Tensile Properties of A514 Steel Butt Joints Containing Cluster Porosity

Tensile tests suggest weld inspection specifications for tensile applications could be relaxed for working stress design, not for limit stress design

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ABSTRACT. The effects of cluster porosity on the tensile properties of A514 steel butt weldments were assessed. Cluster porosity was measured both in terms of the actual total area of pores and of the area of the cluster (including metal ligaments, or webs, that connect pores). Results showed that the tensile strength of the welded metal is not significantly reduced if the area of pores and the cluster area are below critical sizes; however, ductility is rapidly reduced until these sizes are reached.

Consideration of the implications of tensile test data on both working stress design and limit stress design indicate that relaxation of welding codes may be considered for certain tensile loading applications if the codes are based on working stress design. This would be beneficial in terms of reduced project costs for weld rework. Relaxation of codes based on limit stress design should not be considered for the conditions of porosity covered in this study.

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Introduction

Problem

There is a need for acceptance guide specifications for welds based on actual mechanical behavior of a structural weld in any given application. To this end it is necessary to relate weld discontinuity characteristics — such as size, type, shape, location, orientation, and spacing — to mechanical properties of the weld. Such a relation is needed to replace the empirical approach currently used in most cases of specification for structural welds — an approach that often results in overdesigned or underdesigned welds.

Objective

Various types of weld discontinuities, such as cracks, porosity and inclusions, have been shown directly responsible for premature brittle fracture of structural components. The purpose of this study was to evaluate the effect of cluster porosity on the tensile properties of A514 steel weldments. Nondestructive tests and static tensile tests were used to establish the dependence of tensile properties on cluster porosity size.

This investigation provides a partial basis for the evaluation of inspection criteria relating allowable discontinuity parameters to given levels of performance. These criteria would fulfill part of the needs stated above.

Procedure

The procedure consisted of fabricating the specimens, determining their tensile properties, examining their fracture surfaces, and evaluating the radiographs of the welds.

Materials

The base metal used was an ASTM A514 grade F structural steel. The electrode was E110S.* The chemical compositions of the base and filler metals are given in Table 1, and their mechanical properties in Table 2.

Fabrication

The tensile specimens were fabricated from 6 × 10 ft (1.83 × 3.05 m)

**Minimum tensile and yield strengths 110 and 98 ksi respectively, according to AWS Structural Welding Code, Table 4.1.1. Airco's AX110 was used, although other proprietary bare wire electrodes are available.*

Table 1 — Chemical Composition of A514 Base Metal (¾ In. Thick) and E110S Electrode (1/16 In. Diam)

Material	C	Mn	P	S	Si	Ni	Cr	Mo	V	Al	Ti	Zr	B	Cu
A514[(a)]	.15	.89	.009	.027	.27	.90	.52	.42	.06	—	—	—	.0015	.21
E110S[(b)]	.084	1.54	.008	.008	.45	2.43	.049	.48	.008	.004	.0075	.004	—	—

(a) Data from independent analysis
(b) Data from manufacturer

A514 steel plate stock. The plates were flame cut into 10 × 36 in. (25.4 × 91.4 cm) blanks, and each of these was sawed in half. The sawed edges were machined to form a double-V 60 deg groove. Before welding, the beveled edges of the blanks were cleaned with acetone to insure oil and dirt-free welding surfaces. A 100 F (38 C) preheat was used to remove any moisture on the machined surfaces.

All welding was performed using the gas metal-arc welding (GMAW) process with an argon-2 percent oxygen shielding gas mixture; the welding parameters are listed in Table 3. The procedure consisted of the deposition of two weld passes, which completely filled one-half of the weld groove. The root pass was then back ground using disc and carbide grinders, after which two additional passes were placed to complete the weld deposit.

The weldments containing internal discontinuities were produced similarly to the sound welds except that the flow of the shielding gas was interrupted during the placement of the third pass (Ref. 2). This created an unstable arc, which in turn produced the clustered porosity. Interruption of the gas flow was accomplished using a solenoid-activated valve situated between the welding gun and the shielding gas tank; the shielding gas was reduced or turned off for varying lengths of time, depending upon the size of cluster desired.

