caused by pressure + dead weight and any other non-self-limiting loads < 25% of the nonintensified allowable stress at temperature	N/A	Visual examination at fit-up by contractor's in-house inspector	Visual examination at fit-up by contractor's in-house inspector	N/A

General Notes:

- (A) All welds shall be given a visual examination in addition to the type of examination specified.
- (B) RT - radiographic examination; UT - ultrasonic examination; MT - magnetic particle examination; PT - liquid penetrant examination; VT - visual examination.
- (C) Surface examination (MT, PT, or VT) shall apply to the outside surface and inside surface, where readability accessible, of longitudinal groove welds.
- (D) Weld types apply to welds in pipe and fittings.

Figure 6

(API) 1104 permits not only slag and porosity, but incomplete penetration up to 2 inches in 12 inches of weld length, incomplete fusion, and cold laps up to 2 inches in 12 inches of weld length. It also permits crater cracks up to 1/2 inch in length. Interestingly, API 1104 is not as tolerant of undercut as the B31 Code Sections.

API 1104 also has a procedure for evaluating crack-like flaws using fracture mechanics if the toughness of the steel is

known. This method includes considerations for fatigue and dynamic loading.

In the maintenance and repair codes:

1. British Standard PD-6493 provides a generic method for evaluation of flaws in any welded structure.

2. ASME Section XI, Inservice Inspection of Nuclear Power Plant Components, Code Case N-494, provides a complete method for evaluating flaws in piping. This code case was written for

Class 1 piping, and it should be applied to other piping systems only by knowledgeable parties.

3. The Metals Properties Council (MPC) of the Welding Research Council has developed software for analysis of flaws in welds in vessels and piping.

4. API is in the final stages of issuing RP-579, Recommended Practice for Fitness for Service, which will contain methods for evaluating flaws in piping and vessels.

All of these references and materials are available to the public, except for the MPC software, which is available only to members of MPC.

Although the maintenance and repair codes are not written for new construction, the concepts and methodologies they use certainly are reasonable for use in determining the need to perform nondestructive examinations beyond those required by code.

To this end, the writer has prepared a concept table that relates service conditions to the extent of inspection (see **Figure 6**). This table recognizes that the stresses in piping systems come from different sources (pressure, dead weight, thermal expansion, hydraulics, etc.) and that the extent of inspection should be related to the nature of these loads and to their magnitude, as well as to the nature of the fluid being handled.

This approach also recognizes that a visual inspection of pipe welds at fit-up (after the joint has been cut, beveled, and tack-welded together but before the root pass is put in) goes a long way toward ensuring adequate weld quality. In fact, the most cost-effective inspection method is to have someone, in addition to the welder who will be making the weld, inspect the fit-up.

Taking the Steps

Piping system designers should evaluate their systems in terms of the fluids being handled, the stresses in the system (especially at changes in direction), the number of pressure and temperature cycles that the system will

experience, and any unusual service or operating conditions.

Establishing the typical stress throughout the system and finding the high-stress locations are the first steps in using a fracture mechanics approach to determining the required weld quality.

The second step is to approximate or specify the toughness of the material at each set of operating conditions. These include normal operating conditions, start-up conditions, and any excursions.

The last step is to determine, through fracture mechanics and a suitable safety margin, the largest flaw that can be tolerated before catastrophic failure will occur.

If the permissible flaw is large enough that the pipe will leak before it fails catastrophically (similar to the first case study), there is little justification for additional nondestructive examination, provided leakage of the fluid can be tol-

erated (it is not flammable, explosive, toxic, etc.). If leakage is not tolerable, then additional nondestructive examinations that reduce the largest expected flaw size must be specified.

If examinations beyond those specified by code are necessary, the designer should specify the additional requirements in the purchase order. The designer should understand that the customer will have to pay not only for the nondestructive examination but also for the cost of making welds that have fewer and smaller flaws than might otherwise be allowed.

The work that is currently being done in the maintenance and repair codes may eventually filter into the new-construction codes, and it is likely that someday the extent of nondestructive examination and the applicable acceptance criteria found in those codes will be related to service conditions.

Until then, the industry must depend on the education, experience, and judgment of design engineers to determine the level of weld quality required in piping systems. ●

Walter J. Sperko, P.E., is President of Sperko Engineering Services, Inc., 4803 Archwood Drive, Greensboro, North Carolina 27406, phone 336-674-0600, fax 336-674-0202, e-mail sperko@asme.org. Sperko is also the technical consultant to the NCPWB. Sperko Engineering provides engineering consulting in welding, metallurgy, corrosion, and quality assurance with specialization in piping/pressure vessels.

Although Sperko is a member of several ASME and AWS committees, any code interpretations in this article should be considered his personal opinions and not the official opinion of ASME or AWS.



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The NCPWB WPSs and BPSs are reviewed and accepted by the Hartford Steam Boiler Inspection and Insurance Co., which has verified that they are in conformance with ASME Boiler and Pressure Vessel Code, Section IX, Welding and Brazing Qualifications.

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