30 INCH BUBBLE CHAMBER MAGNET

DESIGN REPORT

Cryogenic Welding Metallurgy

Report #MP 1

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Introduction

This report is a review of cryogenic welding metallurgy for the 30" Bubble Chamber Magnet. Fracture mechanics is the primary emphasis. Only 316L welding is discussed. An example of high cycle fatigue loading more applicable to Energy Doubler problems is given.

BRIEF OVERVIEW OF FRACTURE MECHANICS

Fatigue failure is a three-step process of crack initiation, crack propagation, and fracture. Often used fatigue life curves can be misleading since the crack initiation phase may account for as much as 90% of the total fatigue life. In large structures and welds, cracks may exist or may be assumed to exist. For these cases fatigue life is determined completely by crack growth rates.

The basis of linear elastic fracture mechanics is from Griffith's work. He demonstrated that the strain energy released upon crack extension is the driving force for fractures. It is found that the crack tip stress field is given by the expression

$$\sigma_{ij} = K\ f\ (\text{position})$$

where K, the stress intensity factor, is dependent upon applied stress σ, crack length a, and a geometry factor Y(a).

$$K = Y(a)(\pi a)^{1/2}\ \sigma$$

Values of K for various geometries and boundary conditions are published in handbooks and textbooks. It has been demonstrated that the strain energy release rate G and the stress intensity K approaches to fracture mechanics are related by

$$K^2 = E'G$$

where $E' = E$ for plane stress and $E' = E/(1-\nu^2)$ for plane strain. Fracture occurs when $K = K_c$, the critical stress intensity. K_c is also referred to as the fracture toughness and is an experimentally determined value. Now it can be seen that the critical flaw size is given by

$$a_c = \frac{1}{\pi}\left\{\frac{K_c}{Y(a)\sigma}\right\}^2$$

Critical flaw size is extremely dependent upon the applied stress. Highly stressed materials require much greater fracture toughness.

When physical samples are tested for fracture toughness, the plastic zone ahead of the crack must be considered. The plastic zone does not carry its share of an incremental load, thus the crack appears longer in an elastic sense. This plastic region is geometry dependent especially in the thickness direction. As the sample is made large in comparison to the plastic zone at the crack, a minimum constant value K_{IC} known as the plane strain fracture toughness is obtained. The standard test specimen for plane strain fracture toughness is specified by ASTM E399 and is shown in Fig. 1. Often these samples become prohibitively large, and an elastic-plastic fracture toughness test, usually the J integral test, is made instead. Correlation to K_{IC} is made with the expression

$$K_{IC}(J) = \left(\frac{E'J_{IC}}{1-\nu^2}\right)^{1/2}$$

Subcritical crack growth is given by the Paris equation

$$\frac{da}{dN} = C(\Delta K)^n$$

where C and n are emperical constants and da/dN is the crack growth per cycle. $\Delta K = K_{max} - K_{min}$ with K_{max} and K_{min} being the maximum and minimum stress intensity factors per cycle. The fatigue life can then be estimated by integrating between an assumed initial flaw size and the critical flaw size.

$$N = \frac{1}{C}\int_{a_i}^{a_f} \frac{da}{(\Delta K)^n} = \frac{1}{c(\Delta\sigma)^n}\int_{a_i}^{a_s} \frac{da}{f(a)^n}$$

Fracture toughness data is not always available. Impact tests such as the Charpy V (CVN) and notched tensile tests give a general idea of a materials relative fracture toughness but should not be relied upon for design of a highly stressed cyclically loaded structure. Large differences in fracture toughness are possible among samples that have only small differences in yield strength and impact strength. Correlation is good, however, between 77 K Charpy V impact energy and critical J integral values, $J_{I.C.}$. If the ASME pressure vessel code is to be followed, Charpy impact tests (CVN) samples should show 0.015" lateral expansion.

Stainless Steel Cryogenic Welding Metallurgy

This section reviews the cryogenic properties of 316L shielded metal arc (SMAW) and gas tungsten arc (GTAW) welds. References 2-7 and phone conversations with some of these authors are the sources for the following information.

The cryogenic properties of 316L welds have been investigated fairly well over the past few years. Much of this effort has been to characterize welds used in the Mirror Fusion Test Facility Magnet. Some of these welds reach peak stress levels of 90 ksi.

Stainless 316 is normally considered to be an austenitic stainless steel. It is, however, metastable and is partially able to transform to a martensitic phase under stress at low temperatures. The martensitic phase most probably increases the fatigue crack growth rate, but its exact effect is difficult to characterize.

Carbon, nitrogen, and ferrite all dramatically affect fracture toughness and/or fatigue crack growth resistance. Use of filler metal with carbon and nitrogen contents less than 0.02% is desirable for maximum fracture toughness. A substantial loss of fracture toughness occurs when the carbon content reaches 0.06% (e.g., 316 SS). See figures 11 and 13. This is the reason for selecting the L grade electrode or rod. Chromium carbide and probably carbonitride precipitates at the grain boundaries are a major embrittlement mechanism. Carbon and especially nitrogen, however, provide increased strength. Figures 2 and 3 show the dramatic effect of high nitrogen levels on weld metal impact resistance and ductility at 77 K. Only low nitrogen welds can be expected to meet the ASME 0.015" lateral expansion criterion. Helium temperature data is not available although a 10% to 30% decrease may be expected by assuming test data on plate material is applicable to weld metal [8]. For SMA welding it is important to weld in the down flat position and to use good technique to avoid nitrogen pickup (i.e., weaving should be avoided). With TIG welding a ~ 0.02% nitrogen pickup may be assumed.

Ferrite a body centered cubic (b.c.c.) phase is a potentially serious problem in austenitic stainless steel welds. B.C.C. metals (e.g., steel) are notorious for their low temperature brittleness. Ferrite unlike the b.c.c. martensite can be controlled by small changes in chemical composition of the weld filler. Ferrite can be measured with a Magne-Gage or can be estimated from the modified DeLong diagram, Fig. 5. Calculated values usually give a reasonable estimate of the ferrite fraction. It is clearly seen that carbon and nitrogen are very strong "austentizers".