After welding, the weld reinforcement was removed by disc grinding and an initial radiograph was taken to determine the approximate nature and size of the porosity cluster produced. Using a template and shape-cutting unit, the welded blanks were then flame cut to the test specimen configuration shown in Fig. 1. The flame cut edges were filed and sanded in the direction of the longitudinal axis of the specimen. The specimen faces were then milled flat and sanded to the same smoothness as the edges.

Each weldment was first examined by normal incidence radiography to determine the extent and location of weld defects. Stereoradiographs, taken using the procedure of Carlson and Lawrence (Ref. 3), then provided greater understanding of the character of each defect.

Table 2 — Tensile Properties of Base Metal and Weld

	Base metal(a)	Weld metal(b)
Tensile str., ksi	120.8	140.0
Yield str., ksi	113.1	126.3
Elong. in 2 in., %	36.0	50+(c)
Red. in area, %	66.4	—

(a) Properties of base metal provided by manufacturer
(b) Average of three specimens taken from weld metal (Ref. 1)
(c) Elongation in 3/4 in.

Mechanical Testing

The specimens were mounted in a 6×10^5 lb capacity MTS tensile load frame and loaded directly to fracture at the constant crosshead rate of 0.03 in./min. All tests were conducted at room temperature. The deformation occurring in a 1 in. (2.54 cm) gage length straddling the weld was measured with a linear variable differential transformer (LVDT) extensometer attached to the centerline of each specimen. The load and LVDT extension signals were recorded throughout the test with x-y plotters, and the load and LVDT signals were converted from analog dc to digital signals and recorded on magnetic tape. The latter step was performed to retain a separate permanent record of the data, especially if autographic plotting errors should later be discovered.

The percent strain was determined as the ratio (times 100) of the measured extension to the gage length. The strain and stress at maximum load were termed the uniform strain, ε_u, and the ultimate (tensile) stress, σ_u, respectively. The yield stress, σ_y, was determined at 0.2% plastic strain offset.

Table 3 — Welding Parameters

Voltage, V	Current, A	Travel speed, in./min	Interpass and preheat temp, F	Heat input, kJ/in.	Shielding gas comp, %
22-24	340-360	11	200	44	98 Ar-2 O_2

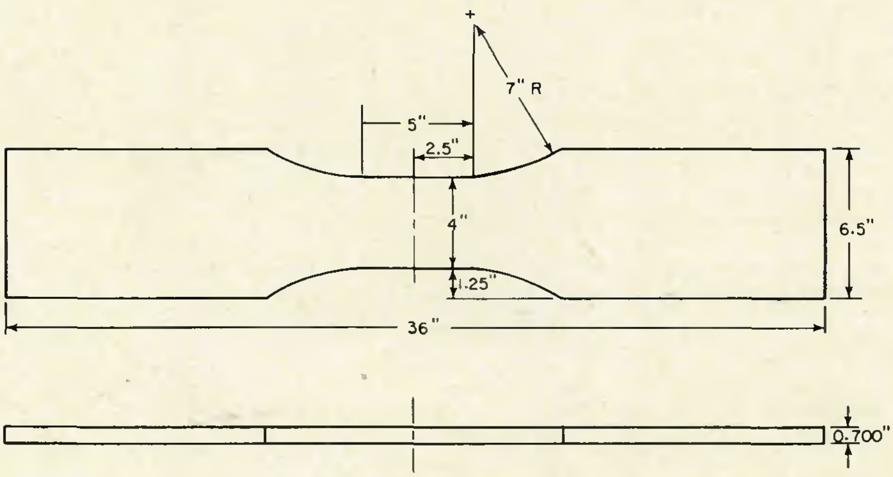

Fig. 1 — Tensile specimen configuration

Fracture Surface Examination

After testing, the ends of the specimen halves were sawed off to permit easy measurement of the porosity clusters and storage of the fracture surfaces. Each fracture surface was examined to determine its nature and the actual dimensions of the cluster porosity. A photograph, roughly 2X, was made of each pair of fracture surfaces, as shown (somewhat reduced) in Fig. 2. Two measures of the porous area, the area of the pores and the area of the region enclosing the pores on the fracture surface, were determined by using a polar planimeter directly on the photograph.

