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A VACUUM - ASSISTED REPLICATION TECHNIQUE FOR

J_{IC} ZONE TESTING IN HSLA STEEL EB - WELDS

by

ANDREW STEWART HERBST, B. ENG.

A thesis submitted to the Faculty of
Graduate Studies in partial
fulfillment of the requirements for the
degree of Master of Engineering

Department of Mechanical and Aeronautical Engineering

Faculty of Engineering

Carlton University

Ottawa, Ontario

March 2, 1981

The undersigned hereby recommend to the Faculty of Graduate Studies, Carleton University, acceptance of the thesis: "A Vacuum - Assisted Replication Technique for J_{IC} Zone Testing in HSLA Steel EB - Welds", submitted by Andrew Stewart Herbst, B.Eng. in partial fulfillment of the degree of Master of Engineering.

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March 2, 1981

ABSTRACT

A laboratory technique for measuring the room temperature local fracture toughness in and near a weld is presented. The technique involves the silicone rubber replication of the notch-tip under load. Both J_{Ic} and $CTOD_1$ results are obtainable for any location and orientation of a crack with respect to the weld centerline.

The technique is applied here to EB-welded HSLA steel and to an unwelded sample of CSA G40.8/A-3 structural steel. Compact specimens are used with the assistance of a newly devised vacuum chamber to assist the flow of the replicating rubber into the notch-tip region.

Results indicate that, for notch-tips located in the same metallurgical zone of a weld, the fracture toughness of the zone evaluated on the basis of the Merkle-Corten equation for J_{Ic} will vary significantly depending upon the initial orientation of the crack or notch. The same result is found for $CTOD_1$ values.

The text also contains a review of weld morphology with particular attention to HSLA steels, and a comprehensive review of current notch-toughness testing techniques with the emphasis on weld applications.

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PRINCIPLE SYMBOLS AND ABBREVIATIONS

COD	- Crack Opening Displacement measure anywhere along the crack surface.
CTOD	- Crack-Tip Opening Displacement, the COD at the crack-tip.
CTOD _i	- Critical CTOD occurring at crack initiation or crack extension.
COS	- Crack Opening Stretch, the CTOD prior to CTOD _i .
K _I	- Stress Intensity for Mode I (see figure 2.18a).
K _{II}	- Stress Intensity for Mode II (see figure 2.18b).
K _{III}	- Stress Intensity for Mode III (see figure 2.18c).
K _{Ic}	- Critical stress intensity in plane-strain, Mode I; a material property, and a function of temp. and strain rate.
K _Q	- A candidate value for K _{Ic} .
K _c	- Critical stress intensity factor for Mode I, with plane-strain conditions not existing, and is a function of sample thickness, temperature, and strain rate.
K _R	- Critical stress intensity factor for plane-stress.
J _I	- Value of the J-Integral, Mode I.
J _{Ic}	- Critical value of J, a material property.
J _{Io}	- J _{Ic} calculated at the "onset" of stable crack growth.
V _g	- Clip gauge displacement.
Δ	- Load point displacement.
δ	- Symbol for COD.
δ _t	- Symbol for CTOD.
δ _c	- Symbol for Critical CTOD.
δ _i	- Symbol for CTOD _i .
ε	- Strain.
σ	- Stress.

USEFUL CONVERSION FACTORS IN FRACTURE TESTINGDistance

1 m = 39.370079 in

1 in $\approx$ 0.0254 m

Force

1 N = 0.22480894 lb

1 lb = 4.44822 N

Area

1 m² = 1550.0031 in²

1 in² = 6.4516 cm²

Stress

1 kPa = 1 kN/m² = 0.145038 psi

1 psi = 6.89476 kPa

1 MPa = 1 MN/m² = 0.145038 ksi

1 ksi = 6.89476 MPa

Energy

1 J(Int.) = 0.737684 ft-lb

1 ft-lb = 1.3556 J

1 J = 8.8522 in-lb

1 in-lb = 0.11297 J

1 kJ = 8.8522 in-kip

1 in-kip = 0.11297 kJ

Fracture Toughness

1 MN-m^{-3/2} = 1 MPa√m = 0.910048 ksi√in

1 ksi√in = 1.09884 MN-m^{-3/2}

1 kN-m^{-3/2} = 1 kPa√m = 0.910048 psi√in

1 psi√in = 1.09884 kN-m^{-3/2}

J-Integral Values

1 J/m² = 1 N/m = 0.00571015 lb/in

1 lb/in = 175.127 J/m²

1 kJ/m² = 1 kN/m = 0.00571015 kip/in

1 kip/in = 175.127 kJ/m²

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CHAPTER 1

INTRODUCTION

R

I N T R O D U C T I O N

The brittle fracture of steel and steel weldments has been the subject of a great deal of research since the unfortunate experiences with the T-2 tankers and the Liberty ships during World War II.¹ As the field of fracture mechanics developed and data became available relating microstructure to toughness, it became known that a finer ferrite-grain size would produce both higher strength and higher fracture toughness^{2,3}. Thermo-mechanical processing techniques were subsequently developed to produce steels having finer grain sizes.⁴ Unfortunately, the process of welding these steels results in new microstructures of varying grain size and grain shape.⁵⁻⁷ Thus while the parent plates in a ship's hull or a pipeline might possess adequate strength and toughness, the narrow zones of coarse-grained material near a weld could have significantly lower toughness. This is of special concern because the greatest incidence of defects in welded structures are associated with either the heat-affected-zone (HAZ) or with the weld metal itself.⁸

As techniques for laboratory testing of material properties have improved, weld toughness testing has remained a difficult problem.^{9,10} This is primarily the result of the non-homogeneity of welds, and the fact that this non-homogeneity occurs over such a narrow region. The specimens used for weld toughness tests are generally very much

larger than the weld dimensions, and rarely can a suitable specimen can be machined entirely out of weld metal.

The philosophy of preventing fracture initiation from flaws inherent in the material is concerned with ensuring sufficient local toughness in the material immediately surrounding the defect.^{9,11} Only a very limited amount of experimental work has been performed in attempting to measure the local toughness in an actual weld.¹²

This paper introduces a new technique for fracture toughness testing of welds. The technique evaluates the toughness of welds for a crack-tip located in any metallurgical zone of a weld, and at any orientation with respect to the weld centerline.

The material chosen for the tests was a high-strength-low-alloy (HSLA) steel, a material designed for weldability in applications such as arctic pipelines where toughness is important.¹³ A brief description of these steels will be given. In addition, a fairly comprehensive review of conventional weld toughness testing techniques will be presented. These techniques have their advantages and disadvantages, and their description can serve as a background against which the new technique introduced here can be viewed.

CHAPTER 2

BACKGROUND AND
LITERATURE REVIEW

2.1 HSLA STEELS

2.1.1 Controlled Rolling

The HSLA steels are a family of steels designed to give moderately high strength together with good low-temperature toughness and good weldability.⁴ They are approximately twice the price of hot-rolled structural steels.

Higher strength is usually associated with lower toughness. This is because the same metallurgical mechanisms that increase strength, eg. cold-working and precipitation hardening, decrease the ability of the material to deform by dislocation slip. This promotes brittle cleavage. The exception to this inverse relationship between strength and toughness is achieved through the process of grain refinement. By increasing the number of grains in a metal, both dislocation slip and cleavage crack propagation are inhibited.^{2,3}

In the hot-rolling of steels, the austenite-grains become deformed and may recrystallize. If sufficient time at temperature is allowed, the fine recrystallized austenite-grains grow, and grain coarsening occurs. The coarse grained austenite will transform to a coarse grained ferrite upon cooling. Conversely, a fine grained austenite structure will transform to a fine grained ferrite. This is because austenite grain boundaries are the preferred nucleation sites for the ferrite to austenite transformation.¹⁴

To obtain grain refined ferrite, one tries to have a high grain boundary surface area/volume ratio in the pretransformation austenite. This may be achieved through either grain refinement or grain elongation.

In the controlled rolling process of HSLA steels, two controls are imposed upon the austenite during deformation:

- 1) Microalloying additions of Nb, Ti, Al, and V act to retard recrystallization and/or grain growth through both a solid solution effect and a precipitation mechanism that stabilize a substructure in the austenite.¹⁵⁻¹⁷ Niobium is the most effective of these elements in retarding recrystallization.^{17,18}

The retardation of grain growth is thought to result from the interaction of second-phase particles with the austenite-grain boundaries. The interaction stems from the elimination of grain boundary area (energy) at the interface of the grain boundary and the second-phase particle. The particle has a drag effect on the grain boundary since any movement of the boundary away from the particle will require a local energy increase. These precipitate particles are the nitrides, carbides, and carbonitrides of the microalloying elements Nb, Ti, V, and Al.

- 2) Low temperature rolling, in the range 950°C to the Ar₃ temperature (750°C) results in deformed austenite that does not have sufficient time to recrystallize during the rolling process. These elongated grains will contain deformation bands that also act as ferrite nucleation sites.¹⁴ As the amount of deformation in this temperature range increase, the number of deformation bands increases, and their distribution becomes more uniform.¹⁹ This gives rise to a finer and more uniform ferrite-grain size. Since the ferrite-grain size is a function of the number of nuclei, then the more nuclei there are the finer will be the ferrite.

The controlled rolling process gives microalloyed steels high strength and high toughness primarily through grain refinement. Unfortunately, welding usually undoes much of the microstructural modifications just described. The fusion zone completely melts and resolidifies

with no "memory" of its former grain size. Fortunately, the use of filler metals permits the introduction of additional alloying elements into the weld pool. Hence the fusion zone may be essentially a "high alloy casting" in some cases, and can have higher strength and toughness than the parent metal.

The heat affected zone does not have the "option" of changing its chemical composition during welding since it never melts. If the heat input is too severe, then excessive grain growth may occur and the controlled rolling benefits may be lost. Testing to evaluate just how much is lost locally by welding is the subject of this paper.

A technique capable of measuring local toughness is clearly required to develop welding procedures and to design steels of optimum toughness on a rational basis.

2.1.2 Weldability

HSLA steels are designed for welded applications. That is, these steels exhibit good "weldability". The evaluation of a steel's weldability is presently done by judging the integrity of a weld by a number of mechanical tests and non-destructive evaluation techniques. The weld properties evaluated in determining weldability may include:^{13,20}

- 1) strength
- 2) ductility
- 3) toughness, especially at low temperatures, in both
 - a) the fusion zone, and
 - b) the heat affected zone.
- 4) resistance to hydrogen-induced cracking
- 5) resistance to lamellar tearing.
- 6) resistance to solidification cracking.

This paper is concerned only with the measurement of weld fracture toughness. A host of tests are currently used to assess the notch toughness of welds, and some of these will be described. Then a new variation in notched toughness testing will be introduced. It is hoped that the new method suitably refined, could aid in assessing the weldability of a steel, and in the selection of the optimum welding procedure for a particular steel and application.

2.2 MECHANICAL TESTING OF WELDMENTS

2.2.1 Overview

Fusion welding is a process of joining metals that requires that the materials in the joint region be heated to temperature above their melting points. The nature of this process generally adds residual stresses to the weldment, and introduces two types of modifications to the parent materials:

- 1) geometric
- 2) metallurgical.

Geometric modifications may produce physical discontinuities that will effect the state of stress ~~within~~ and near a weld. These discontinuities stem from two basic sources:

- 1) joint design, eg,
 - a) fillet vs. butt, etc
 - b) effect of reinforcement
 - c) distortion (from residual stresses)
- 2) flaw formation, eg,
 - a) cracking
 - b) slag inclusion
 - c) undercutting
 - d) porosity.

Metallurgical changes have the effect of producing a new material or spectrum of materials within and near the weld.

The response of each of these materials or "metallurgical zones"

to a particular state of stress or other environment may differ radically from that of the parent material. Examples of metallurgical changes found in and near welds include:

- 1) phase transformations
- 2) dilution and segregation of alloying elements
- 3) recrystallization
- 4) grain growth

The designer seeking to predict the behavior of the weldment may find that the combination of geometric and metallurgical modifications resulting from welding frequently overrides the parent properties. The weld zone then becomes the governing factor in design. Unfortunately, the complex nature of welds makes experimental measurement and the theoretical prediction of their mechanical properties difficult.

A rather large variety of mechanical test methods are used today in weld evaluation. Stout ²¹ has classified mechanical tests for weldments into three broad categories:

- 1) static strength tests
- 2) cyclic tests
- 3) notched toughness tests.

These tests may be performed over a range of temperatures and in a variety of chemical environments to reflect the intended application of the weldment.

In the next section the morphology of typical welds will be described in greater detail to illuminate the complexity of their structure. In the following section some of the presently used notched toughness tests will be described to demonstrate their diversity. With these descriptions as a background, the field of fracture mechanics is introduced and a new technique in notched toughness testing is developed.

2.2.2 Weld Morphology

The classical description of weld morphology consists of three metallurgical zones: (refer to figure 2.1 (a)):

- 1) fusion zone (FZ) - material that has been melted during the welding process. This includes all filler metal.
- 2) heat affected zone (HAZ) - material that has had its metallurgical structure modified by the heat of welding but which has not been melted. This zone has the same chemical composition as the parent material.
- 3) parent material (PM) - the aggregate material, unmodified by the welding process.

This three-zone description is useful, but oversimplified. Savage et al⁵ have used a two-stage nital and sodium bisulfite etching procedure to reveal solidification structural details at the fusion boundary in HY-80 welds. At the fusion boundary of bead welds they detected a zone of partial melting and a zone of melted base metal (the unmixed zone or UMZ) which has not mixed significantly with the bulk of the weld metal. The unmixed zone will etch to a different appearance using sodium bisulfite due to selective staining of the iron-rich regions.

The partial melting adjacent to the weld pool during welding is thought to be the result of:

Fig.2.1 Schematic Metallurgical Zones in Welds

(a) Classical Three-zone Model
(for single-pass, full penetration)

(b) More Detailed Model (adapted from Savage et al⁵)
(for bead-on-plate, partial penetration)

(c) Effect of Multi-pass Welding (after Kameda, et al⁷)

- 1) The constitutional liquation of sulfide and other non-metallic inclusions, and
- 2) grain boundary liquation occurring when migrating grain boundaries intersect with regions of constitutional liquation resulting in wetting of the grain boundaries.

The UMZ has been completely melted and will have a composition essentially identical to the base metal. There will also be a region on the hot side of the UMZ that will have a composition gradient blending the composite region with the base metal. A schematic representation of Savage et al's model is shown in figure 2.1 (b) where:

- zone 1) - composite region
 - comprises the bulk of weld metal
 - is fairly well mixed with elements of filler metal.
- zone 2) - unmixed zone
 - consists of melted and solidified PM
 - composition essentially identical to PM
 - also includes a composition gradient region between 1) and 2).
- line L) - weld interface
 - the degree of melting is not complete beyond this line.
- zone 3) - partially - melted zone
 - portion of HAZ that has undergone any amount of localized melting.
- zone 4') - coarse - grained HAZ
 - results from ferrite transforming to austenite and grain growth occurring in the austenite prior to transformation back to ferrite.
- zone 4'') - fine grained HAZ
 - ferrite transformed to fine-grained austenite and upon cooling transforming to fine-grained ferrite.