Ferrite in austenitic welds is both an advantage and disadvantage for cryogenic applications. Ferrite is beneficial in eliminating hot cracking, microfissuring, and increasing the weld strength. Both yield strength and ultimate strength increase with increasing ferrite content as shown in Fig. 6. Ferrite can also have a very large detrimental affect on impact strength and fracture toughness. In general, fracture toughness decreases as yield strength increases, Fig. 7. Fatigue crack growth rates are relatively independent of the ferrite content.

Figures 8 to 11 clearly demonstrate the adverse role that ferrite plays in reducing low temperature impact strengths and ductility (CVN tests). Fracture toughness vs. % ferrite is plotted in Fig. 12. Superior ductility of 316L electrode over the more common 308L filler typically used with 304 stainless steel is shown in Fig. 13. Lime-covered electrode (-15) are preferred over the titanium-covered electrodes (-16).

Unfortunately these charts don't give a complete picture of the effect of ferrite in austenitic stainless welds. Microfissuring and variation in welding parameters must also be considered. Microfissuring can occur when a low melting temperature grain boundary component is remelted by a subsequent welding pass. Microfissuring can be completely eliminated by adjusting the weld composition for 5% to 10% ferrite. The ferrite morphology changes from isolated patches to a continuous network at a ferrite number of approximately 7. It was suggested during phone conversations that 316L 4 K welds should definitely be lower than 7%-8% ferrite. Figure 14 shows a typical microfissure. Both microfissuring and hot cracking are most likely to occur in fully constrained welds. Unfortunately cryostat/structure closure welds for large superconducting magnets are typicaly fully constrained. Although microfissures are undesirable it is found that they have little effect on fracture toughness, impact or tensile strength [3]. They can influence fatigue crack growth rates somewhat. Microfissures generally appear transverse to the weld axis and consequently have the most pronounced effect when loading is in the longitudinal direction of the weld. Figure 15 is a crack growth rate curve.

Since fracture toughness is a maximum in ferrite free welds and possible microfissures don't appear to seriously affect weld integrity, one would assume that 0% ferrite in 316L SMA welds is the composition by choice. Changes in welding parameters can have a large influence on fracture toughness of 4K ferrite-free welds, however, as shown in Fig. 16.

Lawrence Livermore Lab is presently building a large superconducting magnet, the MFTF. Their closure welds are up to 6" thick, fully constrained, stressed as high as 90 ksi in some local areas, and subject to low cycle fatigue. For all welds made in the downflat position, they are using Kryokay 316L electrode. LLL has had problems with cracking when using this electrode for vertical welds. Teledyne McKay is currently manufacturing a special 5% ferrite 316L SMA electrode, Ferrite #5, for these welds. No 4K data currently exists for this electrode when used in the downflat position. Dalder and Witherell at Livermore recommend using small electrodes, less than 5/32". Although no published data exists, 316L rod for GTAW is equal to or superior to SMAW since the welds are cleaner. Remember that fracture strength $\propto 1/\sqrt{a}$ where a is the crack length.

The problem with GTAW rod is that its ferrite content normally varies from 0% to 12%. Special handpicked lots must be used although a higher ferrite level can be tolerated in GTAW as compared to SMAW.

Welds for the 30" Bubble Chamber Magnet Cryostat

Kryokay 316L SMAW was selected for the closure welds and all major structural welds in the 30" cryostat. The root pass and top pass of the closure welds were specified to be 316L GTAW (TIG). 1/16" rod was used for the root pass and 1/8" was used for the cover pass. The bottom side of the cryostat had two TIG root passes to prevent burn through to the coil with the stick electrode. A total of six SMA weld passes were made, three with 1/8" and three with 5/32" electrode. All SMA welds start and stops were staggered. Each of these weld passes developed a crater crack at the end of the weld. All of these were completely ground out before the next pass was made. After the first cover TIG pass was made on coil #1, it was discovered that 316LHF had been used instead of 316L. HF refers to an extra high ferrite content (FN $\propto$ 11). No heat numbers could be found for the rod used to make the root pass. The cover pass rod heat number was 30896. Teledyne McKay informed me that this material has a calculated ferrite number of 12.5 FN. The cover pass was completely ground off. Thus the root passes on the number 1 cryostat can be assumed to have a ferrite number of approximately 12. Specially picked rod of 3% to 6% ferrite will be used for all cover passes and the two root passes on coil #2.

Support structure weldments on the outer cryostat rings were all made by Youngstown Welding with Kryokay 316L. Undoubtedly some of these were made in the vertical position. All welds appear to be free of cracks (dye penetrant) except for the tack welds on the back of the axial support structure pads. Large cracks appeared here as the closure welds were completed. These will be ground out and filled in with the special ferrite GTA rod. Any other dubious welds will be repaired in the same manner. The tack welds are not required for structural integrity. The closure welds on cryostat #1 were tested ultrasonically and appear sound. The test report will be attached as an appendix.

Stresses in the closure welds are approximately 15,000 psi. Stress concentration should also be taken into account. This is very difficult to estimate since this particular case does not appear in the usual handbooks, and the rounding of the corners from the root pass is unknown. A stress concentration of four (60,000 psi) is arbitrarily chosen for the root pass.

Extrapolating figure 16 to 12% ferrite gives a plane strain fracture toughness of $\propto$ 90 MPa$\sqrt{m}$ = 82 ksi$\sqrt{in}$. Assume a possible defect to be equivalent to a hairline crack on the edge of the plate with width W. Then from Reference 1, Energy Release Rate $G = K^2/E = \frac{\sigma^2 W(1-\nu^2)}{E} \text{Tan}\left(\frac{\pi L}{W}\right)$

$$(82{,}000)^2 = (60{,}000)^2 \times 0.675 \times (1-0.3^2) \quad \text{Tan}\left(\frac{\pi L}{0.675}\right)$$

Critical Flaw Size = L = 0.27"

This says that a 1/4" deep crack would be required for catastrophic failure upon the application of the first pressure cycle. This crack would also have to extend around the complete circumference of the cryostat.

