# Correlation of Discontinuities and Physical Properties in Steel Weldments

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NONDESTRUCTIVE testing techniques are used to locate and define the shape and size of discontinuities in steel weldments. Ultimately the question that must be answered from these tests is, "Does the discontinuity affect the strength of the weld?" In the past, a heavy reliance has been placed upon service performance, experience, and engineering judgment. There is a tendency, and justifiably so, to error on the safe side. Flaws that have little effect on the performance of the weld are removed. This increases cost and may even damage the weld by the introduction of other flaws. In addition, there is a greater demand placed on weld reliability and performance for the minimum weight. Therefore, the need to know more precisely the effect of a flaw on weld performance has become more urgent. This has given rise to studies on the correlation between weld flaws and physical properties.

In 1960 the Japanese produced a document on the nondestructive testing of welds and their strength.[1] More recently, Professor R. B. McCauley of the Ohio State University has studied the effects of porosity in weldments.[2] Mr. R. Newman of the British Welding Research Association has also published information on the significance of weld defects in relation to fatigue fracture.[3]

It is not the intent of this paper to present new information, but rather to review what is available and to point out some of the differences.

## WELDMENT FLAWS

Since the primary purpose of nondestructive testing is to locate and describe flaws in welds, it is worthwhile to discuss some of the flaws that occur. No discussion will be given on dimensional discrepancies which can be found by visual inspection and careful measurement of weldments. Structural discontinuities such as porosity, cracks, inadequate joint penetration, slag inclusions, etc. encountered in welds require a nondestructive test to locate them.[4]

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**Porosity**—Porosity is the term used to describe spherical voids that arise from gas released by the cooling weld metal. Although they are generally spherical, they may be elongated, uniformly distributed throughout the weld, or concentrated in clusters. Linear porosity describes a condition where the gas cavities are aligned in the root of the weld and is usually associated with inadequate joint penetration. Figure 1 shows radiographs of weldments containing scattered porosity, cluster porosity, and linear porosity.[5]

**Inclusions**—Slag inclusions refer to oxides and other nonmetallic solids that are entrapped in the weld metal or between the weld and base metal. They are caused by the contamination of the weld metal by the atmosphere or entrapment of electrode coating material or fluxes between layers in multi-layer welds. The shape of these inclusions is irregular and many have sharp edges. A radiograph of a weld containing slag is shown in Fig. 2a, where the dark regions are slag inclusions.[5] Tungsten inclusions occur in the tungsten arc process when particles of the tungsten electrode transfer to the weld metal. These appear as white spots on the radiograph and are irregular in shape. Figure 2b illustrates such a condition.

**Incomplete Fusion**—Incomplete fusion is often referred to as lack of fusion and describes the failure of adjacent layers of weld metal to fuse together. This condition arises from failure to raise the temperature of the adjacent metal to the melting point or of foreign material on the surface of the adjacent material. Figure 3 shows the radiographic appearance of this defect.[5]

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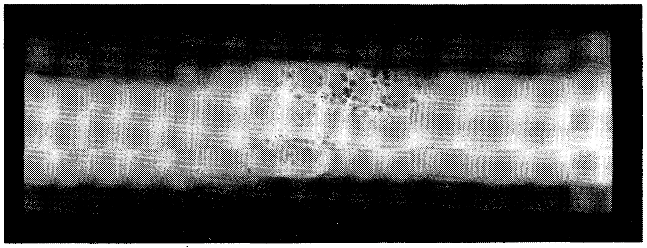
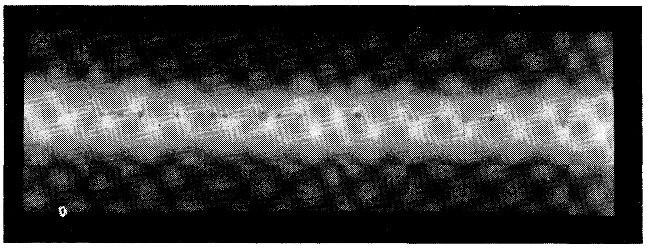
(*a*) *Scattered porosity*