If the parent material is cold-rolled or contains cold-worked material in the vicinity of the weld, then the HAZ may actually be comprised of four sub-zones⁶. In this case zones 4') and 4'') which have been re-austenitized will be followed (in the direction of heat flow) by another pair of coarse-grained and fine-grained zones. The second CGHAZ is the result of ferrite-grain growth following ferrite recrystallization. The second FGHZ which will be adjacent to the true PM is the result of recrystallization only. There may also be some overaging effects in precipitation hardening steels.

The situation becomes still more complicated if multipass welding is performed. Additional passes may partially or fully re-austenitize the previous weld or may cause tempering. Without going into further detail in this situation, one may gain some appreciation of the complexity by studying figure 2.1 (c) after Kameda et al⁷. In the above figure, the dashed lines labelled A_1 and A_3 represent the peak reheat temperature reached in the corresponding pass, where conventionally:

- A_1 - is the eutectoid temperature in steel (723°C).
- A_3 - is the ferrite-to-austenite transformation temperature (approximately 900°C in low-carbon steel).

The real situation is more complex than any of the models just described. Impurities such as slag inclusions are frequently present, and geometric defects such as porosity and microcracks can and will occur.

When fracture occurs in or near a weld, the advancing crack-tip must encounter the various metallurgical zones either sequentially or in some combination. The plastic zone surrounding the crack-tip will be far from uniform in shape, and the behavior of the crack becomes very difficult to predict with current fracture mechanics theory. Mechanical testing of actual welds is then the best way to understand their behavior and is needed to guide the development of new theory.

2.2.3 Notched Toughness Testing

This section will describe some of the notched toughness testing techniques currently in use. Most of these techniques have found their way into various government or industry standards, and these standards will be cited in those cases. As will be seen there are a wide variety of specimen types and configurations, some of which are dimensionally quite large.

For economic reasons, small, easily fabricated specimens are desirable. Even if cost were not a serious consideration, many materials for which notched toughness data are desired are simply not available in large shapes. In these cases, certain testing techniques may be immediately ruled out since the size requirements of the test cannot be met.

Cheap and simple test techniques that are reliably reproducible are highly desirable. It is an additional advantage to use equipment that is common and readily available.

With these thoughts in mind, it is appropriate to introduce and briefly describe the most popular of notched toughness tests, the Charpy V-notch, a special case in the general category of notched bar impact testing.

2.2.3.1 Notched Bar Impact Testing

Standard: ASTM Standard E23-72.²²

Essential Features:

- 1) suitable specimen
- 2) anvil or support for specimen
- 3) moving mass of known kinetic energy.
- 4) device for measuring residual energy in moving mass after specimen is fractured.

Specimen Dimensions:

Two basic types of specimens are recognized in the above standard:

- 1) Simple-beam (Charpy)
- 2) Cantilever -beam (Izod)

Some of the variations in specimen and notch geometry are shown in Figure 2.2 and 2.3. The specimen that has gained the most widespread use is Type A of Figure 2.2, the Charpy V-notch.

The specimen orientation for the Charpy and Izod tests are shown in Figures 2.4 and 2.5 respectively.

The popularity of the Charpy V-notch test is due to:

- 1) Simple specimen design
- 2) Relatively small specimen size
- 3) Adaptability of test technique to a wide range of test temperatures.
- 4) Test equipment widespread, and simple to operate
- 5) Charpy values reported frequently in the literature, making comparisons with past practice possible.

Figure 2.2 Three Charpy Specimen Dimensions, Types A, B & C

Figure 2.3 Izod Specimen Dimensions, Type D

Figure 2.4 Charpy Impact Test Configuration

Figure 2.5 Izod Impact Test Configuration

Applications to Weld Toughness Testing

In applying the Charpy or Izod tests to the study of weldments it is common to place the notch root in the FZ or HAZ such that the crack propagates parallel to the welding direction.²¹ If the heat input is high enough it may be possible to obtain full-size²¹ or 2/3 size²³ samples machined entirely out of FZ or HAZ material. In these cases the crack is forced to travel within the zone in which the notch-tip was placed.

In lower heat input welds these zones may be too narrow to be machined into homogeneous Charpy samples, especially if the HAZ is treated as several very different sub-zones as described in section 2.2.2. The samples can then be machined out of the heterogeneous weld region and notched in the zone of interest. Unfortunately, the fracture may choose to jump out of the notched zone and travel in an adjacent zone^{10,24,25}. It has been shown that the path of fracture is not necessarily the lowest energy path¹⁰. In this case high energy ductile fracture is forced to initiate in a softer zone adjacent to a hard and brittle zone where a much lower energy cleavage fracture could occur.

To overcome this fracture path difficulty, a cross-weld Charpy test has been used^{10,24,26} so that the fracture is forced to pass through the weld. In these tests, the absorbed energy is not meaningful. Instead the fracture appearance is used to measure toughness. The areal percentage of ductile fracture is measured in SEM micrographs from the zone of interest.

Charpy tests have been advanced in two other ways:

- 1) Fatigue pre-cracking^{21,27} to enhance the acuity of the crack tip. This sharp crack minimizes the size of the plastic zone during crack initiation.
- 2) Instrumenting of the striking tup²⁸. In these tests load-deflection or load-time oscillograms can be obtained for fracture toughness estimation.

Reporting of Charpy Data

Three measurements are typically made on Charpy test specimens:

- 1) Absorbed energy (ft-lb or J)
- 2) Notch-root or lateral contraction (mils, mm, or %)
- 3) Fracture appearance (% shear or ductile fracture as indicated by a dimpled fracture morphology)

All of these measurements can be performed on each sample. Samples are typically tested over a wide range of temperatures and a ductile-brittle transition temperature can be established. For the cross-weld test for evaluating particular zones, only the fracture-appearance-transition-temperature (FATT) is meaningful.

2.2.3.2. Dynamic Tear Test (DT).

References: - ASTM Committee E-24 on Fracture Testing of Materials²⁹
- W.S. Pellini³⁰

Essential Features:

- 1) suitable specimen
- 2) pendulum or drop-weight machine
- 3) device for measuring the total energy loss during separation
(the DT energy).

Specimen Dimensions:

The only specimen dimensions to be used are shown in Figure 2.6. The specimen blank is 0.625" (15.8 mm) thick by 1.60" (38.0mm) wide by 7.125" (191.0 mm) long.

Details of the knife for pressing the sharp tip of the notch are given in figure 2.7. Notch details are given in Figure 2.8.

Applications to Weld Toughness Testing:

The DT test is used to measure the resistance to rapid progressive fracture in base metal and weld metal only. No provision for testing heat-affected zone fracture resistance is made in the proposed ASTM standard²⁹. Furthermore the weld metal must be a minimum of 5/8" (16 mm) wide and the fracture path must be parallel to the welding direction as shown in Figure 2.9. The notch-tip is placed on the weld centerline.

Reporting of Dynamic Tear Test Data:

The DT energy is reported along with the test temperature. The test may be performed over a wide range of temperatures.

Comments: Although similar in many respects to the Charpy V-notch test, the DT test provides a longer fracture path and allows more complete development of the plastic zone at the crack-tip. The DT results serve as a measure of the "enhanced resistance that may develop about one plate thickness of crack extension from a sharp notch"²⁹. Thus it more closely simulates fracture in a large plate.

Dimensions and Tolerances for Specimen Blank

Parameter	Units	Dimension	Tolerance
Length, L	in.	7.125	±0.125
	mm	181.0	±3.2
Width, W	in.	1.60	±0.10
	mm	38.0	±2.5
Thickness, B	in.	0.625	±0.033
	mm	15.8	±0.8
Angularity, α	deg	90	±2

Figure 2.6 Dynamic Tear Test Specimens, Anvil Supports, and Striker.

Figure 2.7 Material: tool steel (60 HRC) Knife for Sharpening Tip of Notch in Dynamic Tear Specimen.

Dimensions and Tolerances for Notch Tip

Parameter	Units	Dimension	Tolerance
Net width, (W-a)	in.	1.125	±0.020
	mm	28.5	±0.5
Machined notch width, N _a	in.	0.625	±0.005
	mm	16.0	±0.12
Machined notch root angle, N _g	deg	60	±2
Machined notch root radius, N _r	in.	0.005	max
	mm	0.13	max
Pressed tip depth, I _p	in.	0.009	±0.002
	mm	0.20	±0.05
Pressed tip angle, I _a	deg	40	±5
Pressed tip root radius, I _r	in.	0.001	max
	mm	0.025	max

Figure 2.8 Details of the Notch in a Dynamic Tear Specimen.

Figure 2.9 Dimensions of a Weld Metal Dynamic Tear Specimen.

2.2.3.3. The Drop-Weight Test to Determine the Nil-Ductility

Transition Temperature (NDT).

Standard: ASTM Designation: E208-69.³¹

Essential Features:

- 1) suitable specimen with crack-starter weld bead
- 2) guided free-falling weight with an energy of 250 to 1200 ft-lb (340 to 1630 J) depending on yield strength (see Table 2.1)
- 3) special anvil with appropriate deflection stops
- 4) means of controlling temperature of specimens over the required range of temperatures.

Specimen Dimensions:

There are three specimen sizes (types). These are given in Table 2.1. The smallest of these is the Type P-3 specimen with dimensions: 5/8" thick x 2" wide x 5" long (15.9mm)x(51mm)x(127mm).

Applied to the surface of the plate to be tested is a brittle weld bead with a notch cut into it. The notched weld bead serves as a cleavage crack starter. Crack-starter weld notch details are given in Figure 2.10.

Applications to Weld Toughness Testing.

Although ASTM E208-69 does not specifically mention any applications for measuring the NDT in welds, the method has been used. Bryhan and Troyer³² performed NDT tests on welds in a low-carbon Mo-Nb X-70 steel to help assess weldability. The specimens were of the dimensions shown in figure 2.11. Note that the plate thickness in these tests was only 0.56" (14mm) which is somewhat less than the minimum of 5/8" (15.9 mm) required by ASTM E208-69. Unfortunately, 0.56" was the thickness of the plates that they wished to investigate, and so they conformed in all respects except thickness to the dimensional requirements of a type P-3 specimen.

Reporting of Drop-Weight Test Data

NDT results are reported as : "break", "no-break", or no-test" for the temperature of the test. A specimen is considered "broken" if the fracture reaches one or both of the specimen edges of the tension surface. The specimen is "not-broken" if a visible crack in the crack-starter weld bead had not propagated to either edge of the tension surface of the sample. The test is "invalid" if the weld-deposit notch is not visibly cracked or the sample is not fully deflected to the anvil stop after testing.

The Nil Ductility Transition Temperature is the maximum temperature at which a specimen breaks.

Comments: Since the purpose of the small crack-starter bead is to initiate a cleavage crack, it is important that the heat-affected-zone of the crack-starter not be made more fracture resistant than the unaffected plate. This is possible in heavily cold-worked materials and in quenched and tempered steels of high hardness³¹. This effect is also a possibility in welds, which makes the applicability of the technique to welds somewhat questionable.

Figure 2.10 Weld-Notch Details and Example of a Notched Weld.

Figure 2.11 -Dropweight test specimen, ASTM-E208-69

2.2.3.4. The Drop-Weight Tear Test (DWTT).

Standard: ASTM Designation: E436-74³³

Essential Features:

- 1) suitable specimen with pressed notch
- 2) pendulum type or vertical-dropped-weight type testing machine of sufficient energy to fracture completely a specimen in one impact (up to 2000 ft-lb (2712 J) may be required).
- 3) means of measuring the percent shear area of the fractured specimen.

Specimen Dimensions:

The specimen dimensions for the DWTT are 3" by 12" (76.2 x 305mm) by full plate thickness as shown in figure 2.12. The notch is pressed in with a very sharp chisel to a depth of 0.200" (f.08 mm). The included angle of the notch is 45°.

Applications to Weld Toughness Testing:

The specimen may contain a weld across the three-inch width. The sharp notch can then be pressed into various locations in the weld metal or the heat-affected zone³⁴. Of course, as with the Charpy test, it is important that the fracture actually propagates in the zone of interest.

Reporting of DWTT Data.

The results of the DWTT are expressed as "percent shear area" where the shear-fracture surfaces are considered as "those having a dull gray silky appearance which are commonly inclined to the specimen surface". The fracture surface used in the shear-area determination is shown in Figure 2.13.

It is common to perform the test over a range of temperatures and to plot the results as percent shear area versus temperature. In this way, the 50% shear fracture appearance transition temperature (FATT) can be determined. Some representative DWTT fracture surfaces are shown in Figure 2.14.

Figure 2.12 Drop-Weight Tear Test Specimens and Support Dimensions and Tolerances (for Specimens $\frac{1}{8}$ to $\frac{1}{4}$ in. in Thickness).

Figure 2.13 Fracture Surface Included in Shear-Area Determination.

Figure 2.14 Representative DWTT Fracture Surfaces.

2.2.3.5 The Nick-Break Test.

Standard: API Specification 1104.³²

Essential Features:

- 1) suitable welded specimen
- 2) tensile machine or impact hammer and anvil (either simple beam or cantilever).

Specimen Dimensions:

9 in. (230 mm) long x 1 in. (25 mm) wide x pipe thickness.

The weld is centered transverse to the specimen and notched on both sides as shown in Figure 2.15.

Figure 2.15 -Nick-break test specimen

Reporting of Nick-Break Test Data

The fracture surfaces are examined after either a slow-pull or hammer impact has broken the specimen in two pieces. This is a pass/fail test performed at room temperature. To pass, the exposed fracture surfaces must show complete penetration and fusion. There is a limit on the individual size and combined net area of gas pockets:

greatest dimension of any gas pocket $\leq 1/16"$ (1.6 mm)

combined area of all gas pockets $\leq 2\%$ of exposed surface area.

In addition, the size and spacing of slag inclusions is limited:

max. slag inclusion depth $\leq 1/32"$ (0.8 mm)

max. length of slag incl. $\leq 1/8"$ (3.2 mm) or $\frac{1}{2}$ max. wall thickness,
whichever is smaller.

min. spacing between
adjacent slag inclusions $\geq \frac{1}{2}"$ (12.7 mm)

2.2.3.6. Linear Elastic Fracture Mechanics (K_{Ic} - testing)

Standard: "Standard Method of Test for Plane-Strain Fracture Toughness of Metallic Materials", 1974 Annual Book Of Standards, Part 10, Designation E399-74, American Society for Testing and Materials, Philadelphia, 1974.³⁵

Essential Features:

- 1) suitable specimen
- 2) fatigue pre-cracking capability
- 3) tensile or compressive machine and suitable load fixture (described in E399-74).
- 4) load vs. displacement chart recording apparatus, including a means of autographically measuring displacement to within ± 0.000020 in (0.5) mm).