Radiographic Evaluation

The weld quality of each specimen was evaluated by using the radiograph of the specimen and military specification MIL-R-11468 (ORD), *Radiographic Inspection.*

Results and Discussion

The two measures of the porous area mentioned above are the key independent variables in the analysis of this problem. It is useful to consider the projection of the fracture surface on the plane transverse to the tensile axis, as in Fig. 2. The *porous region intercepted by the fracture surface* is defined here as the least area, in this plane of projection, that contains all the projections of the pores visible on the fracture surface. In this region the greatest dimension parallel to the weld axis is defined as the *cluster length (fracture surface)*. The cluster width is the greatest dimension, in this region, transverse to the cluster length. Both the cluster width and length are transverse to the tensile axis.

The *porous region intercepted by a radiograph* is defined here as the least area that contains all the visible radiographic images of the pores. In this region, the greatest dimension parallel to the weld axis is defined as the *cluster length (radiographic)*. This cluster length is the information an inspector in the field would have available for most nondestructive weld examinations. This dimension is parallel but not necessarily equal to the cluster length (fracture surface). This inequality follows from the fact that a cluster of porosities is three-dimensional, of unequal extent among the dimensions. Hence the projection of the cluster on the radiographic plane is not necessarily the same as the projection on any other plane. Moreover, through errors of radiographic technique, the radiographic images (or projections) of some pores may not be discerned.

Table 4 — Undepicted Data

Specimen	Reduction in area, %	Cluster width, (fracture surface) in.	Cluster width,[a] (radiographic) in.
S -1	14.2	0	0
CN-2	(b)	0	0
AS-21	4.02	0.31	0.40
AS-22	4.51	0.31	0.43
AS-23	4.02	0.22	(c)
AS-24	11.87	0.27	0.41
AS-25	1.02	0.31	0.40
AS-26	1.28	0.22	0.38

(a) This is greatest dimension perpendicular to cluster length (radiographic) in the radiographic plane
(b) Extensometer capacity exceeded by extension at maximum load
(c) Linear porosity (split cluster)

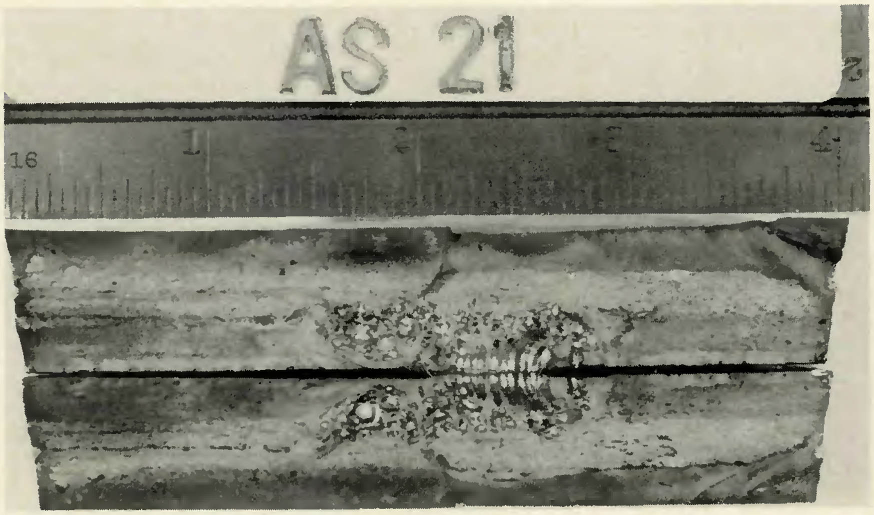

Fig. 2 — Typical fracture surface passing through a cluster porosity

Results

Some of the data, not depicted, are given in Table 4. Figure 3 shows the rapid decrease of uniform strain, ε_u, with pore area. Only about 0.03 in.^{2} pore area can be tolerated before ε_u is reduced to less than 5%. However, up to 0.20 in.^{2} pore area can be tolerated for which ε_u exceeds 3%. Similar results appear in Fig. 4 for ε_u as a function of the area of the porous region. This region, the fracture surface projection defined above, includes not only the pore area, but also the area of the connecting ligaments between the pores. If it is assumed that these ligaments rupture very early in the loading of the specimen, then the area of the cracked region at large loads would be this area enclosing the pores. A region about 0.09 in.^{2} causes ε_u to drop below 5%, yet up to 0.62 in.^{2} porous region can be tolerated for which ε_u exceeds 5%.