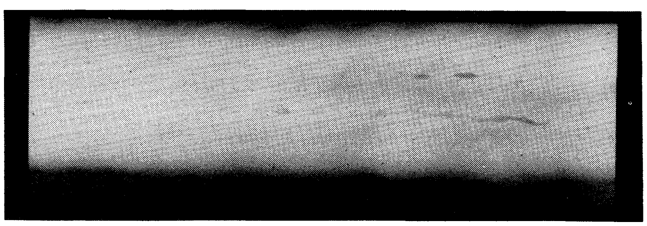


(*b*) *Cluster porosity*

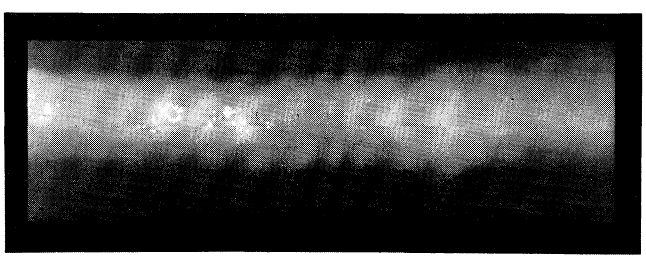


(*c*) *Linear porosity*
*Fig. 1. Radiograph of porosity in welds*

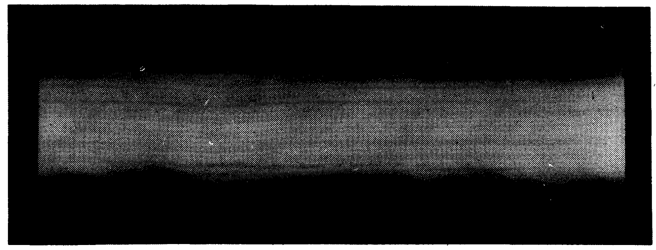
**Inadequate Joint Penetration**—When the joint penetration is less than specified, the condition is called inadequate joint penetration. This is also referred to as incomplete penetration. Figure 4 shows this condition for a butt and a tee joint.[5] If a joint requires full penetration and it is not obtained, it is usually rejectable



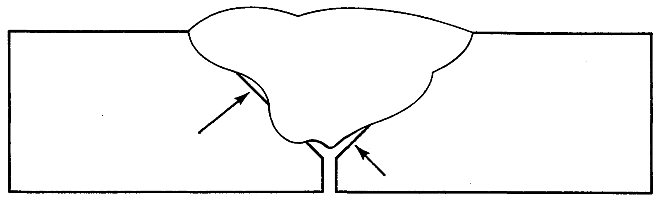
(*a*) *Slag inclusion*



(*b*) *Tungsten inclusion*
*Fig. 2. Radiographs of inclusions in welds*



(*a*) *Radiograph—the dark line shows incomplete fusion*



(*b*) *Incomplete fusion in a groove weld*
*Fig. 3. Incomplete fusion*

because it leaves a very sharp notch at the root of the weld. This arises from the use of the wrong size of filler metal rod, too small a root opening, or too small an included angle of the vee-type groove.

**Cracks**—Cracks are linear defects in the weld metal. They can also occur adjacent to the base metal, longitudinally, transversely, or can originate at craters. Most specifications do not permit cracks of any type. Longitudinal cracks are usually found in the weld metal with the length of the crack parallel to the length of the weld. A transverse crack occurs perpendicular to the length of the weld and sometimes extends into the base metal. Crater cracks are star-shaped and occur where the welding operation is interrupted. Whenever a welding rod is changed, cracks can form in the crater remaining. The crack is usually melted out when the operation is resumed. Sketches of the various types of cracks are shown in Fig. 5.

**Undercut**—This defect occurs on the surface of a weldment where a groove is melted adjacent to the toe of the weld. This condition is easily detected by visual inspection and can also be detected on a radiograph. Undercut is not usually permitted.