Specimen Dimensions:

There are two types of specimens allowed in E399-74:

- 1) bend specimen (fig. 2.16)
- 2) compact specimen (fig. 2.17)

While the specimen dimensions have been standardized as shown in figures 2.16 and 2.17, there is some provision in section 7.3 of the Standard for alternative specimen dimensions. In that section it is stated that the thickness, B, may be allowed to lie between $0.25W$ and $0.5W$ for the compact specimen where W is the specimen width as defined in Figure 2.17. This alternative specimen provision adds a degree of flexibility to the rather demanding dimensional requirements of E399-74. However, the post-mortem dimensional check, described below, puts severe limitations on the ability to test material by this standard method and obtain "valid" results, i.e. results that meet the standard.

FIGURE 2.16 PRECRACKED BEND SPECIMEN WITH CHEVRON NOTCH

FIGURE 2.17 COMPACT K_{Ic} SPECIMEN FOR TENSILE LOADING

Figure 2.18 Three Modes of Cracking

To obtain valid K_{Ic} results, the specimen must meet the following requirements, many of which can only be checked by "post-mortem" analysis:

- 1) crack length: $0.45W \leq a \leq 0.55W$; $a \geq 0.050"$
- 2) thickness: $B \geq 2.5 (K_Q / \sigma_{ys})^2$
- 3) fatigue pre-crack:
 - a) crack angle $\leq 10^\circ$
 - b) $\Delta K_f > 0.9 K_{fmax}$.
 - c) $K_{fmax} / E < 0.002$ in.
 - d) $|a_1 - a_2|$ and $|a_2 - a_3|$ and $|a_3 - a_1| \leq 0.05 a_{avg}$.
- 4) load-displacement curve form and shape
 - a) $P_{max} / P_Q \leq 1.10$
 - b) $0.7 \leq dP/d\Delta \leq 1.5$

5) loading rate (stress intensity rate):

$$30 \text{ ksi } \sqrt{\text{in}}/\text{min} \leq \dot{K} \leq 150 \text{ ksi } \sqrt{\text{in}}/\text{min}$$

where: $K = \sigma \sqrt{a} f(a/w)$ is the stress intensity.

For the compact specimen:

$$K = \frac{P}{BW^{3/2}} \cdot \left[29.6 (a/w)^{3/2} - 185.5 (a/w)^{3/2} + 655.7 (a/w)^{5/2} - 1017.0 (a/w)^{7/2} + 639.9 (a/w)^{9/2} \right]$$

where: P is the load

B is the specimen thickness

W is the specimen width

a is the crack length

σ_{ys} is the material yield strength

E is the Young's Modulus of the material

Stress Intensity "Language".

Stress intensity is the simplest measure of the stress singularity at a crack tip. By adding subscripts to K , the stress intensity symbol, a variety of particular stress intensity values are denoted. Some of the more important stress intensities are:

K_{Ic} - The critical stress intensity for mode I cracking as determined by using E399-74. This is a material constant, dependent only upon temperature.

K_Q - a "questionable" or qualifying candidate for K_{Ic} . The corresponding load is denoted P_Q and is defined in the standard. $K_Q = K_{Ic}$ if all of the validity requirements of the test are met.

K_f - ($K_{fmax} - K_{fmin}$) - the fatigue pre-cracking stress intensity range

K_I - stress intensity in mode I loading (see fig. 2.18a)

K_{II} - stress intensity in mode II loading (see fig. 2.18b)

K_{III} - stress intensity in mode III loading (see fig. 2.18c)

ASTM E399-74 is concerned only with mode I loading, which is generally considered the "worst case".

Estimating K_{Ic} Before Testing.

The thickness requirement is frequently the most difficult to attain in testing for K_{Ic} since many of the materials of interest are supplied as rolled plate, and are not available in large thicknesses. The thickness required to achieve plane strain conditions in the centre portion of the sample may be

estimated prior to testing by using Table 2.2., adapted from the ASTM Standard. To use the table, the yield strength and Young's modulus of the material must be known.

Table 2.2 Estimating Thickness Requirements

σ_{ys}/E	<u>Required Thickness</u>	
	in.	mm.
0.0050 to 0.0057	3	75
0.0057 to 0.0062	2½	63
0.0062 to 0.0065	2	50
0.0065 to 0.0068	1-3/4	44
0.0068 to 0.0071	1½	38
0.0071 to 0.0075	1½	32
0.0075 to 0.0080	1	25
0.0080 to 0.0085	3/4	20
0.0085 to 0.0100	½	12½
0.0100 or greater	¼	6½

For an HSLA steel with $\sigma_{ys} = 483$ MPa and $E = 20.6$ GPa, then $\sigma_{ys}/E = 0.0023$ and the required thickness is over 75 mm, and is outside the range of the estimating table.

If the approximate toughness of the material is known (say from published data on similar material or from invalid tests) then one may estimate the required thickness from:

$$B \geq 2.5 \left(\frac{K_{Ic}}{\sigma_{ys}} \right)^2$$

For the same HSLA steel assuming $K_{Ic} \approx 110 \text{ MN-m}^{-3/2}$, then $B \approx 130 \text{ mm.}$

Applications to Weld Toughness Testing:

Since it is very unlikely that a sufficiently large specimen can be fabricated entirely from the fusion zone of a weldment and since the other metallurgical zones are even smaller, K_{Ic} tests cannot be performed in their valid form on weldments. More importantly, since the component is much thinner than

130 mm. it will not fail in plane strain and E399 has little significance.

A conceivable approach to weld toughness testing that incorporates the techniques of ASTM E399-74 is to use multiple identical specimens of a welded material, identical except that the tip of the fatigue crack is located in different zones of the weld. The resulting spectrum of values could serve as a measure of the weld toughness. These values could be either:

- 1) invalid K_Q values, i.e. critical stress intensity factors that are representative only of that thickness of the test samples, or
- 2) the specimen strength ratio, R_{sc} , as defined in ASTM E399-74 sect. 9.1.7. for the compact specimen:

$$R_{sc} = [2P_{max}(2W + a)] / [B(W-a)^2 \sigma_{ys}]$$

This approach might at least give the investigator a means of comparing different welding procedures for a particular thickness.

The present work has extended this philosophy into the realm of elastic-plastic fracture mechanics. The result is a new form of weld toughness testing that attempts to test the toughness of each zone in a weld. This technique will be described later.

2.2.3.7. Plastic Fracture Mechanics

Structural steels are frequently used in thicknesses that do not allow valid ASTM E399 tests. Furthermore, when economics permit, it is good design practice to use materials that can fully yield before fracture so that load redistribution may occur, and so that overloaded members can be visually identified. A logical and easily interpreted method of testing materials in the fully plastic regime for their notched toughness is the method of Soete and Denys⁹.

Wide Plate Tests for Plastic Fracture Mechanics

Reference: Soete and Denys⁹

Essential Features:

- 1) suitable wide-plate, center-cracked specimen
- 2) large tensile machine

Specimen Dimensions:

Rectangular plates of material of the same thickness as the design thickness of the structure should be used. The plates should be wide enough so that crack lengths longer than those easily detectable by the intended inspection technique can be accommodated. The plate length is nominally two to four times the plate width. The nature of the tests permits any rectangular dimensions to be used as long as the dimensions are measured prior to testing.

Defect Acceptability Criterion:

"Each defect which initiates no fracture before plastic deformation occurs in the defect free zone is acceptable".⁹

This is the fundamental criterion in Soete and Denys method.

- If this criterion is met, then yielding should be observable in the gross section, and adequate forewarning of overload will be possible. To meet this criterion, the material must exhibit strain hardening properties and, of course, a certain amount of ductility.

Figure 2.19 illustrates the four possible situations for a centre-cracked plate in tension with the crack plane perpendicular to the direction of pull. Case (a) represents the linear-elastic case with little or no plastic zone formation at the crack-tip. Case (b) is the elastic-plastic situation where relatively large plastic zones form at the crack-tip but do not extend throughout the plate. Cases (c) and (d) fall into the regime of plastic fracture mechanics. Case (c) is the so-called "full yield" situation where the plastic zones have extended from the crack-tips to the edges of the plate. In case (d) the phenomenon of "general yielding" occurs in the uncracked section before final fracture occurs in the cracked cross-section. Note that there is no concern here with subcritical crack growth.

Case

- (a) $\sigma_y > \sigma' > \sigma'' > \sigma$
- (b) $\sigma' > \sigma_y > \sigma'' > \sigma$
- (c) $\sigma' > \sigma'' > \sigma_y > \sigma$
- (d) $\sigma' > \sigma'' > \sigma > \sigma_y$

where:

- σ = the applied tensile stress
- σ' = the stress at the notch-tip
- σ'' = the stress at the free border in the plane of the notch
- σ_y = the yield stress of the metal

Figure 2.19 Basic Concepts of Plastic Fracture Mechanics

Figure 2.20 Yield and Fracture Sequences in Transverse Welds without Defects

Depending upon the intended application, one may use either full yield or general yield as the acceptable criterium. By using multiple specimens with a range of initial crack lengths, one can obtain an empirical plot of critical defect size versus nominal stress. These may either be performed over a range of temperatures to show ductile-brittle transition, or at the minimum design service temperature. Part-through cracks may also be tested. Test results can be compared to NDE data to determine the acceptability of a given defect.

Application to Weld Toughness Testing.

If these wide-plate tests are applied to a plate containing a weld with centerline perpendicular to the pull direction, then there are six possible failure sequences as illustrated in Figure 2.20. If there are no defects present, then the ideal welding procedure would give case E results where yielding occurs first in the parent plate and then in the weld. Then at a higher stress the parent metal fractures. Hence the weld has not limited the strength of the structure.

If a defect is present in the weld, then an important criterium is that full yielding occur in the plane of the defect prior to fracture. In comparing welding procedures or consumables, the optimum procedure would be that which permits the largest defect size satisfying the above criterium. The heat affected zone should be tested in this manner as well.

Discussion on The Method.

For transverse welds, the stresses are the same for all sections perpendicular to the applied load, but the strains will vary. For longitudinal welds, strain will be constant across the section and stresses will vary. Soete and Denys limited their tests to the transverse case, and made the following comment about the transverse case:

" Up to now, no systematic work has been done on longitudinal welds with defects. This case is difficult because the notch, being oriented perpendicular to the weld, has its apex, according its length, located in metallographic structures changing from one point to the other. The only valid recommendation for the time being is to repair this kind of defect or to apply a heat treatment restoring the ductility of the heat affected zone."

It is conceivable that the technique could be applied to longitudinal welds by first establishing where the most fracture prone location for the notch-tip is within the weld vicinity. This location might be defined as the one where the critical crack's tip was initially located in a specimen having multiple parallel cracks, of identical size, each with its tip at a slightly different distance from the weld centerline.

This most sensitive location being established, one could now perform the remainder of a series of tests with progressively smaller crack lengths, all cracks having one tip in the sensitive zone. Since it represents the "worst case", the critical crack size determined in this way would be a pretty good yardstick for comparing welding procedures.

The technique is, unfortunately, very expensive and time consuming.

2.2.3.8.1. The Crack Tip Opening Displacement, CTOD.**

Standard: B.S.I. Draft No. 19.³⁶

Essential Features:

- 1) suitable specimen
- 2) slow-bend or tension testing machine
- 3) means for continuous load-loadpoint displacement recording

Specimen Dimensions:

Most commonly the specimens used are fatigue-precracked or saw-cut three-point bend specimens, although compact, centre-cracked, or edge-notched tension specimens have been used.

There is no fixed size or dimensional requirement, although the specimens tend to conform to the type used in ASTM E399-72.^{1,35}

For a conventional compact specimen with attachable knife edges, the CTOD may be calculated from the clip gauge displacement, V_g by the means shown in Figure 2.21. This calculation requires that the rotational factor, r be determined.

Rotational Factor, r .

By assuming that the crack faces open in a simple hinge mechanism,

** The abbreviation "CTOD" is used here to mean the special case of the crack-opening-displacement (COD) measured at the tip of the crack, as distinct from the COD measured at any point along the crack. Although the literature commonly uses the abbreviation "COD" to mean the crack-tip-opening-displacement, the distinction is made in this paper because of the nature of the experimental work to be presented later.

The greek letter " δ " is used as a mathematical symbol for the COD so that " δ_t " is used to symbolize CTOD.

Figure 2.21 Schematic Representation of the Notch Profile During Opening. (Not to scale)

V_g = Clip Gauge Displacement

$$\Delta = V_g \times \left[\frac{a + r(W - a)}{z + \frac{W}{4} + a + r(W - a)} \right] = \text{Load point displacement}$$

$$\delta_t = V_g \times \left[\frac{r(W - a)}{z + \frac{W}{4} + a + r(W - a)} \right] = \text{Crack-tip Opening Displacement}$$

$$\cos \theta \cong 1 \text{ for small } \theta$$

Ingham et al³⁷ showed that the apparent centre of rotation, as defined by Figure 2.21, moves from its initial position at or near the crack-tip toward the centre of the uncracked ligament as the crack faces open.

To determine the value of r for a particular clip guage displacement, V_g , one needs to measure the displacement at several points along the crack face. A best fit line drawn through these displacements intercepts the crack centerline at $x = -r(W-a)$. A graphical construction of the method is shown in Figure 2.22 for data obtained in the present work. While Ingham et al used photographic records of the displacements of microhardness indentations along the outside surface of the samples to obtain r , the present work utilizes a silicone rubber replication technique (to be described later) to obtain r .

The sample geometry is "calibrated" when r has been obtained for a range of values of V_g , and a plot of r vs. V_g is usually made. For small angles of rotation, θ , the clip guage reading may now be translated into the COD at any point along the crack surface, including the crack-tip.

Critical CTOD. Initiation Criterion, CTOD_i.

Fracture in mild steels is generally preceded by fibrous crack growth³⁸, and it has become common to specify the critical value of CTOD as that at which fracture initiates^{12,38,39,40}.

To determine the point of initiation, heat-tinting of multiple identical specimens that have been loaded to different deflections is frequently utilized^{12,40,41}. These specimens are subsequently fractured at low temperatures and the extent of fibrous crack growth is measured. By extrapolating back to the point of zero crack growth, one obtains

Figure 2.22 Variation of COD with Position of Measurement for CTS with $a/W = 0.45$.

the value of $CTOD_i$.

Robinson and Tetelman⁴² developed a technique whereby on-load values of CTOD could be measured using silicone rubber replicas. In addition, fracture initiation was detectable in the replicas. This allowed single-specimen $CTOD_i$ tests to be performed within the temperature range over which the silicone rubber would catalytically harden. This silicone rubber technique is used in a modified form in the present work, and further description will be deferred until later.