Assume a 0.025" deep crack, then

$$\sigma_{critical} = 3 \times 10^5 \text{ psi}$$

Elliptical surface and buried cracks have been extensively studied. Reference 1 gives a short summary.

$$K_I^{\,2} = 1.21 \ \pi\sigma^2 \ \frac{a}{Q}$$

where a is the flaw depth and Q is the flaw shape parameter which is a function of σ/σ_{ys} and the aspect ratio of the flow. Assume a length/depth ratio of 5 to 1 for a surface crack and $\sigma/\sigma_{ys} = 2/3$, then Q = 1.2. For 60,000 psi stress

$$a_{critical} = 0.59"$$

or for a 0.025" flaw, $\sigma_{critical} = 2.9 \times 10^5$ psi.

Subcritical crack growth must also be considered. This will determine the number of cycles before a subcritical crack grows to a critical crack size.

Arbitrarily assume a 0.025" surface crack again. Our loading is non-reversing so $K_{I\,max} = \Delta K$. $\Delta K = 1.6 \times 10^4$ psi$\sqrt{in}$ = 18 MPa$\sqrt{m}$. Since the crack is small in comparison to the plate width, both previous formulas give the same result. From Fig. 15 da/dN ~ 2×10^{-5} mm/cycle = 7.9×10^{-7} inch/cycle. The 30" magnet will experience less than 1000 cycles in its lifetime. The crack will grow ~ 0.8 mil. This small growth permitted the use of da/dN as a constant.

Conclusion: Although impact strength is very low for high ferrite rode, both fracture toughness and subcritical crack growth rate is more than adequate for the 30" magnet closure welds. This is not necessarily true for very thin material, or highly stressed material subject to millions of cycles.

Example of High Ferrite Rod Used in Other Applications

Fracture strength $\propto (K_{IC})/\sqrt{a_c}$ where a_c is the critical flow size or $a_c = (k_{ic}^2)/\sigma^2$.

4K Comparison

	316L HF rod	316L rod (typical)	304 plate
$a_{critical}$	1	4	14.0
$\sigma_{critical}$	1	2	3.9

From Fig. 15 we may approximate the fatigue crack growth rate by

$$\frac{da}{dN} = 5.5 \times 10^{-10}\ \Delta K^{3.5}\ \frac{mm}{cycle} = 5.5 \times 10^{-13}\ \Delta K^{3.5}\ \frac{meter}{cycle}$$

Again use the elliptical crack formula. Assume σ = 90,000 psi (621 MPa), then Q = 1.1.

$$K_I = 1154\sqrt{a}\ (MPa\sqrt{m})$$

This stress level could easily appear in relatively low stressed materials when stress concentrations are considered. For 90,000 psi a_{cr} = 0.24" = 0.0061 meter. Integration of the Paris equation gives the cycle life

$$N = \int_{a_i}^{a_{cr}} \frac{da}{C\ \Delta K^n} = \int_{a_i}^{0.0061} \frac{da}{(5.5 \times 10^{-13})(1154)^{3.5}\ a^{1.75}}$$

$$N = -46.4 \left[\frac{1}{(0.0061)^{0.75}} - \frac{1}{a_i^{0.75}} \right]$$

$$N = \frac{46.4}{a_i^{0.75}} - 2126$$

Fatigue Cycles N	Initial Flaw Depth 10^{-3} meters	(inches)	
9,470	0.64	(0.025)	
20,940	0.25	(0.010)	
127,000	0.025	(0.001)	
727,000	0.0025	(0.0001)	
1.4×10^6	0.025	(0.001)	45,000 psi stress level

For low cycle applications fracture toughness is the material property of most concern. For million cycle applications fatigue crack growth rate, initial flaw sizes, and stress level are the parameters to be closely watched. Fracture toughness is only of secondary importance at least in materials with only small defects.

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2. Charles Witherell, "Welding Stainless Steels for Structures Operating at Liquid Helium Temperatures," Welding Research Supplement, p. 326-342, (November 1980). Added details from UCRL 83863.
3. T.A. Whipple, H.I. McHenry, and D.T. Read, "Fracture Behavior of Ferrite Free Stainless Steel Welds in Liquid Helium," Welding Journal, NBS.
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6. E.R. Szumachowski and H.F. Reid, "Improved Weld Metal Safety at Liquid Nitrogen Temperatures," Cryogenics, May 1980.
7. R.L. Tobler and R.P. Reed, "Fatigue Crack Growth Resistance of Structural Alloys at Cryogenic Temperatures," Advances in Cryogenic Engineering, Vol. 24, page 82.
8. LNG Users Handbook.
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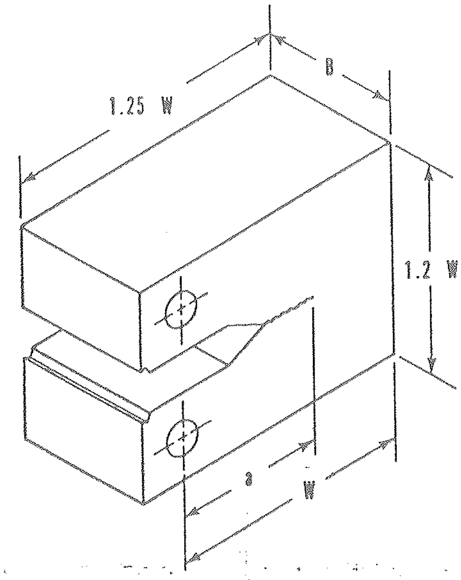

Fig. 1. ASTM E399 compact specimen for fracture toughness testing[10].