Figure 5 shows a nearly linear dependence of the ultimate tensile strength, σ_u, on the area of the pores. However, the scatter in the dependence of the yield stress, σ_y, is broad, and no attempt has been made to pass a line or curve of correlation through those data. It is again clear that a pore area larger than about 0.03 in.^{2} causes a significant reduction in tensile properties, while such an area up to about 0.20 in.^{2} does not reduce σ_y below 110 ksi. In Fig. 6, both σ_u and σ_y are fairly linearly related to the area of the porous region. These tensile properties decrease sharply when the pores are distributed over an area up to about 0.09 in.^{2} However, over 110 ksi tensile strength can be maintained with a porous area up to 0.26 in.^{2}

Figures 7 and 8 show fairly linear dependences of σ_u on the cluster length (fracture surface) and on the cluster length (radiographic). These figures are related to Fig. 6 in that they pertain to the extent of the region having pores. The tensile properties are certainly affected for porous regions longer than about 0.4 in. or radiographic lengths larger than 0.6 in.

Discussion

The quantitative effect of the pores can be measured in terms of their area. Figures 3 and 5 indicate that pore areas in excess of 0.03 in.^{2} cause a strong reduction in tensile strength, while ductility is markedly reduced at this defect size. The quantitative effect of pore *distribution* can be measured in terms of the area of the region occupied by the pores. Such an area up to about 0.09 in.^{2} (Fig. 6)