Maximum load criterion, $CTOD_{max}$.

The CTOD at maximum load, $CTOD_{max}$, is easier to detect than $CTOD_i$ since it is obtainable from the load-displacement charts alone. As a result, it is sometimes used to measure fracture toughness⁴³. Knott⁴¹ has shown that $CTOD_i$ and $CTOD_{max}$ can be related by the approximation (for mild steels):

$$CTOD_{max} = CTOD_i + 0.17mm$$

Fracture Strain, ϵ_f .

If it is assumed that the CTOD represents strain over a gauge length equal to the slot-width, S , then the fracture strain may be calculated from the CTOD at initiation by:

$$\epsilon_f = \frac{CTOD_i}{S} \quad (\text{see note below})$$

Applications to Weld Toughness Testing.

Because of the tiny crack extension during initiation of fibrous fracture, the CTOD method is frequently used for testing the parent material, weld metal, and heat-affected-zone in weldments.^{12,40,43} Although a crack-tip could theoretically be placed perpendicular to the weld centerline to test the resistance to fracture in very narrow metallurgical zones in and near welds, there does not seem to be any zone testing data of this kind in the literature. Usually, the PM, FZ, and HAZ are tested so that fracture propagates parallel to the welding direction.

Note - The slot-width would be equal to the saw-cut or machine-cut in mechanically made cracks. The question arises in fatigue-cracked specimens if the slot-width should be taken as, say, one atom-diameter?

Dolby¹² has used the CTOD technique to investigate the effect of defect orientation on HAZ fracture toughness. This appears to be the only work with this approach. Results of Dolby's work will be described later when the concept of J_{1c} zone testing is introduced.

2.2.3.8.2. R-Curve Analysis.

The R-curve test measures the resistance to fracture of a material under plane stress conditions. It is analogous to the plane-strain fracture toughness test with the major difference that the sample thickness is an important variable. The material fractures when the plane-stress stress intensity factor, K_R , reaches a critical value, K_c . K_R is analogous to K_I , and K_c is analogous to K_{Ic} .

Reference: ASTM "Recommended Practice for R-Curve Determination". 44

Essential Features:

- 1) suitable specimen
- 2) load-controlled tensile machine, or displacement-controlled tensile apparatus
- 3) COD measuring devices, eg. clip guage, vernier micrometer.

Specimen Dimensions:

A modified compact specimen is generally used with the specimen thickness being equal to the design plate thickness. The width of the specimen should be wide enough so that the uncracked ligament (W-a) is large in comparison to the plastic zone that will develop at the crack-tip. Fatigue pre-cracking is called for in the ASTM recommended method.

Reporting of R-Curve Data

K_c tests are usually performed over a wide range of temperatures with the sample thickness held constant.

The measurement of a rotational factor is performed in a method similar to that shown in Figure 2.22. This is used to obtain the value for CTOD. The CTOD is used to calculate the value of the elastic-stress-intensity value, K_R , from:

$$K_R = (E \times \sigma_{ys} \times CTOD)^{\frac{1}{2}}$$

Alternatively, K_R may be calculated from the linear-elastic formula if there is no back surface yielding:

$$K_R = \frac{P \times f(a/w)}{B \times W^{\frac{3}{2}}}$$

where the symbols are as defined on page 34.

The value of K_R is plotted against the amount of stable crack growth, a , as shown in Figure 2.23. Since the specimens are thin, the crack growth can be monitored by surface observations. K_C is the value of K_R at which the crack becomes unstable.

Applications to Weld Toughness Testing

The author found no examples of R-curve testing on welds in the literature. The difficulty seems to lie in the stable crack growth action that takes place during testing. This stable crack growth would occur in a spectrum of microstructures in and near a weld. When the crack becomes unstable it is due to two events: the crack reaches a critical length and the crack tip reaches a brittle zone. The assessment of weld toughness from this type of test is complicated by these two variables, crack length and crack-tip location.

Figure 2.23 Typical R-Curve

2.2.4. Definition of the J-Integral.

The J-Integral was originally defined by Rice^{45,46} while considering a homogeneous body of linear or non-linear elastic material subjected to a two-dimensional field. The material is assumed to contain a notch having flat surfaces parallel to the x-axis with a rounded tip denoted by the arc Γ_t as shown in Figure 2.24

Fig. 2.24 Notched homogeneous material with Γ - contours.

For these conditions, the material's strain-energy density, W , is defined by:

$$W = W(x, y) = W(\bar{\epsilon}) = \int_0^{\epsilon} \sigma_{ij}^0 d\epsilon \quad (1)$$

where $\bar{\epsilon} = [\epsilon_{ij}]$ is the infinitesimal strain tensor and σ_{ij} are components of the stress tensor, $\bar{\sigma}$, referred to a set of Cartesian coordinate axes: $x_1 = x$, $x_2 = y$.

Rice then defined a line integral, the so-called J-integral, as:

$$J = \oint_{\Gamma} (W dy - \vec{T} \cdot \frac{\partial \vec{u}}{\partial x} ds) \quad (2)$$

where:

Γ is any closed path surrounding the notch-tip, beginning on one crack surface and running to the other crack surface in a counterclockwise direction.

ds = incremental arc length along Γ

$\vec{T}$ = traction vector (with units of stress) acting on a plane with outward normal vector $\vec{n}$ along Γ , such that:

$$T_{ij} = \sigma_{ij} n_j$$

and $\vec{u} = (u_1, u_2)$ is the displacement vector.

The first term in the integral represents the strain-energy density within the material (for the non-linear elastic case) or the strain-energy plus plastic work density (for the elastic-plastic case using deformation theory).

The second term in the integral may be interpreted as the work done (per unit area) by the traction vectors along Γ .

Rice then proceeded to show that for any closed path within the body, such as shown in Figure 2.25, the value of $J = 0$.

Fig. 2.25 Closed Path: $\Gamma + \Gamma'$ along crack surface.

Since for this choice of axes, $dy = 0$ and $\vec{T} = 0$ along the crack surface, then $J_r = -J_{r'}$. In other words, any counter-clockwise evaluation of the line integral is constant for a given crack and stress-strain field, and the J-integral is said to be path-independent. The path-independence of J implies that it is a parameter of the crack tip, and can be evaluated from contours remote from the crack tip.

For more detailed description of the mathematical foundations of the J-integral, the interested reader is referred to the original papers by Rice^{45,46} and to a more recent, and more easily read, topical paper by Paris⁴⁷.

Fig. 2.26 —Energy rate determination of J.

Fig. 2.27 —Procedure for experimental J_K measurement: multiple specimen R-curve.

load vs. load point displacement curves are obtained. The area under these curves are measured at various displacement points, V_1 , and plotted against the corresponding crack length, a . The slope of these curves can be interpreted as J from equation (4). These are then plotted against v . The difficulty with this method is in determining the point where $J=J_{1c}$.

The above method was subsequently improved upon using identical specimens.⁵⁰ In this case the samples were loaded to different displacements, and then unloaded. Any crack advance, Δa , that has occurred is marked by heat tinting, and the specimens are broken open and Δa measured. J is evaluated from the Rice-Paris-Merkly equation⁵¹ for a deeply notched beam in pure bending:

$$J = \frac{2A}{Bb} \quad (\text{RPM}) \quad (5)$$

where A = area under the load vs. load pt. displacement curve
 B = specimen thickness
 b = remaining uncracked ligament length

Values of J are then plotted against Δa and the intersection, ξ , of the resulting $J - \Delta a$ curve with the crack blunting line is taken as J_{1c} . The method is shown schematically in figure 2.27.

The equation of the blunting line is given by :⁵⁰

$$J = 2 \sigma_{\text{flow}} \Delta a \quad (6)$$

where

$$\sigma_{\text{flow}} \doteq \frac{\sigma_{\text{yield}} + \sigma_{\text{ult}}}{2}$$

The significance of the intersection point, ξ , is that the blunting line represents the crack opening stretch (COS) and resulting plastic extension of the crack. However, no actual material separation has occurred (with the exception of internal void formation) until the point ξ is reached. Hence there is a good argument for taking $J_{\xi} = J_{1c}$.

2.2.4.2. Corrections to the RPM J-integral equation.

2.2.4.2.1 Axial force correction.

The RPM equation given earlier (eqn. 5) was originally derived from considerations of a deeply notched beam in pure bending, and then extended for use with very deeply notched compact tension specimens having $a/w \geq 0.6$.^{52,53}

A more exact equation, although somewhat more complicated, is the equation of Merkle and Corten⁵⁴:

$$J = \frac{[\eta_r + \eta_c \left(\frac{A_c}{A_r}\right)]}{B b} A_r \quad (\text{M-C}) \quad (7)$$

where:

$$A_r = \int_0^A \Delta dP = \text{real strain energy or the } P - \Delta \text{ curve, and is identical to } A \text{ in the RPM equation.}$$

$$A_c = \int_0^P \Delta dP = \text{Complementary strain-energy or the area above the } P - \Delta \text{ curve (bounded by the line } \Delta = \Delta_c \text{).}$$

$$\eta_r = \frac{2(1+\alpha)}{(1+\alpha^2)} = \text{real energy coefficient}$$

$$\eta_c = \frac{2\alpha(1-2\alpha-\alpha^2)}{(1+\alpha^2)^2} = \text{Complementary energy coefficient}$$

α = dimensionless ratio of the internal stress block equilibrating the applied load at plastic collapse to the ligament width, b (see Figure 2.28)

Figure 2.28 Stress Conditions in a Compact Specimen at Plastic Collapse. (from Merkle and Corten⁵⁴)

In the elastic range, the M-C equation reduces to the RPM equation since $A_r = A_c$ for a straight line.

In the elastic-plastic range, the M-C eqn. has the effect of replacing the constant, 2, in the RPM eqn. with a material and geometry dependent variable. Fortunately, values of α and η have been calculated for the CT specimen and are given in Table 2.3 for a range of a/W values⁵⁴.

Table 2.3 Axial force correction coefficients for CTS.

a/W	α	η_r	η_c
0.30	0.25	2.352	0.194
0.35	0.23	2.336	0.202
0.40	0.21	2.318	0.206
0.45	0.18	2.284	0.206
0.50	0.16	2.262	0.198
0.55	0.14	2.238	0.188
0.60	0.12	2.206	0.174
0.65	0.10	2.178	0.156
0.70	0.09	2.164	0.144

A recent application of the M-C equation may be found in reference 55.

2.2.4.3.2. Plastic zone correction.⁵⁶

Due to considerable plasticity at the crack tip in ductile materials, the plastic zone forming in J_{Ic} tests is perhaps an order of magnitude larger than the plastic zone in K_{Ic} tests, since the latter tests are usually applied to more brittle materials.⁵⁶ Consideration of the above together with the observation that there is a certain degree of discrepancy in the literature between reported values of J_{Ic} and K_{Ic} and the theoretical relationship between these two material properties, has led Lantegigne et al⁵⁶ to derive a plastic zone correction.

Basically, the plastic zone correction term, γ_y , is considered to increase the effective crack length. Therefore the new crack length a' , to be used for all calculations (for example those involving the ratio, a/w) is given by:

$$a' = a + \gamma_y$$

For a description of how to determine γ_y , see reference⁵⁶.

Penelon et al⁵⁷ have determined γ_y for three Nb-bearing HSLA steels. The values range from 0.15 mm to 0.76 mm. For a plain, low-carbon steel γ_y was found to have a value of 3.687 mm. (Note: γ_y should not be confused with the plastic zone radius, r_y , which for the above HSLA steels ranged from 0.15 mm to 0.58 mm, and had a value of only 0.9 mm for the plain, low-carbon steel.)

The application of the (Lantegigne) plastic zone correction to a welded material with its nonhomogeneity is not clear. For this reason, no attempt will be made to apply this correction to the present work.

2.2.4.4. The J-Integral in Non-homogeneous Materials

A logical step toward generalizing the J-integral to non-homogeneous materials is to consider the bimaterial case, where each of the two material domains are simply connected.

This case has been studied by Smelser and Guertin⁵⁸ for the case of a crack lying along the interface of the two materials. Chen and Wu⁵⁹ have analyzed the case of a pressurized crack normal to and terminating at the interface as shown in Figure 2.29.

Figure 2.29 Γ - Contours for Crack-tip at Bimaterial Interface

In this latter case, Chen & Wu assumed that the two materials had different shear moduli and Poisson's ratios. The bimaterial was then divided up into three homogeneous subdomains, R_1^+ , R_1^- , R_2 , bounded by the crack surfaces and the x_2 axis. The value of the bimaterial J-integral, J^b , for this pressurized crack geometry is derived by Chen and Wu to be:

$$\begin{aligned}
 J^b = & \int_{\Gamma_2 + \Gamma_3 + \Gamma_1} (w dx_2 - T_1 \partial u_1 / \partial x_1 ds) + \left\{ \int_{\ell_{13}^+} (w dx_2 - T_1 \partial u_1 / \partial x_1 ds) \right\} \\
 & + \left\{ \int_{\ell_{13}^-} (w dx_2 - T_1 \partial u_1 / \partial x_1 ds) \right\} + \left\{ \int_{\ell_{23}^+} (w dx_2 - T_1 \partial u_1 / \partial x_1 ds) \right\} \\
 & + \left\{ \int_{\ell_{23}^-} (w dx_2 - T_1 \partial u_1 / \partial x_1 ds) \right\} - \left[\int_{\ell_1} T_1 \partial u_1 / \partial x_1 ds + \int_{\ell_2} T_1 \partial u_1 / \partial x_1 ds \right]
 \end{aligned}$$

The "polymaterial" case of a weld can be expected to result in a much more complicated J-integral equation. A mathematician may someday solve the weld case, and hopefully present a laboratory method of measuring J_{Ic} for cracks in the weld vicinity. It may turn out that the lab method so derived will not be very different from the Landes and Begley method. On this optimistic note, the present experimental technique is introduced. It will be seen to be an extension of some of the experimental techniques currently in use in homogeneous material testing.

2.2.4.5. The J-Integral Near a Weld.

As previously described in section 2.2.2., welding transforms a relatively homogeneous material into a very non-homogeneous material in the weld vicinity. In most cases, however, the elastic moduli and Poisson's ratio are not significantly affected by welding, and a welded material may be considered homogeneous with respect to these two parameters. Hence the approach described in the previous section, with Γ - contours along the interfaces of the various materials may not be appropriate even if it were presently possible to evaluate J in this way for a weld in which the interfaces are actually transition-gradient zones.