Figure 1 (Ref. 9)

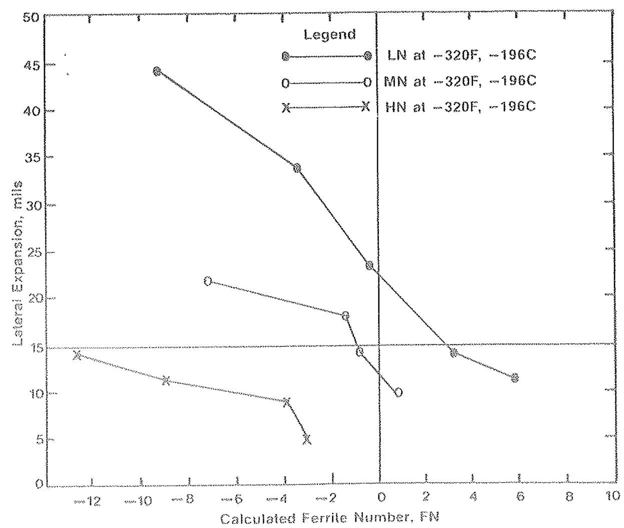

Fig. 1—Effect of nitrogen on lateral expansion of Type 316L-15 weld metals

Fig. 2 (Ref. 5)

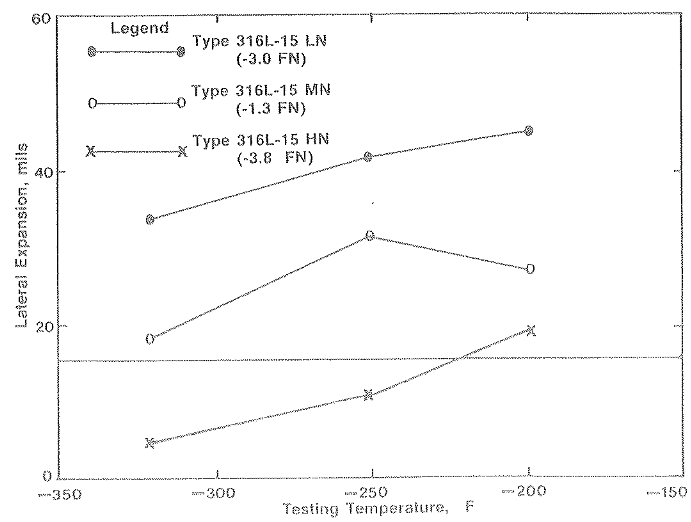

Fig. 2—Lateral expansion of Type 316L-15 weld metals containing various amounts of ferrite and nitrogen

Fig. 3 (Ref. 5)

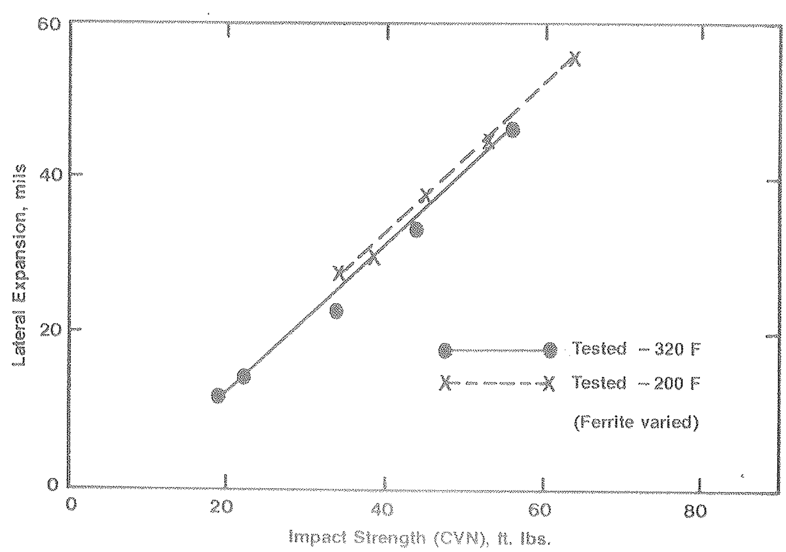

Fig. 9—Lateral Expansion vs. impact strength for 316/316L grade-series materials

Fig. 4 (Ref. 5)