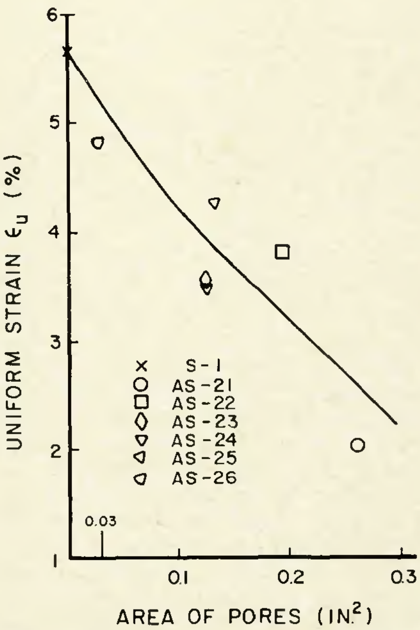

Fig. 3. — Uniform strain vs. area of pores

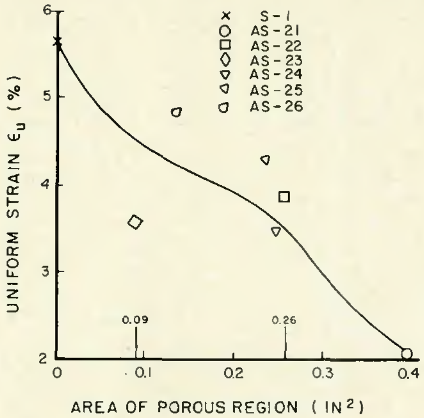

Fig. 4 — Uniform strain vs. area of porous region

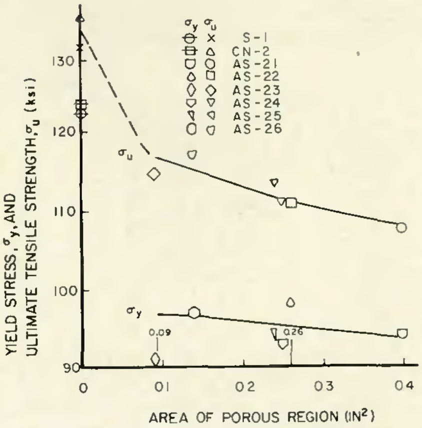

Fig. 6 — Yield stress and ultimate tensile strength vs. area of porous region

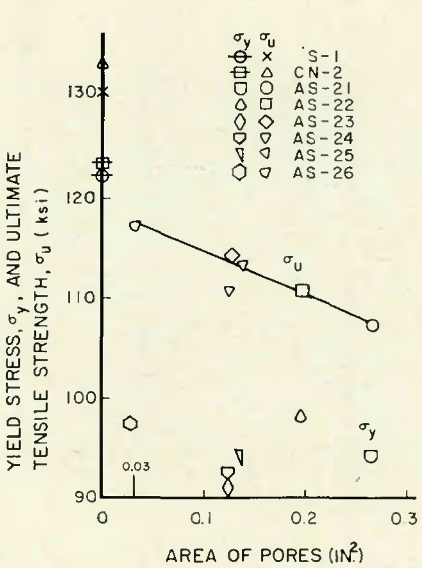

Fig. 5 — Yield stress and ultimate tensile strength vs. area of pores

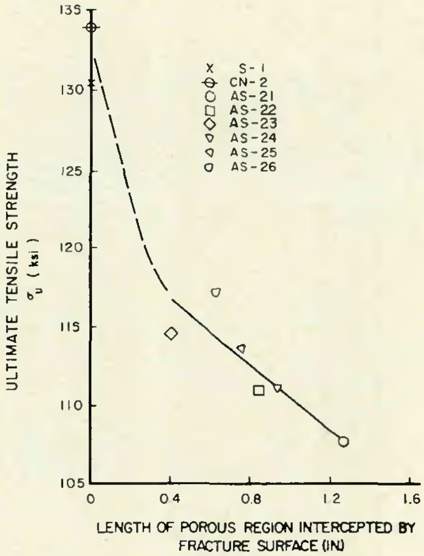

Fig. 7 — Ultimate tensile strength vs. length of porous region intercepted by fracture surface

causes a significant reduction in tensile strength, while Fig. 4 shows that the same area range causes a sharp loss of ductility. The porous region area of 0.09 in.^{2} seems to correspond to a cluster length (fracture surface) of about 0.4 in.^{2} (Fig. 7), or an effective radiographic length of about 0.6 in. (Fig. 8).

The foregoing analysis indicates the qualitative nature of analyzing welds from radiographic images alone since a single normal incidence radiograph cannot provide information on the depth (in the plate thickness direction) of a defect. This in turn emphasizes the qualitative nature of accept/reject standards.

Radiographic inspection of the specimens in accordance with MIL-R-11468 showed that specimens AS-23 and AS-26 could be accepted: AS-26 as "borderline, standard I" and AS-23 as "borderline, standard III." This judgment was based on the observation that the porosities most nearly fitted the specification's "scattered cavities" classification. Specimen AS-26 was judged comparable to radiographic standard CI-2, while specimen AS-23 was judged comparable to standard CI-3.

Relation of Experimental Results and Construction Design Criteria to Weld Specifications

Broadly speaking, there are two construction design philosophies, or criteria, commonly in use. The older criterion is "working stress design," in which only elastic strains are permitted in the structure. This design criterion is thus quite conservative, since only very small deflections are permitted. The newer criterion is "limit stress design" in which (not accounting for factors of safety) the structure is allowed to be loaded to the yield point as long as a large amount of ductility can be obtained. Consequently, this design criterion is far less conservative than the older one. Although these criteria are actually not nearly as simple as stated, these statements do show the rough distinctions between the two design philosophies.

Welding codes do not explicitly state which of the above criteria are reflected in weld specifications. The AWS *Structural Welding Code* D 1.1-72 in discussing the permissible weld design stresses of new buildings and bridges, states that "the permissible stresses . . . for complete joint penetration groove welds . . . shall be those allowed for the same kind of stress for the base metal" and that "the base metal stresses shall be those specified in the applicable Building Code" (Ref. 4), such as the codes of AISC and AASHTO. The AISC code, section 1.5.1.1 (Ref. 5), states that the allowable tensile stresses in structural steel may be as large as 0.6 σ_{ym} (except at pin holes), but not greater than 0.5 σ_{um}, where σ_{ym} and σ_{um} are the minimum values of the yield and ultimate strengths respectively, for the grade of steel of interest. The AISC commentary on the code states that the basic working stress factor of safety is 5/3 with respect to σ_{ym} and that, at the net section of axially loaded members, the factor of safety is 2 with respect to σ_{um} (Ref. 6). The AASHTO code for bridges states that the design stress for axial tension in members without holes is 0.55 σ_{ym} (Ref. 7).