From a more practical standpoint one may ask: Are the RPM and M-C equations applicable to a specimen containing a weld? Can one perform the mechanical tests applicable to homogeneous materials to obtain the value of J for cracks located near a weld? If so, one may be able to locate, for a given welding procedure, the worst location and orientation for a crack or flaw, and to evaluate its severity by fracture mechanics principles. This information may then be used in at least two ways:

- 1) to help determine an optimum welding procedure for the particular application
- 2) to assist in the quantitative interpretation of non-destructive testing results with reference to the location of the flaw.

Now, although the mathematical analysis of the J-integral near a weld is considerably more complicated than for a homogeneous material, the mechanical testing for J is only slightly more complicated. One need only ensure that the crack tip is located in the zone of interest, and then test as for any material. Results from these tests can be expressed in the same units (kip/in, or $K\sqrt{in}$ for example) as "valid" J_{Ic} values, but without the support of a mathematical proof, these values may have no more meaning than the absorbed energy in a conventional Charpy test.

2.2.4.6. Testing to investigate the validity of J_{Ic} near a weld.

Consider two compact specimens of identical dimensions and cut from the same welded plate. Consider further that the samples are prepared in such a way that Sample A has the notch-tip located in the centre of the coarse-grained HAZ with the fusion zone located in the uncracked ligament as shown in figure 2.29a. Sample B also has the notch-tip located in the centre of the CGHAZ but the crack has already proceeded through the FZ so that only HAZ and parent material lie ahead in the uncracked ligament as shown in figure 2.29b.

Figure 2.29 Identical compact specimens with different
Locations of weld centerline.

When pulled apart, the crack in sample A will run through the FZ, whereas in sample B the crack will run away from the FZ.

The intense zone of deformation ahead of the crack-tip will, metallurgically, be very different for these two specimens, the path of the J- integral may, mathematically, also be very different. On this basis, one would not expect the value of J_{Ic} obtained from conventional tests on these two specimens to be the same. Yet if one assumes that the notch-tip is located in the centre of a narrow, but homogeneous band of material, then J_{Ic} evaluated on the basis of a tiny crack extension within this band is based upon the same physical phenomenon in both cases - physical separation of identical material.

The value of the critical CTOD in these two samples should be the same since this quantity is based upon properties of the narrow homogeneous band of material in which the crack extends. The results of Dolby¹² shown in figure 2.30 support this, where the direction of initiation by fibrous tearing in the HAZ of welded mild steel was not found to significantly affect $CTOD_1$ except for thicker samples at very low temperature (-80°C). In these 45mm x 90mm samples, the measured toughness for initiation towards weld metal was lower than towards parent material, and in the former case seemed to correspond closely to the weld deposit toughness. In fact, there was some evidence of the

Fig. 2.30. Effect of direction of initiation on the HAZ fracture toughness of HY80, welded with mild steel consumables (10 mm square section specimens). Ref. 12

possibility that cleavage fracture actually initiated in the weld metal, which had lower toughness, although the notch-tip had been located in the HAZ approximately 0.75 mm from the fusion boundary. More tests are probably required to draw any true conclusions about the effect of notch orientation on critical CTOD.

As a means of assessing the applicability of J in the vicinity of a weld, and as a means of simultaneously obtaining additional information about the CTOD in this area, consider the equation of the crack blunting line:

$$J = 2 \sigma_{\text{flow}} \Delta a_p$$

If Δa_p is measured on-load using replication techniques while a P- Δ plot is obtained for analysis by the RPM or M-C equations, then if the J-integral is applicable here it is to be expected that:

$$J_{Ic} \Big|_{\Delta a_p} = J_{Ic} \Big|_{\text{(RPM or M-C)}}$$

where both values of J_{Ic} are evaluated at the onset of crack extension.

For the present work, samples of an EB-welded HSLA steel have been prepared as compact specimens with a sharp notch located in various positions of the weld. Using silicone rubber replication techniques after Robinson and Tetelman⁴² and after Lereim and Embury⁵⁸, notch-tip conditions could be replicated at any point of the $P-\Delta$ curve. These replicas could then be measured under a microscope for CTOD and Δa_p . The replicas also serve as proof that crack extension has occurred.

The details of the experimental procedure are given in the next chapter.

CHAPTER 3

EXPERIMENTAL

3.1. Materials

A controlled-rolled microalloyed HSLA steel was used for this experiment. The chemical composition and mechanical properties of this steel, Stelco X-70, are given in Tables 3.1 and 3.2.

A sample of (unwelded) structural steel, CSA G.40.8/A-3 was also tested to provide a check on the technique. This steel has been used in some previous fracture studies at Carleton University^{61,62}. The chemical composition and mechanical properties of CSA G.40 8/A-3 are given in Tables 3.1 and 3.2.

Table 3.1 Chemical Compositions of Steels Used.

<u>Steel</u>	<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>	<u>N₂</u>	<u>Mo</u>	<u>Cr</u>	<u>Ni</u>	<u>Al</u>
Stelco X-70	.05	2.04	.01	.006	.29	-	.58	.06	.25	.04
CSA G40.8/A-3	.18	1.31	.006	.024	.20	.005	-	-	-	-

Table 3.2. Mechanical Properties of Steels Used.

<u>Steel</u>	<u>Transverse Yield Strength ksi</u>	<u>Transverse Tensile Strength ksi</u>	<u>Elongation %</u>
Stelco			
X-70	83.3	112	39 (2" gauge)
CSA			
G.40.8/A-3	36	68.9	26 (10" gauge)

Welding Procedure

Preparation. Prior to welding, the HSLA steel was sandblasted to clean off mill scale, rust, and paint.

The steel was then demagnetized in an a/c magnetic field.

Welding Parameters. The welding parameters are given in

Table 3.3. All welds were autogenous or bead-on-plate.

Table 3.3. Welding Parameters.

Current	40 mA
Voltage	70 kV
Speed	5 ipm (11 mm per sec)
Thickness at time of welding	0.72 " (18 mm)
Number of passes	2 (one each side)
Filler metal	none
Rolling direction	parallel to weld

3.2. Specimen Design.

As shown previously, a variety of specimen types are in use today in the study of weld toughness.

In selecting a specimen for a new toughness testing technique, it is prudent and reasonable to choose one that is already in use. In this way one can expect that test apparatus and specimen fabricating experience will be available. Comparison with existing and future test results from other experimentors is facilitated by the use of standard specimens.

The specimen chosen for this experimental work is a modified compact specimen of the type described in ASTM E399-74.³⁵ The modifications to the standard compact specimen are in the width-to-thickness ratio, and in the crack tip acuity.

In paragraph 7.3. of E399-74 it is stated that the sample thickness, B , is allowed to lie between $0.25W$ and W , where W is the sample width from the loadline to the un-cracked back surface. Ordinarily compact specimens have a thickness equal to one-half of the width.

Fatigue-cracked specimens were tried initially but two difficulties were encountered:

- 1) The location of the fatigue-crack tip is to some degree a matter left to serendipity. The result of pre-cracking does not always produce a crack-tip in the zone of interest. Only after the tests are performed, and the specimens are broken open, can one check and be sure of the crack-tip location during testing. The large number of specimens required would make this approach expensive.

Figure 3.1 Compact Specimen Dimensions Used for all Tests

(all dimensions in inches)

2) The replicas cannot be easily removed from a fatigue-crack. Tearing or permanent stretching was encountered in preliminary tests with fatigue-cracks. To safely remove a replica from a fatigue-crack, the specimen should be broken in half. This was the procedure used by Robinson and Tetelman⁴² in their pioneering work on replication. Lereim and Embury⁶⁰ used a sharp sawcut in their experiments.

For the above reasons, a machine-notch with a 60° angle at the tip and a notch-tip radius of 0.075 mm was used in the present experiments. A 5" x 3/32" Do-All slitting saw was specially ground to provide this tip geometry. The bulk of the notch material was removed with an ordinary slitting saw with a 180° angle at the tip. To prolong the life of the special saw, only the final 3 mm was cut using the 60° tip.

The samples were machined so that the notch-tip was located at different distances from the weld centerline. In some cases, after testing to the point of crack extension, the samples were remachined to provide a new location of the notch-tip. These were then retested to the point of crack extension.

For the parallel tests, the notch tip was located in the fusion zone or in the coarse-grained HAZ.

The weld orientations are given in Figure 3.2.

Knife edges were screwed onto the outside surface of the specimens to hold the clip guage. The knife edge thickness, Z , was 0.080".

Figure 3.2 Weld Locations for Different Specimens.

Symbols for all
specimens

$b = 1.32"$ (33.5 mm)

$W = 2.40"$ (61.0 mm)

$a/W = 0.45$

$B = \text{thickness} = 0.700"$ (17.8 mm)

Fusion zone width = approx. 0.20" (5.0 mm)

3.3. Testing Apparatus

Tests were performed on a model 907.95-850 MTS electrohydraulic closed-loop structural system. The system was operated on stroke control with a compressor setting of 1500 psi, or one-half of the maximum available pressure.

A W12 x 72 steel beam was designed and fabricated for use as a base beam. The dimensions of this beam are shown in Figure 3.3. Although the maximum load required for testing was only 25 kips approximately, the base beam and indeed the MTS girders themselves were found to deflect significantly under this load. Once deflected, these beams could deliver a powerful springback force when the sample underwent crack extension. This was the source of much grief in the early stages of testing where the rebounding beams would cause the extended crack to run through the samples in an uncontrolled manner.

The problem was overcome by prestressing the base beam to approximately 28 kips. This was higher than the maximum load reached in the tests so that the prestressing was never overcome by the test loads. The prestressing

MTS BASE BEAM
MECH. ENG. (CARLETON)

Nov. 1, 1978

DRAWN BY: A. HERBST

was achieved by driving steel wedges under the base beam with the 28 kip load on. These wedges would "prop-up" the base beam in a concave-down shape which it would retain throughout the tests. The concrete floor was able to bear the low compressive stresses delivered by these wedges since the wedges distributed the 28 kip load over a total surface area of approximately 36 sq. in.

The deflection of the base beam was measured by dial gauges before and after the prestressing. The deflections are shown in Figures 3.4a and 3.4b.

The clevises of G. Wiseman's ⁶³ previous work were used. The MTS/clevice interface was adapted by means of a 2" thick steel plate (figure 3.5). A column and lower clevice adaptor plate were also designed and fabricated. The dimensions of these components are shown in figures 3.6 and 3.7.

New resistance strain gauge clip gauges were prepared and the calibration curve for the gauge used is shown in Figure 3.8.

The knife edges were also provided by Wiseman, ⁶³ but these were modified slightly to provide an adjustable range of knife edge gap distances. One edge of each existing knife edge was ground down slightly so that the screw hole became eccentric to the edges. Now

Figure 3.4 Effect of Prestressing on Base Beam Deflection

FIG. 3.5 MTS HEAD/CLEVICE ADAPTOR

FIG. 3.6 MTS Column/Clevice Adaptor

2

Fig. 3.2 MTS Column

FIGURE 3.8 CLIP GAUGE CALIBRATION CURVE

NOTE: ZERO DISPLACEMENT TAKEN AT UNLOADED
KNIFE EDGE DISPLACEMENT ON SAMPLE WS-5.

the experimenter could rotate one or both of the knife edges mid-test to provide a new zero. This proved very helpful during testing since the more ductile samples could open to a clip gauge distance that was beyond the range of the gauge. The new knife edge dimensions are shown in Figure 3.9.

Figure 3.9 Knife Edge Dimensions

3.4. Silicone Rubber Replication Technique

3.4.1. Background

A crack tip replication technique was developed by Robinson and Tetelman⁴² for on-load measurement of the crack-tip-opening-displacement (CTOD) in fatigue-precracked Charpy V-notch specimens loaded in slow, three-point bending. By infiltrating the crack-tip region with a catalytically hardening silicone rubber of the type used in dental impression work, a rubber "casting" of the on-load crack-tip geometry could be produced. This casting or "replica" could then be analyzed microscopically to yield a variety of geometric measurements. These measurements were used to quantify the behaviour of the material at the crack-tip. Information obtainable from these replicas include:

- 1) CTOD
- 2) COD at points remote from the crack-tip, thus providing data for the determination of the rotational constant, r .
- 3) Δa_p , the plastic extension of the crack-tip
- 4) R , the crack-tip radius
- 5) detection of the onset of fracture (Initiation)

This last information was used by Lereim and Embury,^{39,60} to determine J_{1c} values for an HSLA steel and for Q & T 4340 steel. In the above works, it was assumed that: $J_{1c} = J_{10}$ and J was calculated from the RPM equation using sharply notched three-point bend specimens. The critical point was taken at halfway between the last uncracked replication point, and the following replication point where

crack extension first appeared in the replica. The critical CTOD, $CTOD_1$, was calculated at this same midpoint. The method is shown schematically in Figure 3.10.

In all of the previous work^{39,42,60} the specimens were of the bend type, and the crack-tip was at the gravitational bottom of the crack. The rubber would then have both gravitational and capillary attraction to assist its flow to the crack-tip.

In the present work with compact specimens, a vacuum chamber was devised to assist the infiltration of the rubber. Since tensile machines are typically designed with the pull axis vertical to the ground, the testing of a compact specimen requires that the crack plane be horizontal. The vacuum chamber provides some extra persuasion forcing the rubber to fully infiltrate the crack-tip region.

The vacuum chamber consists of two sealing flaps connected by an O-ring ligament. The O-ring ligament seals the machine-notch front, while the flaps seal the specimen sides, and provide an inlet for the rubber compound and an escape route for the air. The dimensions of the sealing flaps are shown in figure 3.11.

Figure 3.10 Schematic of the Fracture Process.

Figure 3.11. Sealing Flaps.

All Dimensions in Inches.

Replication Procedure (using DeTrey "Reposil").

With the sample under load, a replica of the crack-tip conditions may be obtained using the following procedure:

- 1) Spread a thin layer of high vacuum grease in the vicinity of the crack-tip on both outside surfaces of the sample. Also spread vacuum grease on the contact sides of the sealing flaps, on the O-ring ligament, and on the outside surfaces of the inlet/outlet tubes.
- 2) Attach the sealing flaps so that the O-ring ligament is in the slot, and the sealing flaps are on either side of the sample. Clamp the sealing flaps in place using the large alligator clip. Ensure that there is a clear passage through the silicone entrance and vacuum exit sides of the now assembled vacuum chamber.
- 3) Pull the O-ring ligament taut from both free ends and release. This removes extra slack from the O-ring ligament.
- 4) Attach the vacuum hose to the exit side of the chamber and start the vacuum pump. The trap valve should be closed from the previous replication.
- 5) Attach an empty syringe assembly to the entrance side of the chamber using a one cm. length of tygon tubing as a coupling. Open the valve to the vacuum and check to see that the syringe plunger can be drawn in by the vacuum created in the crack-tip region. If not, reposition the sealing flaps and secure all leaks.
- 6) Squeeze out approximately 2 cm of Reposil base and an equal amount of catalyst onto the delineated mixing pad supplied with the Reposil. Using a stainless steel spatula, mix Reposil in a circular motion to obtain a uniform colour. (20 seconds).