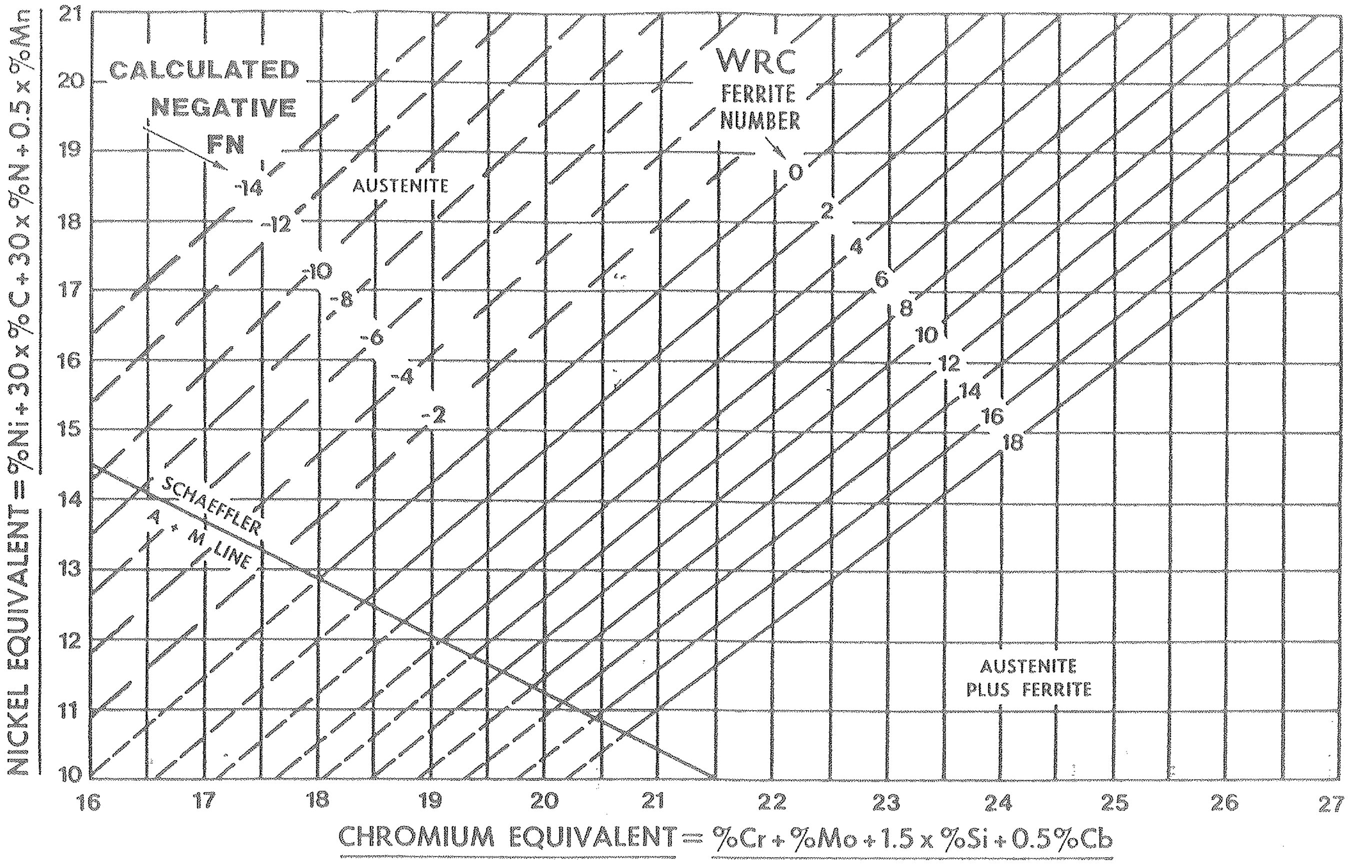

Fig. 3—Modified DeLong diagram

F Fig. 5 (Ref. 5)

For ferrite-free 316 SMAW

σ_y = 106 to 127 ksi

σ_u = 163 to 189 ksi

(Ref. 3)

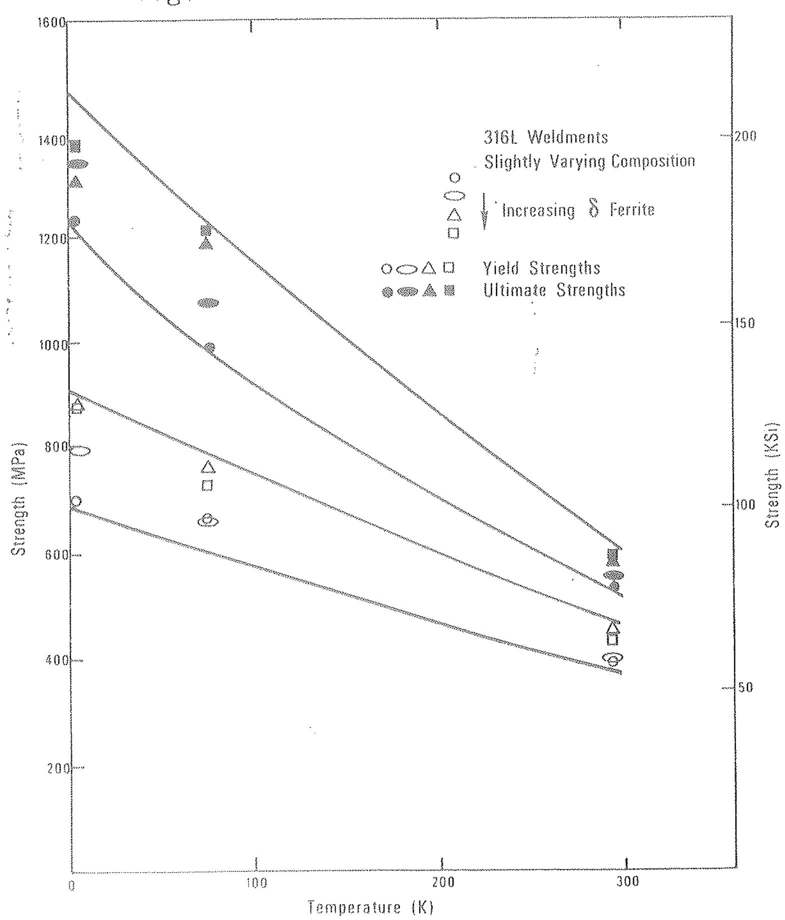

Fig. 2—Temperature dependence of the yield and ultimate tensile strengths of [illegible] weldments with 0.1 (○), 4.1 ([illegible]), 8.5 (Δ), and 10.1% (□) delta ferrite

Fig. 6 (Ref. 4)

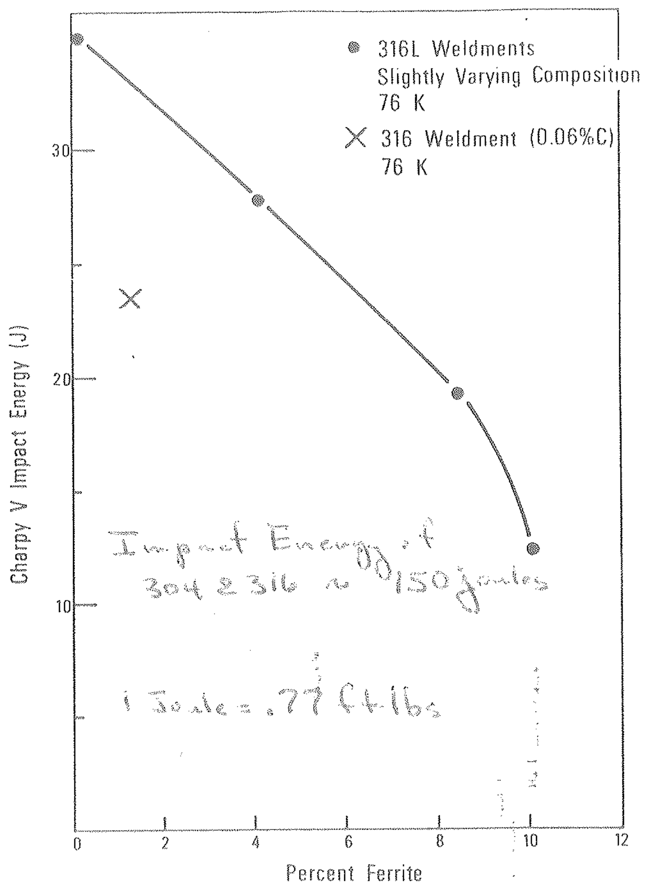

Fig. 11 (Ref. 4)