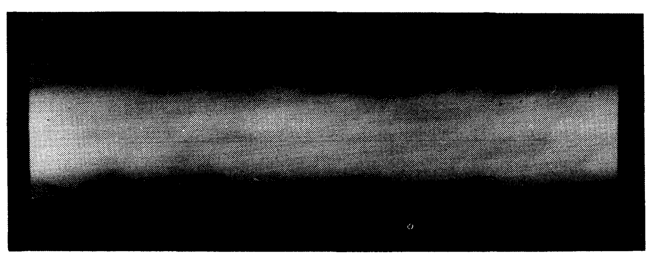


*Fig. 4. Inadequate joint penetration*

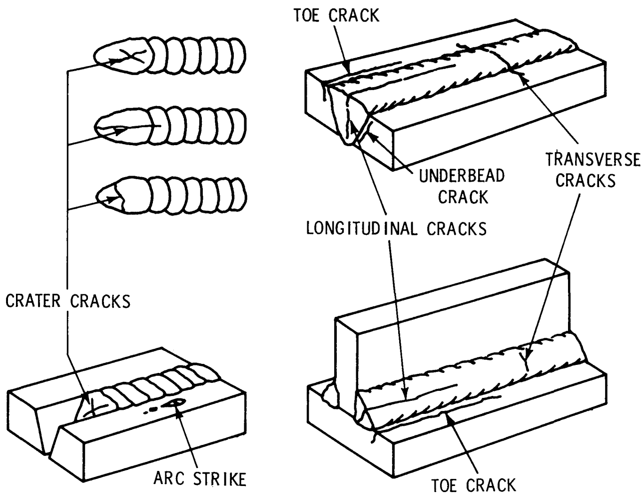



*Fig. 5. Cracks in welds*

**Table 1. Detection Capabilities for Weld Flaws**

| Defect | Radiography | Ultrasonics |
|---|---|---|
| Porosity | | |
| Scattered | Excellent | Fair |
| Cluster | Excellent | Poor |
| Linear | Excellent | Good |
| Inclusions | | |
| Slag | Excellent | Fair |
| Tungsten | Excellent | Good |
| Incomplete Fusion | Poor | Excellent |
| Incomplete Penetration | Good | Excellent |
| Cracks | | |
| Longitudinal | Poor | Excellent |
| Transverse | Fair | Good |
| Crater | Good | Good |

## FLAW DETECTION

The flaws described are detectable by one or more of the nondestructive test methods. Before a satisfactory evaluation of a weld flaw can be made, it is important not only that it be detected, but that it be characterized as fully as possible. Therefore it may be necessary to rely upon several nondestructive tests to obtain the maximum amount of information. Radiography has been used extensively for weld inspection, as it gives a permanent record and a great deal of information about the shape of the flaw. This technique can be applied successfully to weld thicknesses of a few thousandths of an inch or to thicknesses greater than ten inches. For field use, portable equipment and sources are available. Radiographs give information in pictorial form and can easily be interpreted relative to standard references. Flaw sizes of one percent or less of the section thickness can be detected. While most flaws can be found, cracks are difficult to detect if they are not aligned with the X-ray beam to within approximately $\pm 10°$. Other methods should be used to detect cracks and supplement radiographic inspection.

In recent years ultrasonics has been applied to a greater extent for weld inspection. It can locate cracks with relative ease and the equipment is low in cost. Its disadvantages are that no permanent record is obtained and that it requires a highly trained operator to interpret the results, since the flaws are not presented in a pictorial form. However, with improved training procedures for personnel and better record keeping, these disadvantages can be overcome. Ultrasonics can be applied to welds from ¼-in. to 10 in. thick. It is difficult to detect fine porosity and small quantities of slag.

Table 1 shows the capabilities of radiography and ultrasonics for finding weld flaws. It is indeed fortunate that the two methods complement one another so nicely; however, one cannot replace the other on an equal basis. Flaws detected by one method may not necessarily be verified by another.

## FLAW EVALUATION

Most of the correlation work done has been relative to radiography, where the strength of the weld is correlated against the reference radiograph or flaws as measured on a radiograph.