- 7) Using the spatula, scoop the mixture into a clean syringe while holding the syringe at approximately 45° with respect to the vertical. (15 sec.)
- 8) Insert the syringe plunger, turn the syringe point up, and slowly press the plunger to squeeze out unwanted air. (5 sec.)
- 9) Attach the syringe assembly to the sealing flap using another 1 cm. length of tygon tubing as coupling. (10 sec.)
- 10) Open the valve to the vacuum and allow the rubber to be drawn into the crack-tip region under the power of vacuum only. (10 sec.)
- 11) When the rubber can be seen flowing down the vacuum hose toward the trap, close the vacuum valve and apply pressure to the syringe plunger. Allow an additional 2 cm. approximately of rubber to flow down the vacuum hose under the pressure of the plunger. (10 sec.)
- 12) Remove the syringe and detach the tygon coupling. . Attach a short injection needle to the syringe and inject the remaining silicone rubber into the loadline region of the notch. (20 sec.)
(This loadline replica will be used to obtain the load-point displacement and additional displacements for determining the rotational constant, r_s .)
- 13) Remove the plunger, and set the syringe pieces down on the mixing pad. Turn off the pump.
- 14) Allow the silicone to set for approximately 10 minutes. The consistency of the rubber remaining on the the syringe plunger, the mixing pad, and the spatula should be used to judge when the replica has set. {
- 15) When the silicone rubber has set, open the vacuum flaps and clean out the entrance and exit portholes.
- 16) Displace the specimen to the next replication point.
- 17) By gently prodding from both sides with forceps in the direction of the clip gauge, loosen and remove the loadline and crack-tip replicas.
- 18) Repeat the replication procedure for the new point.

The silicone replicas obtained by the procedure just described were subsequently measured under a microscope equipped with a micrometer stage. The dimensions of the replicas were compared with the original notch-tip dimensions as illustrated in Figure 3.12. The results of these measurements are given in the next chapter.

NOTATION

- δ_t = CTOD (crack-tip opening displacement)
- Δa_{pn} = plastic crack extension (no material separation)
- δ_{in} = COD at point x_1, y_1 , and load point n.
 $= y_{in} - y_{io}$ where y_{in} = replica thickness at the n^{th} load point and distance x_1 from original crack-tip.

Figure 3.12 Replica Measurements.

[Note: δ_t calculated as y-intercept in least squares fit eqn. for (x_1, δ_{in}) at each load point n.]

CHAPTER 4

RESULTS

4.1. GENERAL.

A total of nine compact specimens were tested, all specimens having identical geometric dimensions as given in Chapter 3. One sample of unwelded G40.8-A5 steel was among those tested. The other eight welded HSLA steel samples were identical in all respects except that they were machined so that the weld centerline was located at different distances from the notch-tip in each sample. The crack plane was either parallel or perpendicular to the weld centerline.

All samples were pulled intermittently in the displacement controlled MTS machine, and replicas were taken at various intermediate displacements. The resulting load-displacement curves and silicone rubber replicas were used to compute and measure J_{Ic} and $CTOD_i$, both considered as having occurred at the initiation of stable crack extension. This point was defined as halfway between the displacement corresponding to the replica displaying the first sign of crack growth, and the previous replicated displacement in which no crack growth occurred.

4.2. J_{Ic} Results.

The load versus clip gauge displacement graphs are given in Appendix B. These graphs were used to construct load vs. load-point displacement curves as presented in Figures 4.1 through 4.9. The load-point displacement was determined by sectioning the replica cast directly between the load holes. The load centerline had been previously scribed onto the notch faces by a shallow jeweller's saw cut.

The area under the load vs. load-point displacement curve (up to the critical point) was measured graphically. This area, A_r , was used together with the complimentary area, A_c , to calculate J_{Ic} from the Rice-Paris-Merkle (RPM) equation (see Chapter 2):

$$J_{Ic} = \frac{[2.284 + 0.206 \times (A_c/A_r)]}{(0.7) \times (1.32)} \times A_r$$

Table 4.1 gives the values obtained by this method.

J_{Ic} is plotted against notch-tip location in Figure 4.10.

TABLE 4.1. J_{Ic} Results

Sample	x, inch (mm)	y, inch (mm)	J_{Ic} , kip/in (kJ/m ²)
WS-1	1.10 (27.9)	-	2.43 (425)
WS-2	1.10 (27.9)	-	2.94 (515)
WS-3	1.32 (33.5)	-	1.23 (215)
WS-5	1.45 (36.8)	-	1.64 (287)
WS-6	1.38 (35.1)	-	2.24 (392)
WS-7	-	0.11 (2.8)	1.79 (313)
WS-9	1.19 (30.2)	-	2.86 (501)
WS-10	-	0	0.59 (104)
G40.8-A3	-	-	0.58 (102)

Figure 4.1 Load vs. Load Point Displacement

**Figure 4.4 Load vs.
Load Point Displacement**

Figure 4.6 Load vs. Load Point Displacement

Figure 4.8 Load vs. Load Point Displacement

Figure 4.9 Load vs. Load Point Displacement

Figure 4.10 J_{IC} vs. position of notch tip.

4.3. CTOD_i Results

The replicas obtained during testing were subsequently sectioned into thin (~ 1 mm) slices and measured on a microscope designed for Vickers microhardness testing. On this machine measurements were made to an accuracy of ± 0.0001 " ($\pm 3 \mu\text{m}$).

A computer least-squares line fitting program, LFIT, was used to obtain the rotational factor, r , and CTOD. The resulting values of the rotational factor have been plotted against the clip gauge displacement, V_g , in Figure 4.11. Since the rotational factor is not constant for variations in V_g , the LFIT program was used to calculate r and CTOD for each load point.

Over 1000 microscopic measurements were made on the replicas from the nine samples. These measurements appear as raw data in the computer input collection given in the Appendix C. The equation of the best fit line, correlation coefficient, rotational factor, and CTOD value (y-intercept) are also given in Appendix C for each replica. This data is summarized in Table 4.2.

The value of the critical crack-tip-opening-displacement, CTOD_i, is plotted against the initial notch-tip location in Figure 4.12.

TABLE 4.2 Summary of COD Results

Sample	Observ.	Load (kips)	V_g	CTOD	r	CTOD ₁
WS-1	1	19.3	0.0407	0.01035	0.279	0.0205
"	2	20.3	0.0447	0.00839	0.1889	
"	3	21.4	0.0553	0.01605	0.3348	
"	4	22.3	0.0677	0.0250	0.4796	
"	5	24.0	0.0751	0.0282	0.4921	
"	6	23.5	0.0836	0.0335	0.5466	
"	7	23.5	0.0858	0.0344	0.5490	
"	8	23.5	0.0958	0.0509	0.5603	
WS-2	1	21.6	0.0503	0.01268	0.276	0.0199
"	2	22.8	0.0674	0.01668	0.269	
"	3	23.0	0.0746	0.0232	0.3698	
"	4	23.2	0.0800	0.02295	0.329	
"	5	23.45	0.0857	0.02507	0.3382	
"	6	23.4	0.0952	0.02805	0.3418	
"	7	23.4	0.0995	0.02803	0.3213	
WS-3	1	8.0	0.0098	0	0.0015	0.0092
"	2	11.8	0.0160	0.00272	0.152	
"	3	15.7	0.0247	0.0050	0.1946	
"	4	18.4	0.0325	0.00775	0.2379	
"	5	20.5	0.0445	0.01059	0.2483	
"	6	21.5	0.0551	0.01425	0.2745	
"	7	22.6	0.0669	0.01881	0.3105	
WS-5	1	8.2	0.0119	0.00046	0.0357	0.0120
"	2	11.9	0.0202	0.00446	0.2293	
"	3	14.4	0.0302	0.0055	0.2124	
"	4	17.0	0.0317	0.00695	0.2210	
"	5	19.8	0.0459	0.01053	0.2344	
"	6	21.0	0.0534	0.01339	0.2614	
"	7	21.9	0.0688	0.02005	0.3262	
"	8	22.3	0.0815	0.02395	0.3434	

<u>Sample</u>	<u>Observ.</u>	<u>Load (kips)</u>	<u>V_E</u>	<u>CTOD</u>	<u>r</u>	<u>CTOD₁</u>
WS-6	1	5.2	0.0061	0.00013	0.0159	
"	2	9.0	0.0121	0.00151	0.1068	
"	3	13.3	0.0209	0.00407	0.2140	
"	4	15.9	0.0272	0.00636	0.2437	
"	5	18.6	0.0362	0.00801	0.2232	
"	6	20.2	0.0445	0.01008	0.2326	
"	7	21.3	0.0547	0.01326	0.2571	
"	8	22.0	0.0638	0.01743	0.3003	0.0154
WS-7	1	6.0	0.0071	0.00105	0.1248	
"	2	9.0	0.0116	0.00203	0.1640	
"	3	12.3	0.0182	0.00242	0.1232	
"	4	15.1	0.0237	0.00336	0.1288	
"	5	17.5	0.0302	0.00601	0.1914	
"	6	19.5	0.0370	0.00816	0.2199	
"	7	21.0	0.0450	0.01021	0.2278	
"	8	22.2	0.0542	0.01299	0.2491	0.0116
"	9	22.7	0.0658	0.01727	0.2826	
"	10	21.7	0.0784	0.02367	0.3486	
WS-9	1	7.0	0.0094	0.00132	0.1234	
"	2	11.5	0.0179	0.00278	0.1499	
"	3	15.1	0.0260	0.00563	0.2234	
"	4	17.3	0.0327	0.00645	0.2002	
"	5	19.7	0.0423	0.00875	0.2102	
"	6	21.4	0.0516	0.01272	0.2557	
"	7	22.0	0.0653	0.01728	0.2859	
"	8	22.4	0.0768	0.02152	0.3113	0.0194
"	9	22.8	0.892	0.02612	0.3320	
"	10	23.8	0.1218	0.03929	0.3827	

<u>Sample</u>	<u>Observ.</u>	<u>Load (kips)</u>	<u>V_g</u>	<u>CTOD</u>	<u>r</u>	<u>CTOD_i</u>
WS-10	1	5.1	0.0079	0.000043	0.0047	
"	2	7.7	0.0124	0.00109	0.0806	
"	3	11.2	0.0164	0.00184	0.0993	
"	4	14.0	0.0239	0.00178	0.0716	0.0037
"	5	17.0	0.0310	0.00563	0.1823	
"	6	19.2	0.0372	0.00800	0.2174	
"	7	20.7	0.0500	0.01149	0.2496	
"	8	22.0	0.0639	0.01779	0.3188	
G40.8-A3	1	1.4	0.0015	-	?	
"	2	1.9	0.0021	-	?	
"	3	5.2	0.0098	0.00320	0.394	
"	5	7.8	0.0149	0.0046	0.367	
"	6	9.0	0.0188	0.00772	0.427	
"	7	9.6	0.0241	0.00772	0.385	
"	8	10.0	0.0285	0.00987	0.433	0.0115
"	9	10.3	0.0362	0.01312	0.466	
"	10	10.8	0.0424	0.01146	0.3028	

Note: V_g and CTOD are in units of inches.
r is a dimensionless ratio.

Figure 4.11 Rotational Factor vs. Clip Gauge Displacement for $s/W = 0.45$.

- - WS-3
- △ - WS-5
- - WS-6
- ◆ - WS-7
- ◇ - WS-9
- - WS-10

Figure 4.12 CTOD vs. Position of Notch Tip.

4.4. Weld Microstructures.

A sample of the welded plate was sectioned and mounted in bakelite. The ground and polished sample was then etched with a 2% nital solution. Optical photomicrographs of the weld were obtained and are presented in Figure 4.13.

Figure 4.13(a) is a low-power micrograph of the weld macrosection. The coarse, columnar shaped grains of the fusion zone contrast sharply with the very fine, almost unresolved, uniform shaped grains in the heat affected zone and in the parent plate.

The fusion zone is seen to be almost planar in shape, with a slight "nail-heading" at either plate surface. The heat affected zone is somewhat more hour-glass in shape, but is still relatively planar in comparison with manual-arc welds.

The fine-grained HAZ is shown at high magnification in Figure 4.13(b). From this micrograph, the grain-size is calculated to be ASTM 14.5. Figure 4.13(c) shows the fusion zone microstructure with an approximate grain-size of ASTM 4.5. The coarse-grained HAZ is shown in Figure 4.13(d) where the approximate grain-size is calculated as ASTM 7.5.

Figure 4.13(e) is the fine-grained HAZ at the same magnification as Figures 4.13(c) and (d), and is included here to facilitate visual comparison between the vastly different grain sizes present in these welds.

The grain size of the parent material is approximately ASTM 11.5.

Above left: Figure 4.13(a) Weld Cross-section.

Above right: Figure 4.13(b) Fine-Grained Heat Affected Zone.

Following page:

Top left: Figure 4.13(c) Fusion Zone.

Top right: Figure 4.13(d) Coarse-Grained Heat Affected Zone.

Bottom: Figure 4.13(e) Fine-Grained Heat Affected Zone.

0 20 40 60 80
 μm

CHAPTER 5

DISCUSSION

5.1. Testing Techniques.

The crack-tip replication technique provides a wealth of information about conditions at the crack-tip under load. Specifically, the technique permits:

- 1) detection of crack extension in the central part of the specimen, and a permanent replica of that extension
- 2) measurement of the crack-tip-opening-displacement, CTOD
- 3) measurement of the crack-opening-displacement, COD, at points other than the crack-tip; this provides displacement data for the determination of the instantaneous rotational factor, r , for that particular load.
- 4) crack-tip radius measurement as a function of load or SIF
- 5) crack-opening-stretch, COS, the amount of crack advance that has occurred prior to actual material separation
- 6) J_I (and J_{Ic}) determination.

However, there are some problems and disadvantages with the technique:

- 1) the process of taking a replica is inherently discontinuous, and the loading of the material is required to occur in discrete intervals with an approximately twenty minute setting time between intervals. The results are also discontinuous requiring interpolation between data points as was done in this work. This should not be seen as too much of a disadvantage since the Landes and Begley methods for J_{Ic} determination and the COD methods described in Chapter 2 also require interpolation between the first appearance of crack extension and the previous, uncracked load point. This problem is encountered in all of the presently reliable

methods for detecting the point of crack initiation or the onset of stable crack extension. Perhaps in the future some improvements in acoustic emission interpretation or direct optical observations using lasers or fibre optics will permit the instantaneous detection of crack extension. Until then interpolation will be a fact of life.

- 2) because the rubber sets catalytically, its setting time is temperature sensitive. At lower temperatures where fracture toughness data is especially useful, the setting time becomes prohibitively long.
- 3) the viscosity of the silicone can be expected to increase at lower temperatures. This would increase the difficulty in getting the rubber compound to the crack-tip and decrease the ability of trapped air bubbles to escape.