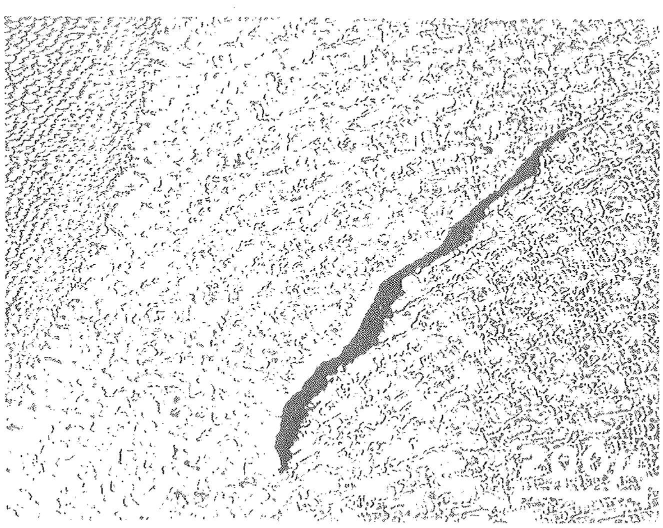

Fig. 1—Optical micrograph showing fissuring in underbead region of 3 in (76 mm) thick fully austenitic Type 316L stainless steel vertical SMA weld As-welded condition. Etchant: mixed acids

Fig. 14 (Ref. 2)

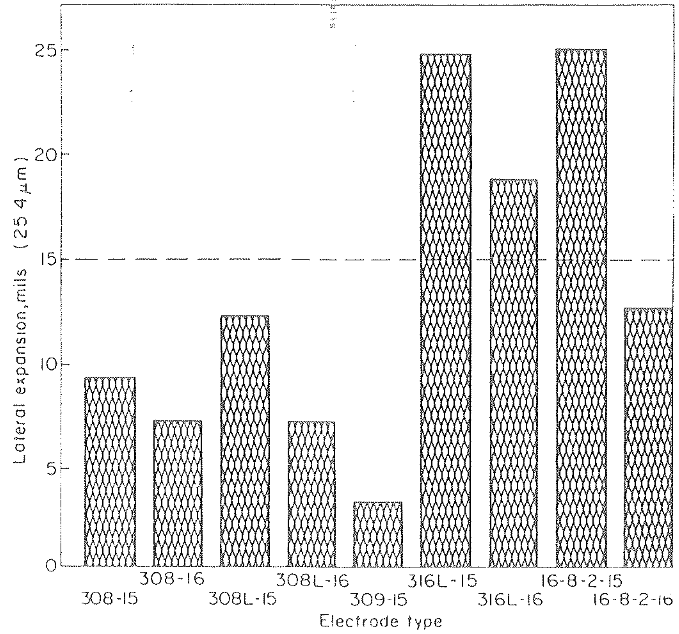

Fig. 4 Lateral expansion of typical, weld metals tested at −196° C (−320° F)

Fig. 13 (Ref. 6)

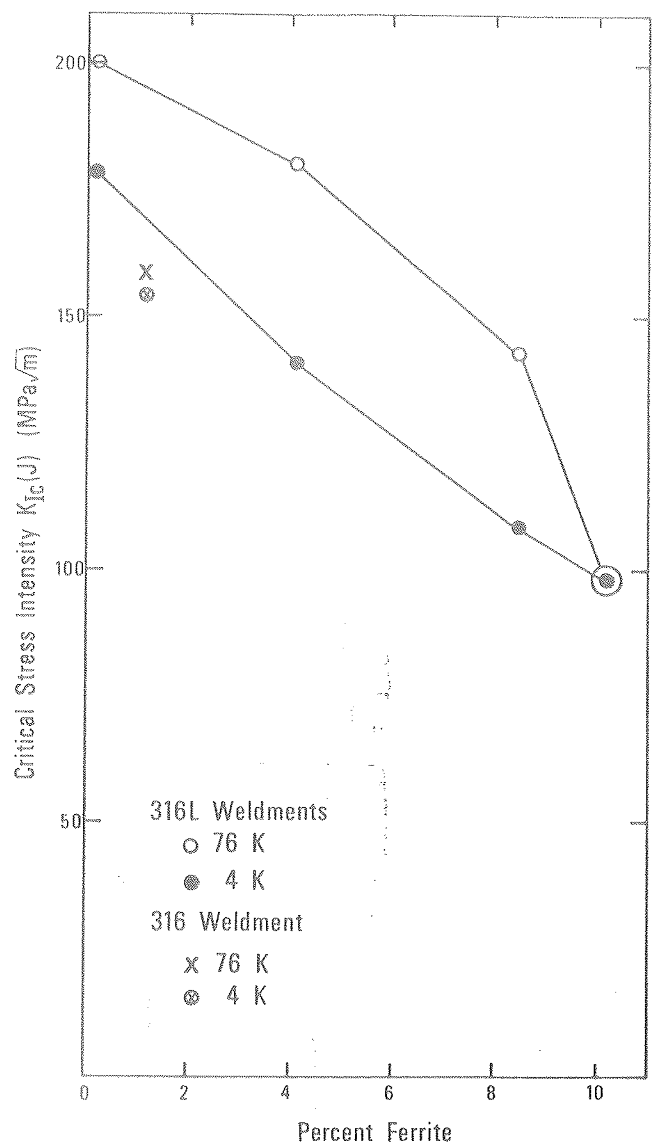

Fig. 12 (Ref. 4)

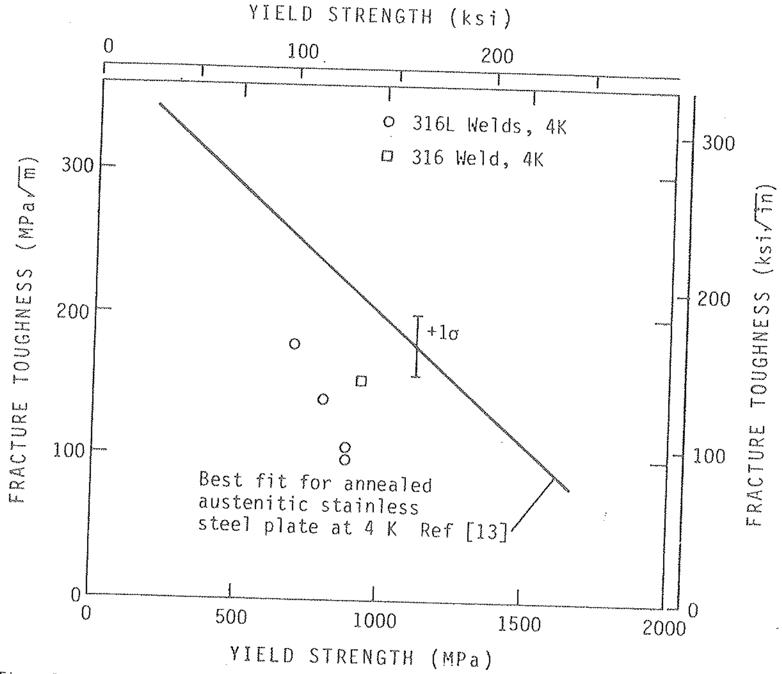

Fig. 13—Fracture toughness at 4 K of E316L weldments as a function of yield strength. Also shown is the best-fit line for the dependence of fracture toughness of wrought and annealed austenitic stainless steel plate on yield strength[13]