A very impressive piece of work is that done by the Japanese, where weld defects were correlated against strength for mild steel. Since the defects were graded according to a Japanese radiographic standard, it is important to define this classification (JIS) directly.[1]

**Classification by Means of JIS Z 2341 "Radiographic Test of Metallic Materials."**—The following are the JIS Z 2341 classification of defects in welds of steel members:

This standard specifies the defectiveness of welds by size and number of defective images on radiographic film, i.e., the figures in Table 1-1 give the maximum allowable number of defects within an area 10 mm × 50 mm where they are most concentrated.

The figures in Table 1-1 show the sum of the numbers of images multiplied by the size factors given in Table 1-2.

If any defect longer than 12 mm or any crack is recognized, then the weld should be graded in Class 6.

The number of defects should be counted by the following specification of the Japanese Society for Nondestructive Inspection: "Any defect smaller in size than 3 percent of the thickness of plate is not counted as effective, unless it shows a remarkable difference in photographic density from the background, or 1 mm over in diameter. . ."

**Table 1-1. Allowable Number of Defective Images Within 10 mm × 50 mm[a]**

| Max. Thickness of Plate (mm) | Class | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| Less than 5.0 | 0 | 2 | 4 | 8 | 12 | More than Class 5 for every thickness |
| 5.1–10.0 | 0 | 3 | 6 | 12 | 18 | |
| 10.1–20.0 | 1 | 4 | 8 | 15 | 25 | |
| 20.1–50.0 | 1 | 5 | 10 | 18 | 30 | |
| Over 50.1 | 1 | 6 | 12 | 20 | 40 | |

**Table 1-2. Multiplying Factor[a]**

| Size of Defects (mm) | Less Than 2.0 | 2.1–4.0 | 4.1–6.0 | 6.1–8.0 | 8.1–10.0 | 10.1–12.0 |
|---|---|---|---|---|---|---|
| Multiplying factor | 1 | 4 | 6 | 10 | 15 | 20 |

[a] From JIS Z 2341 (see Ref. 1)

Figure 6a shows the summary of test results where the relationship between tensile strength and JIS class is given. This information is also shown in a different form in Fig. 6b where the tensile strength of the weld is given as a function of "rate of defective area, %" (% reduction of cross-sectional area). Up to JIS Class 3 there is no reduction of strength and for Class 6 the strength has decreased 20–30 percent.

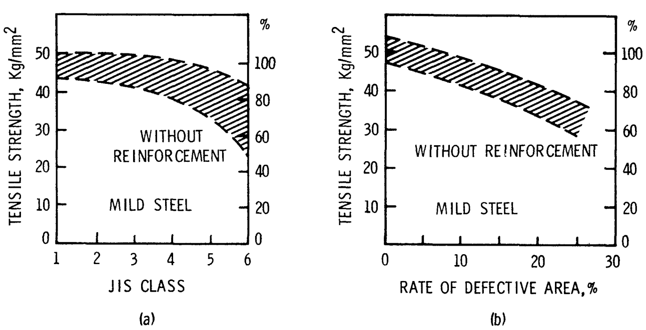



*Fig. 6. Correlation of tensile strength with weld flaws (from Reference 1)*

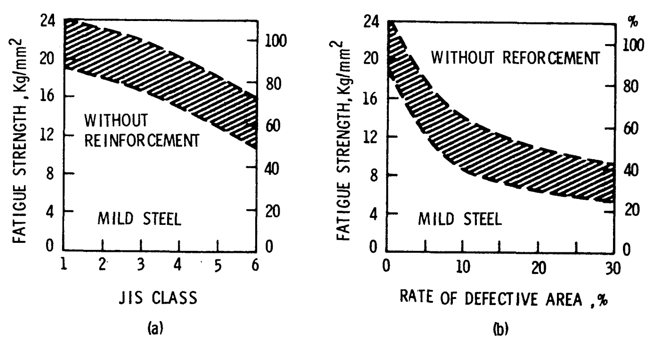



*Fig. 7. Correlation of fatigue strength with weld flaws (from Reference 1)*

The results of fatigue tests are shown in Figs. 7a and 7b, where fatigue strength at 2 × $10^6$ cycles is given for JIS Class 1 to 6 and "rate of defective area, %". Class 6 shows a 40 percent strength reduction. It is important to note from this work that it is possible to correlate nondestructive tests with physical tests. Although this work was done on test coupons and with artificial or simulated defects, the results are nevertheless valid.