Of course, the silicone rubber used here was developed for dental impression work. The curing temperature was designed to be between room temperature and human body temperature. Presumably other replication materials can be developed for low temperature work.

5.2 Discussion of Data.

5.2.1. Effect of notch-tip location on J_{Ic} .

The variation of J_{Ic} with notch-tip location can be seen in Figure 4.10. Clearly, both the location of the notch-tip and the direction of propagation affect the results. Note that samples WS-5 and WS-9 had the notch-tip at the same distance from the weld centerline but at "opposite" sides of the weld. The crack propagated away from the weld in WS-5 and through the weld in WS-9. In all other respects, these two samples were identical.

The measured J_{Ic} values for WS-5 and WS-9 were 1.64 kip/in (287 kJ/m^2) and 2.86 kip/in (501 kJ/m^2) respectively. This is a very large relative difference and the experimenter feels it is unlikely to be the result of experimental error for reasons discussed in the next section. Unfortunately, a limited data base makes it difficult to draw firm conclusions.

The notch-tip-on-weld-centerline tests yielded the lowest J_{Ic} values for both the transverse (cross-weld) and longitudinal (parallel) tests. In both of these tests, WS-3 and WS-10, cracking was observed to initiate at the root of the second pass. All other specimens initiated fracture at the specimen centres.

5.2.2 Effect of Notch-tip Location on $CTOD_i$.

The variation of $CTOD_i$ with notch-tip location and fracture propagation direction can be seen in Figure 4.12. One notices immediately that the shape of the "curve" connecting the data points is very similar to the J_{Ic} data-curve in figure 4.10. This is not a coincidence, but is a logical result of the linear relationship (for constant σ_{flow}) given in section 2.2.4.6:

$$J = 2 \sigma_{flow} \Delta a_p \quad \text{where } 2 \Delta a_p = CTOD.$$

Figure 5.1 is a plot of J_{Ic} versus $CTOD_i$ for all samples tested. This figure contains some very interesting information:

- 1) note the very good linear correlation between J_{Ic} and $CTOD_i$ for the welded specimens. The only data point deviating far from the straight line is that of WS-1. The results of WS-1 are probably the least accurate of all tests performed and the experimenter sees no difficulty in deleting this point from the graph. (WS-1 was the first of the HSLA tests and the high ductility of this material came as a surprise to the experimenter. As a result of the large COD the clip-gauge went beyond its range and fell out of the knife edges.. The test was halted and the load removed. It was at this point that the attachable knife edges were reground so that they could be rotated when the clip gauge reached its maximum opening. The test was resumed and completed on another day for WS-1. The effect of this severe unloading on the results of WS-1 is not known, but it can be expected to lower the J_{Ic} value and not to raise it).

Figure 5.1 J_{Ic} vs. $CTOD_i$

There are two things one can say about the straight-line relationship between J_{Ic} and $CTOD_1$:

a) Since the data fits so closely to the straight line, the experimental data that was so painstakingly obtained has a good degree of reliability or accuracy. The data is better than was expected given the high degree of scatter found in published COD/CTOD results. The use of nearly identical samples and test conditions appears to have narrowed the scatterband successfully.

b) The slope of the line is approximately 145 ksi (1000 MN/m²). This is the applicable flow stress value for all of the welded specimens, independent of the notch-tip location. This is a higher flow stress than was expected, and the constancy of this flow stress for all notch-tip locations came as a complete surprise. This will be discussed further in the next subsection.

2) The slope of the line connecting the origin with the single G40.8/A-3 data point has a slope of 50.4 ksi (348 MN/m²). This is in very close agreement with a flow stress calculated as halfway between the yield and ultimate stress of this material. Taking data from Table 3.2 :

$$\sigma_{flow} = \frac{\sigma_y + \sigma_{ult}}{2} = 36 + 68.9 = 52.45 \text{ ksi (362 MN/m}^2\text{)}$$

The difference between the two values is only 4% !

5.2.3 Comparison of results with other test results on identical material.

As previously mentioned in Chapter 3, Cobanoglu⁶² performed J_{Ic} tests on steel G40.8/A-3. He utilized the more conventional multiple identical specimen technique of Landes and Begley⁵⁰. Cobanoglu also calculated J_{Ic} from some estimating procedures found in the literature. His results for this steel ranged from 0.193 kip/in (33.8 kJ/m²) to 0.800 kip/in (140 kJ/m²) depending upon the estimating procedure or the criterion for "critical" J.

The present test result on steel G40.8/A-3 was a J_{Ic} value of 0.58 kip/in (102 kJ/m²). This is in close agreement with the value measured by Cobanoglu using as a fracture criterion the midpoint of the maximum displacements on the two specimens on either side of the critical point. By this interpolative method, which is essentially the same as the method used in the present replication work, Cobanoglu obtained a value of J_{Ic} equal to 0.605 kip/in (106 kJ/m²). This is only 4% greater than the value found here.

No directly comparable data is available for comparison with the J_{Ic} and CTOD_i zone-testing results obtained here. Using the replication method on a similar HSLA steel (not welded), Lereim and Embury⁶⁰ found an average J_{Ic} of 0.46 kip/in (80 kJ/m²). This is a much lower toughness than the values found in the present work. The difference may be attributable to the notch-root radius used in this work, or to real differences in toughness.

A plane-strain tensile test was performed by J. Lowe⁶⁴ on both the welded material and the parent material used in this work. The dimensions of the special tensile specimens used by J. Lowe are shown in Figure 5.2. The cross-section of these specimens is in the shape of an elongated rectangular. The results of these tests are presented in Figures 5.3(a) and 5.3(b). No attempt was made to test the HAZ in this manner.

These tests show a plane-strain yield stress of 115 ksi (793 MPa) and ultimate stress of 127 ksi (875 MPa) for the weld metal. The softer parent material had ~~plane-strain yield and ultimate stresses of 102 ksi (703 MPa)~~ and 118 ksi (814 MPa) respectively. If the average of the yield and ultimate stresses is taken to be equal to the flow stress⁵⁰, then the flow stress under plane-strain conditions ~~is determined to be 121 ksi (834 MPa)~~ for the weld metal and 110 ksi (758 MPa) for the parent material.

One would expect that the slope of the graph in Figure 5.1 would be intermediate between the flow stress value of the weld metal and that of the parent plate, or approximately 115 ksi (793 MPa). The actual slope in Figure 5.1 is 145 ksi (1000 MPa), and the reason for this discrepancy is not understood at the present time.

Figure 5.2(a) Plane-Strain Tensile Specimen Dimensions
All dimensions in inches (mm in parentheses)

Figure 5.2(b) How Plane-Strain Specimens Were Cut From Plate.

(Material: Stelco X-70 Steel)

Figure 5.4. Plane-Strain Tensile Test On Parent Material⁶⁴

(Pull axis parallel to rolling direction)

Figure 5.3 Plane-Strain Tensile Test on Weld Metal⁶⁴

5.2.4. Other Empirical Relationships

Since the load at each replication point is known, it is a simple matter to calculate the values of the stress intensity at each of these points. Although the crack-tip is undergoing a stress intensity condition that is intermediate between plane stress and plane strain, one can apply the methods of ASTM E399-72 and calculate K_Q for each replication point. K_Q is the stress intensity at some state of stress intermediate between K_I and K_R .

A plot of K_Q versus CTOD for three selected specimens is shown in Figure 5.5. The stress intensity at crack extension can be denoted K_{Q1} and can be used as a comparative toughness value. Note that although WS-7 and the G40.8/A-3 sample had almost identical CTOD₁ values, they are very different from a K_{Q1} standpoint. This is not surprising given the difference in yield strengths of these two materials. Note also that WS-7 and WS-10 have very similar K_Q vs. CTOD curveforms, fracture occurred much earlier in WS-10 giving a very much lower K_{Q1} value. If one were to use the 5% offset or maximum load criterion for determining critical K_Q , then WS-7 and WS-10 would not be easily distinguished. Yet WS-10 was easily the most brittle sample tested, and the only sample to fail in an explosive rapid fracture mode.

Figure 5.5 K_Q vs. CTOD for Selected Specimens

The purpose of introducing this concept of K_{Q1} here is twofold. Firstly, it helps to show that there are many methods of evaluating fracture toughness, and that these methods are not all equivalent. Secondly, it demonstrates the ability of crack replication techniques to record both the strain conditions and the crack extension event.

It is unfortunate that the replication technique is not yet available for low temperature work where fracture toughness is of critical importance.

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1. Summary.

This paper has described the non-homogeneous nature of welds. A comprehensive review of mechanical toughness testing techniques has been presented with emphasis on their applicability to welds. Because of the non-homogeneity of welds, conventional toughness testing techniques are generally not suitable for evaluation of local toughness variations in welds.

The development of a new variation in fracture toughness testing has been described here. The technique essentially combines the methods of Robinson & Tetelman⁴², Lereim & Embury⁶⁰, Dolby¹², and Rice et al⁵¹ into a replication procedure for fracture toughness zone testing in welds. New techniques introduced here include the use of vacuum to permit compact specimen testing, and the pre-stressing of the tensile machine to increase effective machine stiffness.

The technique developed here is used to obtain test results on a welded HSLA steel where the only variable is the crack-tip location (and orientation). The crack length, specimen dimensions, and welding parameters were all held constant. The test results include values of J_{Ic} , $CTOD_1$, and the rotational factor, r .

6.2. Conclusions.

1) The experimental technique that has been developed here permits local fracture toughness evaluation of welds at room temperature for any crack-tip location or orientation.

2) Experiments performed here suggest, but do not absolutely prove, that J_{Ic} (evaluated from the Merkle-Corten equation with crack extension taken as the critical event) is a function of the orientation and position of the crack-tip in the weld vicinity. The same conclusion can be said of the $CTOD_1$. These conclusions are supported by the results shown in Figures 4.10 and 4.12.

CHAPTER 7

RECOMMENDATIONS FOR
FUTURE WORK

7.0 Recommendations for Future Work.

1) The experimental work presented here should be verified by a second experimenter. For this reason, two samples of the welded HSLA steel were left untested.

2) The effect of notch-tip acuity is still uncertain. Ideally, a fatigue-sharpened crack should be used. With careful and patient experimental technique, the author believes that the problems inherent in replicating fatigue cracks can be overcome. The experimenter pursuing this goal will probably not wish to complicate the situation by including a weld in the specimen.

3) Low temperature work is a "must". Silicone rubber does not appear to be a suitable replicating material, but there are other possible materials. Furthermore, it is not necessary to replicate the crack-tip, but only to determine the crack-tip conditions at crack extension.

4) Data is badly needed on the effect of initial crack-tip location on fracture toughness. This data need not be accumulated exclusively from the results of the type of tests developed here. Conventional or pre-cracked Charpy testing, K_{Ic} (or K_Q), DWTT, and other techniques described in this paper are still useful. The important thing is to move the crack-tip in a series of tests to determine the worst (lowest toughness) location.

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APPENDIX A

CALCULATION OF HEAT INPUT
OF EB WELDS

CALCULATION OF HEAT INPUT OF EB WELDS

For all welded samples, the welding parameters for each pass in these two-pass welds were:

Welding Speed $v = 5 \text{ ipm} = 0.212 \text{ cm/sec}$
 Electron Beam Voltage, $V = 70 \text{ kV}$
 Electron Beam Current, $I = 40 \text{ mA}$
 Efficiency $\eta = 0.85 \text{ (from ref. 24)}$
 Plate Thickness $t = 0.72 \text{ in} = 1.83 \text{ cm}$

Using the above welding parameters, the heat input per pass (H/2) is calculated as:

$$\frac{H}{2} = \frac{\eta VI}{tv} = \frac{(0.85)(70)(40)}{(1.83)(0.212)} = 6140 \frac{\text{joules}}{\text{cm}}$$

APPENDIX B

LOAD VS. CLIP GAUGE
DISPLACEMENT GRAPHS

Specimen WS-5

09/06/90

① Replication Points

CLIP GAUGE DISPLACEMENT, V_g , (INCHES) —→

WS-69 11-06-80

B8

WS-10 13-06-80

C1

APPENDIX C

REPLICA MEASUREMENT DATA AND
COMPUTER LEAST SQUARES FIT
RESULTS

G40.8-A3

pt. ①

P = 1.4 K

G40.8-A3

pt. ②

P = 1.9 K

G40.8-A3

pt. ③

P = 5.2 K

G40.8-A3

pt. ④ ⑤

P = 7.8 K

OBSV.	X VALUE	Y VALUE
1	.0896	.0032
2	.1500	.0036
3	.2500	.0031
4	1.7600	.0025

$$r = ? \quad \Delta = \frac{(1.00)(1.0025)}{(1.76)} = 0.0015$$

OBSV.	X VALUE	Y VALUE
1	.0896	.0032
2	.1500	.0033
3	.2500	.0034
4	1.7600	.0035

$$\Delta = .0021''$$

OBSV.	X VALUE	Y VALUE
1	.0896	.0032
2	.1500	.0049
3	.2500	.0045
4	1.7600	.0140

$$r = 0.3941 \quad \delta = .00320''$$

OBSV.	X VALUE	Y VALUE
1	.0896	.0049
2	.1500	.0066
3	1.7600	.0213

$$r = 0.3670 \quad \delta = .0046''$$

[Note: pt. ④ destroyed]

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .736392E-02 + .504835E-03X$$

THE CORRELATION COEFFICIENT = .0090

note: negative slope

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .327535E-02 + .132728E-03X$$

THE CORRELATION COEFFICIENT = .8240

note: correlation

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .319552E-02 + .614239E-02X$$

THE CORRELATION COEFFICIENT = .9930

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .460159E-02 + .949952E-02X$$

THE CORRELATION COEFFICIENT = .9980

G40.8-A3

pt. ⑥

$\rho = 9.0^{\circ}$

QBSV.	X VALUE	Y VALUE
1	.0896	.0067
2	.1500	.0084
3	.2500	.0099
4	1.7600	.0265

$$r = 0.427$$

$$\Delta = 0.0188"$$

$$S = 0.00645"$$

G40.8-A3

pt. ⑦

$\rho = 9.6^{\circ}$

QBSV.	X VALUE	Y VALUE
1	.0896	.0077
2	.1500	.0104
3	.2500	.0126
4	1.7600	.0343

$$r = 0.385$$

$$\Delta = 0.0241"$$

$$S = 0.00772"$$

G40.8-A3

pt. ⑧

$\rho = 10.0^{\circ}$

QBSV.	X VALUE	Y VALUE
1	.0896	.0107
2	.1500	.0129
3	.2500	.0145
4	1.7600	.0402

$$r = 0.433$$

$$\Delta = 0.0285$$

$$S = 0.00987$$

G40.8-A3

pt. ⑨

$\rho = 10.3^{\circ}$

QBSV.	X VALUE	Y VALUE
1	.0896	.0133
2	.1500	.0164
3	.2500	.0203
4	1.7600	.0505

$$r = 0.466$$

$$\Delta = 0.0362$$

$$S = 0.01312$$

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .644566F - 02 + .114320E - 01X$$