Fig. 7 (Ref. 4)

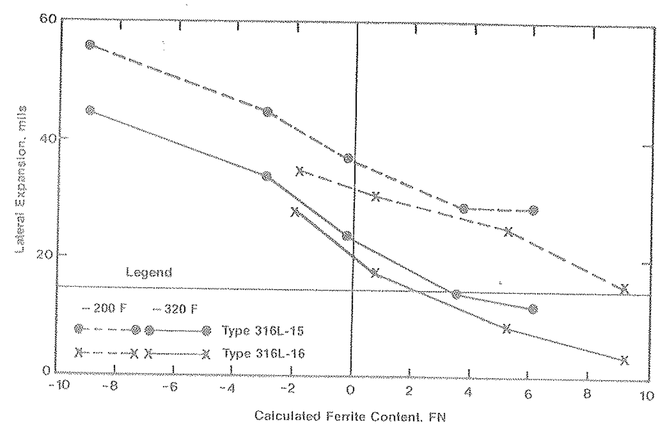

Fig. 7—Lateral expansion vs. Ferrite Number for 316/316L grade-series materials

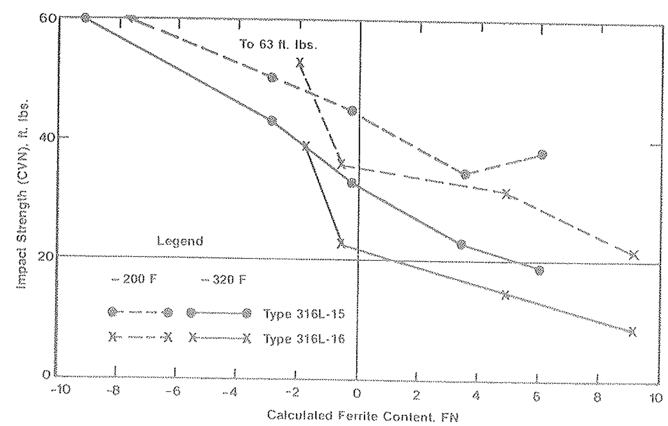

Fig. 8—Impact strength vs. Ferrite Number for 316/316L grade-series materials

Fig. 8 (Ref. 5)

Fig. 9 (Ref. 5)

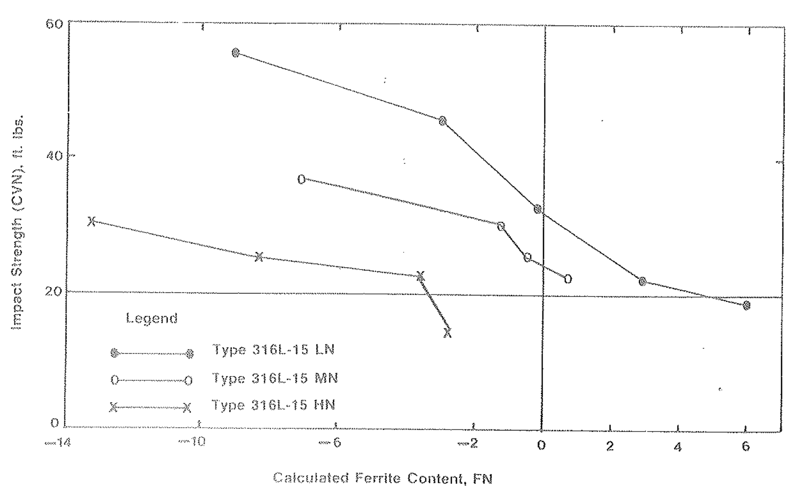

Fig. 3—Charpy V-notch energy of Type 316L-15 weld metal containing various amounts of ferrite and nitrogen after testing at −320 F (−196 C)

Fig. 10 (Ref. 5)