From the *Steel Design Manual*, σ_{ym} = 100 ksi and σ_{um} = 115 ksi for A514 Grade F steel in the size tested in this program (Ref. 8). For the AISC code, the safety factor must be 2 and the design stress 57.5 ksi. For the AASHTO code, the design stress must be 55 ksi. If these codes were applied to these data, the respective design stresses would drop only by about 5 ksi — to 54 ksi and 50 ksi, respectively. This suggests that, for welding codes based on working stress design, cluster porosity in the extent studied here may not significantly degrade the quality of weldments under axial tension. Thus, in these cases, relaxation of cluster porosity restrictions in welding codes may be considered.

This concept is supported by the results of the weld quality evaluation performed in this study in accordance with MIL-R-11468. Application of this specification showed two of the welds in this study to be acceptable; Figs. 5 and 6 show five welds with ultimate strengths exceeding 110 ksi. It is quite plausible that these five welds would have sufficed for a static tensile load in a working stress design. Rejection of these welds for such an application probably would accomplish nothing but increased project costs. Less stringent radiographic standards might thus be beneficial.

However, as Figs. 3 and 4 show, a marked reduction in ductility of weldments occurs when even small amounts of porosity are introduced. This implies that relaxation of welding codes based on limit design concepts would be undesirable, since the ductility required in that design is lost in porous weldments. One example of such a limit design application is found in Section III of the *ASME Boiler and Pressure Vessel Code* (Ref. 8). In this code, the algebraic difference between the largest and smallest principal stresses is defined as the stress intensity, S. For a given material, the largest S permitted is denoted S_m, and is usually $\sigma_{um}/3$. In the code requirements for Class 1 components operating under normal and upset conditions, some combined loading cases allow a peak stress intensity of 3 S_m, which is essentially the yield strength value. It is evident that no reduction in ductility or tensile strength could be tolerated in such a critical design. Acceptance of only the most ductile welds would be essential to the proper implementation of a limit design. Thus, a reduction in the quality of radiographic standards would not be beneficial in a limit design.

Summary

Conclusions

1. There is a combination of pore size (in terms of total area of pores) and distribution of porosity (in terms of area encompassed by pores, i.e., the area of the porous region) that is critical in the sense that the tensile strength is not degraded until that pore size or porosity distribution is surpassed. In this study the critical pore area is about 0.03 in.^{2} and the critical area of the porous region is about 0.09 in.^{2}

2. There is a similar combination of pore size and distribution of porosity that is critical in that the ductility (as measured by ε_u) is sharply degraded until that pore size or porosity distribution is surpassed; beyond the critical point the rate of degradation is reduced. In this study the critical pore area is about 0.03 in.^{2} and the critical area of the porous region is about 0.09 in.^{2}.

3. There is an effective radiographic length of cluster porosity associated with the critical combinations in Conclusions 1 and 2. In this study, the tensile strength was unaffected for radiographic lengths less than 0.6 in., while the ductility dropped sharply until that length was reached.

4. In view of the relation of tensile strength to critical cluster porosity size, relaxation of weld inspection specifications may be possible for certain applications if the specification is based on working stress structural design criteria. However, considering the marked reduction in ductility with increasing porosity, relaxation of weld specifications based on limit design criteria should not be considered.

Future Work

The AWS, AISC, and AASHTO codes contain specifications for the shear of weldments that are distinct from those for the tension of weldments. Data on the shear of weldments containing cluster porosity should be acquired to determine the extent of degradation of the yield and ultimate shear stresses and uniform shear strain. This will test the question of whether working stress design may be unnecessarily conservative in shear as well as in tension of weldments.

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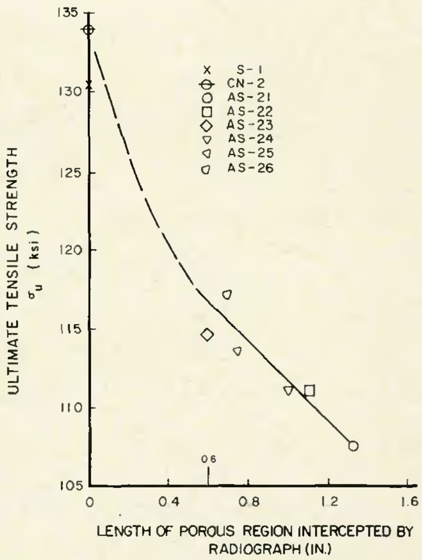

Fig. 8 — Ultimate tensile strength vs. length of porous region intercepted by radiograph

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