J. W. Bradley and R. B. McCauley reported on the correlation of porosity with weld strength.[2] Their work was on butt welds in ½-in. thick T1 steel plate. The welds were radiographically inspected and the test coupons containing porosity were classified by the percent reduction in cross-sectional area of the specimen. Tensile and bend tests were made on the coupons. Figure 8 shows the effect of porosity on ultimate strength. In summary it can be stated that in the work done at Ohio State it was found that only when porosity exceeded 5 percent reduction of cross-sectional area was the strength of the weld decreased. Other data are also presented on impact and bend tests.

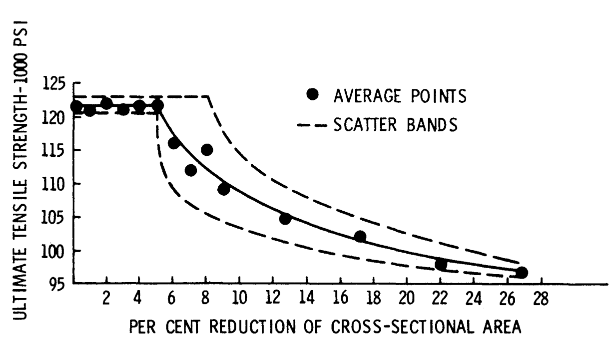



*Fig. 8. Correlation of porosity with weld strength (from Reference 2)*

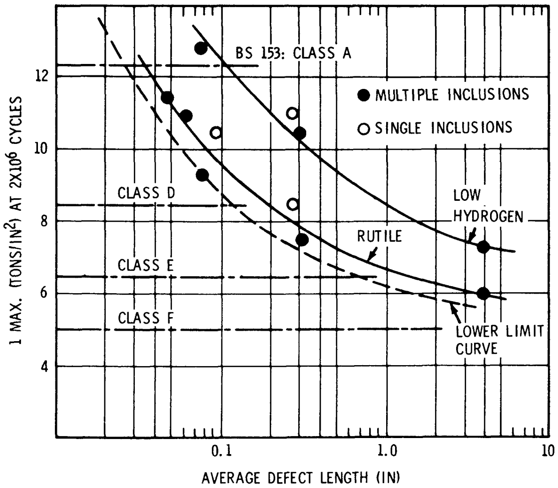



*Fig. 9. Correlation of slag inclusions with fatigue strength (from Reference 3)*

In England, Mr. Newman obtained information on the significance of weld defects in relationship to fatigue.[3] Data on the relationship between length of slag inclusions and fatigue strength have been obtained for ½-in. thick material. The correlation of fatigue strength was obtained for several materials. Figure 9 illustrates that slag as small as 0.2 in. has some effect on strength. In his article Mr. Newman does point out the necessity for considering the stress risers due to surface and shape of weld.

## CONCLUSIONS

In the literature there is some information on the significance of defects on weld strength. While this data is useful it is limited to a few materials and defect types. Most of the work related to radiographic inspection as the test method; perhaps additional data could be obtained if more than one test were applied. There are many deficiencies that need to be considered:

1. Improved NDT methods to better define the shape and size of flaws. It is difficult to obtain from radiography the depth of the flaw and the cross-sectional shape. Ultrasonics lacks the ability to define the shape accurately. Two dimensions can be obtained but no information is available on the third.
2. Correlation of information with respect to flaw types and physical strength is needed. Some data are available but more is required to make specifications more meaningful. Another important question requiring an answer is, "Can ultrasonic test data be correlated directly with physical tests?"
3. Development of better radiographic acceptance standards which are related to physical test data. Development of improved methods to classify flaws ultrasonically.

As additional data are obtained on the correlation of weld defects with NDT, better and more realistic specifications are established. The dependence upon experience and service behavior alone can be reduced.

## REFERENCES

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