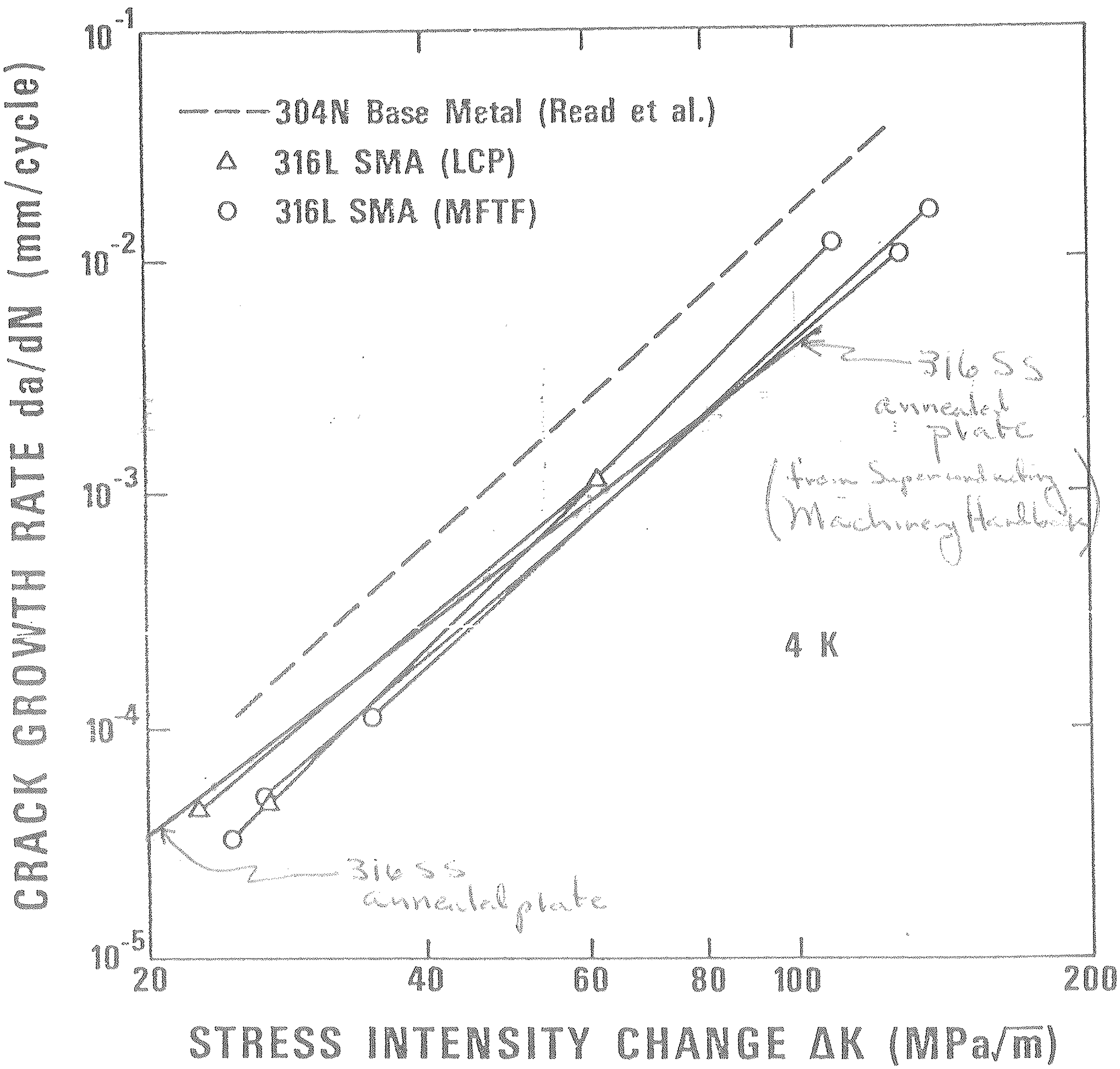

Fig. 8. The 4 K fatigue crack growth rate data for all 316L SMA weldments tested, compared with 304N base-metal data from Read and Reed [17].

Fig. 15 (Ref. 3)

4K Fracture Toughness		
316 plate	270	MPa$\sqrt{m}$
304 plate	340	MPa$\sqrt{m}$

1 MPa$\sqrt{m}$ = 0.91 ksi$\sqrt{in}$

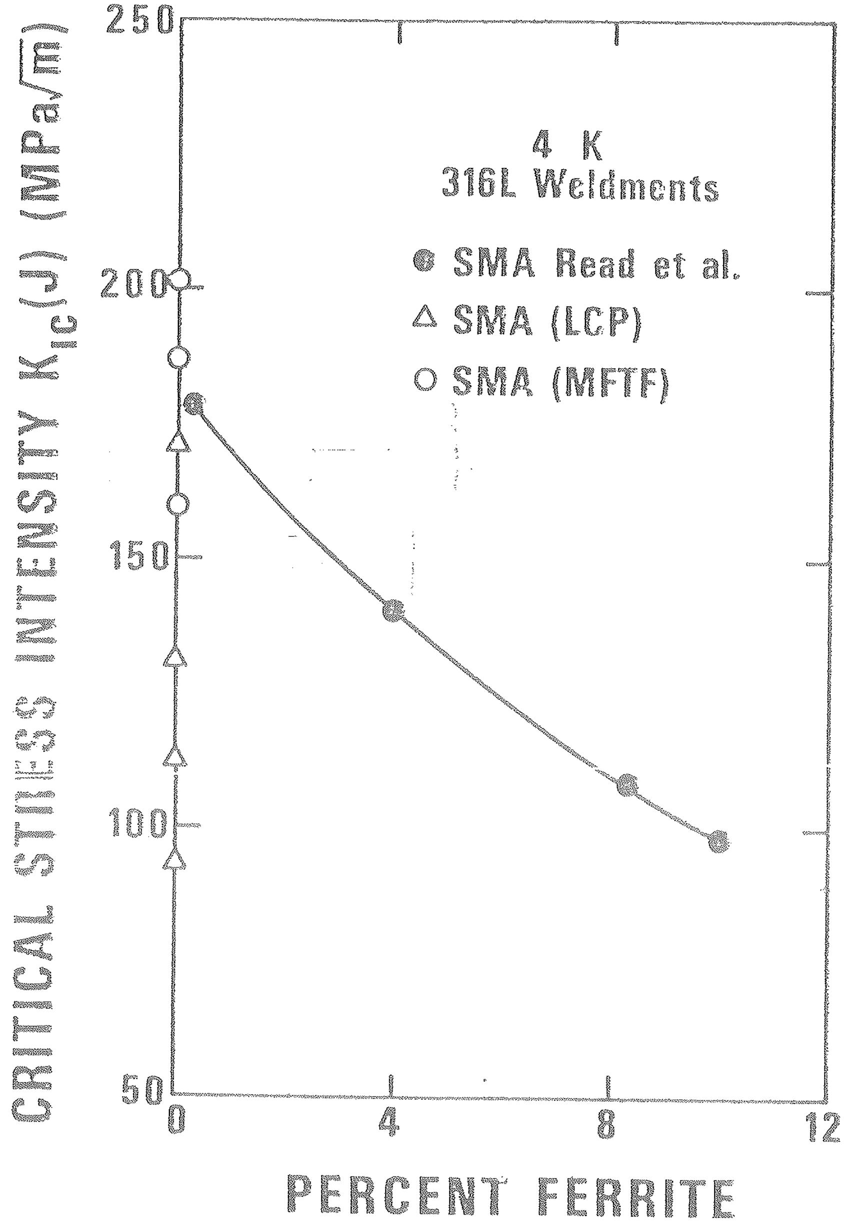

Fig. 1. Critical stress intensity factor, $K_{Ic}(J)$, as a function of delta-ferrite content at 4 K, showing the wide variation in fracture toughness that has been found for 316L SMA weldments with 0% ferrite.

Fig. 16 (Ref. 3)