THE CORRELATION COEFFICIENT = .9980

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .771758E - 02 + .151714E - 01X$$

THE CORRELATION COEFFICIENT = .9960

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .986755E - 02 + .172607E - 01X$$

THE CORRELATION COEFFICIENT = .9990

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .131245E - 01 + .213381E - 01X$$

THE CORRELATION COEFFICIENT = .9960

G40.8-A3 THE LINEAR EQUATION FOR THIS CURVE IS

pt. ⑩

$y = .114556E-01 + .286618E-01x$

$P = 10.8^{\circ}$

THE CORRELATION COEFFICIENT = .9990

$$r = 0.3028$$

$$\Delta = 0.0424$$

$$\delta = 0.01146^{\circ}$$

ORSV.	X VALUE	Y VALUE
1	.0898	.0133
2	.1500	.0154
3	.2500	.0198
4	1.7600	.0618

WS-1
pt. ①

P = 19.3

OBSV.	X VALUE	Y VALUE
1	.0896	.0135
2	.1500	.0154
3	.2500	.0158
4	1.7600	.0600

$r = 0.1279$
 $A = 0.0407$
 $S = 0.01035$

WS-1
pt. ②

P = 20.3

OBSV.	X VALUE	Y VALUE
1	.0896	.0124
2	.1500	.0107
3	.2500	.0186
4	1.7600	.0675

$r = 0.1889$
 $A = 0.0447$
 $S = 0.00839$

WS-1
pt. ③

P = 21.4

OBSV.	X VALUE	Y VALUE
1	.0896	.0192
2	.1500	.0221
3	.2500	.0246
4	1.7600	.0800

$r = 0.3348$
 $A = 0.0553$
 $S = 0.01605$

WS-1
pt. ④

P = 22.3

OBSV.	X VALUE	Y VALUE
1	.0896	.0277
2	.1500	.0318
3	.2500	.0349
4	1.7600	.0945

$r = 0.4796$
 $A = 0.0677$
 $S = 0.0250$

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .103479E-01 + .281421E-01X$$

THE CORRELATION COEFFICIENT = .9990

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .838679E-02 + .336295E-01X$$

THE CORRELATION COEFFICIENT = .9970

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .160490E-01 + .363193E-01X$$

THE CORRELATION COEFFICIENT = 1.0000

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .250090E-01 + .395029E-01X$$

THE CORRELATION COEFFICIENT = 1.0000

WS-1
pt. ⑤

$p = 24.0^k$

WS-1
pt. ⑥

$p = 23.5^k$

WS-1
pt. ⑦

$p = 23.5^k$

WS-1
pt. ⑧

$p = 23.5^k$

OBSV.	X VALUE	Y VALUE
1	.0896	.0301
2	.1500	.0360
3	.2500	.0399
4	1.7600	.1045

$r = 0.4927$
 $\Delta = 0.0751$ " $\delta = 0.0282$ "

OBSV.	X VALUE	Y VALUE
1	.0896	.0357
2	.1500	.0414
3	.2500	.0462
4	1.7600	.1150

$r = 0.5466$ " $\delta = 0.035$ "

OBSV.	X VALUE	Y VALUE
1	.0896	.0377
2	.1500	.0417
3	.2500	.0473
4	1.7600	.1180

$r = 0.5490$ " $\delta = 0.0342$ "

OBSV.	X VALUE	Y VALUE
1	.0896	.0430
2	.1500	.0470
3	.2500	.0526
4	1.7600	.1315

$r = 0.5603$ " $\delta = 0.0389$ "

$\Delta = 0.0958$ "

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .282045E-01 + .434219E-01X$$

THE CORRELATION COEFFICIENT = .9990

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .334803E-01 + .463988E-01X$$

THE CORRELATION COEFFICIENT = .9990

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .344438E-01 + .475309E-01X$$

THE CORRELATION COEFFICIENT = 1.0000

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .389252E-01 + .526312E-01X$$

THE CORRELATION COEFFICIENT = 1.0000

WS-2

pt. ①

 $p = 21.6\%$

WS-2

pt. ②

 $p = 22.8\%$

WS-2

pt. ③

 $p = 23.0\%$

WS-2

pt. ④

 $p = 23.8\%$

OBSV.	X VALUE	Y VALUE
1	.0896	.0155
2	.1500	.0183
3	.2500	.0213
4	1.7600	.0740

$$r = 0.276$$

$$\Delta = 0.0503$$

$$\delta = 0.01260$$

OBSV.	X VALUE	Y VALUE
1	.0896	.0214
2	.1500	.0250
3	.2500	.0265
4	1.7600	.0995

$$r = 0.269$$

$$\Delta = 0.0474$$

$$\delta = 0.01660$$

OBSV.	X VALUE	Y VALUE
1	.0896	.0260
2	.1500	.0343
3	.2500	.0325
4	1.7600	.1070

$$r = 0.3698$$

$$\Delta = 0.0748$$

$$\delta = 0.0232$$

OBSV.	X VALUE	Y VALUE
1	.0896	.0273
2	.1500	.0318
3	.2500	.0356
4	1.7600	.1160

$$r = 0.0329$$

$$\Delta = 0.0804$$

$$\delta = 0.02285$$

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .126780E-01 + .348453E-01X$$

THE CORRELATION COEFFICIENT = 1.0000

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .166794E-01 + .469784E-01X$$

THE CORRELATION COEFFICIENT = .9990

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .232088E-01 + .475483E-01X$$

THE CORRELATION COEFFICIENT = .9970

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .229469E-01 + .528594E-01X$$

THE CORRELATION COEFFICIENT = 1.0000

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .250702E-01 + .561519E-01X$$

THE CORRELATION COEFFICIENT = 1.0000

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .280525E-01 + .621844E-01X$$

THE CORRELATION COEFFICIENT = 1.0000

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .280259E-01 + .561433E-01X$$

THE CORRELATION COEFFICIENT = 1.0000

OBSV.	X VALUE	Y VALUE
1	.0896	.0310
2	.1500	.0336
3	.2500	.0380
4	1.7600	.1240

$$r = 0.3382$$

$$\Delta = 0.08571$$

$$\delta = 0.02507$$

OBSV.	X VALUE	Y VALUE
1	.0896	.0342
2	.1500	.0365
3	.2500	.0439
4	1.7600	.1375

$$r = 0.3418$$

$$\Delta = 0.09571$$

$$\delta = 0.02108$$

OBSV.	X VALUE	Y VALUE
1	.0896	.0345
2	.1500	.0380
3	.2500	.0439
4	1.7600	.1445

$$r = 0.3213$$

$$\Delta = 0.0995$$

$$\delta = 0.02803$$

WS-2

pt. ⑤

$\rho = 23.45^\circ$

WS-2

pt. ⑥

$\rho = 23.4^\circ$

WS-2

pt. ⑦

$\rho = 23.4^\circ$

WS-3
Pt ①

FOLLOWING IS YOUR INPUT

OBSV.	X VALUE	Y VALUE
1	.0849	.0011
2	.3849	.0039
3	.9800	.0088
4	1.0800	.0093
5	1.1800	.0103
6	1.7600	.0180

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = -.193558E-03 + .970079E-01X$$

THE CORRELATION COEFFICIENT = .9910

$$r = 0.00151$$

$$COD = 0.0098" \quad CTOD \approx 0$$

FOLLOWING IS YOUR INPUT

OBSV.	X VALUE	Y VALUE
1	.0849	.0036
2	.1849	.0057
3	.2849	.0079
4	.3849	.0080
5	.9800	.0152
6	1.0800	.0160
7	1.1800	.0173
8	1.7600	.0285

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .271812E-02 + .135455E-01X$$

THE CORRELATION COEFFICIENT = .9890

$$r = 0.1520$$

$$COD = 0.0166" \quad CTOD = 0.002718"$$

FOLLOWING IS YOUR INPUT

OBSV.	X VALUE	Y VALUE
1	.0849	.0056
2	.1849	.0100
3	.2849	.0128
4	.3849	.0118
5	.9800	.0228
6	1.0800	.0247
7	1.1800	.0266
8	1.7600	.0415

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .500526E-02 + .194891E-01X$$

THE CORRELATION COEFFICIENT = .9900

$$r = 0.1946$$

$$COD = 0.0247" \quad CTOD = 0.005005"$$

FOLLOWING IS YOUR INPUT

OBSV.	X VALUE	Y VALUE
1	.0849	.0102
2	.1849	.0126
3	.2849	.0164
4	.3849	.0177
5	.9800	.0301
6	1.0800	.0325
7	1.1800	.0346
8	1.7600	.0545

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .775035E-02 + .246813E-01X$$

THE CORRELATION COEFFICIENT = .9910

$$r = 0.2379$$

$$COD = 0.0325'' \quad CTOD = 0.00775''$$

C10

FOLLOWING IS YOUR INPUT

OBSV.	X VALUE	Y VALUE
1	.0849	.0136
2	.1849	.0171
3	.2849	.0206
4	.9800	.0410
5	1.0800	.0445
6	1.1800	.0474
7	1.7600	.0695

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .105948E-01 + .323215E-01X$$

THE CORRELATION COEFFICIENT = .9980

$$r = 0.2483$$

$$COD = 0.0445'' \quad CTOD = 0.01059''$$

FOLLOWING IS YOUR INPUT

OBSV.	X VALUE	Y VALUE
1	.0849	.0188
2	.1849	.0218
3	.2849	.0269
4	.3849	.0279
5	.9800	.0509
6	1.0800	.0551
7	1.7600	.0855

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .142487E-01 + .393225E-01X$$

THE CORRELATION COEFFICIENT = .9980

$$r = 0.2745$$

$$COD = 0.0551'' \quad CTOD = 0.01425''$$

FOLLOWING IS YOUR INPUT

WS-3

pt. ⑦

OBSV.	X VALUE	Y VALUE
1	.0849	.0235
2	.1849	.0274
3	.2849	.0329
4	.9800	.0621
5	1.0800	.0669
6	1.1800	.0718
7	1.7600	.1020

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .188083E-01 + .458967E-01X$$

THE CORRELATION COEFFICIENT = .9990

$$R = 0.3105$$

$$COD = 0.0669''$$

$$CTOD = 0.0188'$$

OBSV.	X VALUE	Y VALUE
1	.0886	.0010
2	.1886	.0040
3	.2886	.0039
4	.3886	.0054
5	.8885	.0035
6	.9885	.0115
7	1.0885	.0119
8	1.1885	.0109
9	1.2885	.0116
10	1.7600	.0205

WS-5
pt ①

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .459726E-03 + .975893E-02X$$

THE CORRELATION COEFFICIENT = .9150

$$r = 0.0357$$

$$COD = 0.0119 \quad CTOD = 0.00046$$

OBSV.	X VALUE	Y VALUE
1	.0886	.0058
2	.1886	.0077
3	.2886	.0091
4	.8885	.0174
5	1.7600	.0315
6	.9885	.0183
7	1.0885	.0202
8	1.1885	.0211

WS-5
pt ②

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .445848E-02 + .147276E-01X$$

THE CORRELATION COEFFICIENT = .9970

$$r = 0.2293$$

$$COD = 0.0202 \quad CTOD = 0.00446$$

OBSV.	X VALUE	Y VALUE
1	.0886	.0069
2	.1886	.0102
3	.2886	.0110
4	.3886	.0133
5	.8885	.0215
6	.9885	.0235
7	1.0885	.0302
8	1.1885	.0270
9	1.7600	.0405

WS-5
pt ③

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .549673E-02 + .196013E-01X$$

THE CORRELATION COEFFICIENT = .9900

$$r = 0.2124$$

$$COD = 0.0302 \quad CTOD = 0.0055$$

WS-5
Pt 4

OBSV.	X VALUE	Y VALUE
1	.0886	.0097
2	.1886	.0128
3	.2886	.0143
4	.3886	.0168
5	.8885	.0250
6	.9885	.0299
7	1.0885	.0317
8	1.1885	.0343
9	1.2885	.0375
10	1.7600	.0520

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .695361E-02 + .238404E-01X$$

THE CORRELATION COEFFICIENT = .9920

$$r = 0.2210$$

$$COD = 0.0317" \quad CTOD = 0.00695"$$

WS-5
Pt 5

OBSV.	X VALUE	Y VALUE
1	.0886	.0138
2	.1886	.0181
3	.2886	.0204
4	.3886	.0225
5	.9885	.0426
6	1.0885	.0459
7	1.1885	.0543
8	1.2885	.0540
9	1.7600	.0705

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .405258E-01 + .340333E-01X$$

THE CORRELATION COEFFICIENT = .9970

$$r = 0.2344$$

$$COD = 0.0459" \quad CTOD = 0.01053"$$

WS-5
Pt 6

OBSV.	X VALUE	Y VALUE
1	.0886	.0186
2	.1886	.0213
3	.2886	.0236
4	.3886	.0277
5	.9885	.0543
6	1.0885	.0534
7	1.1885	.0563
8	1.7600	.0840

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .133897E-01 + .388104E-01X$$

THE CORRELATION COEFFICIENT = .9960

$$r = 0.2614$$

$$COD = 0.0534" \quad CTOD = 0.01339"$$

WS-5
Pt 7

OBSV.	X VALUE	Y VALUE
1	.0886	.0236
2	.1886	.0299
3	.2886	.0340
4	.3886	.0390
5	1.0885	.0688
6	1.1885	.0734
7	1.2885	.0796
8	1.7600	.1045

THE LINEAR EQUATION FOR THIS CURVE IS
 $Y = .200509E-01 + .465602E-01X$

THE CORRELATION COEFFICIENT = .9990
 $r = 0.3262$

$COQ = 0.0688$ CTOD = 0.02005

WS-5
Pt 8

OBSV.	X VALUE	Y VALUE
1	.0886	.0274
2	.1886	.0349
3	.2886	.0401
4	.3886	.0437
5	.8885	.0701
6	.9885	.0762
7	1.0885	.0815
8	1.1885	.0869
9	1.2885	.0935
10	1.7600	.1160

THE LINEAR EQUATION FOR THIS CURVE IS
 $Y = .239451E-01 + .528202E-01X$

THE CORRELATION COEFFICIENT = 1.0000
 $r = 0.3434$

$COQ = 0.0815$ CTOD = 0.02395

WS-69

pt. 10

OBSV.
1
2
3
4
5
6
7
8
9
10

X VALUE
.0849
.1849
.2849
.3849
.8790
.9790
1.0790
1.1790
1.2790
1.7600

Y VALUE
.0475
.0544
.0623
.0698
.1058
.1138
.1218
.1286
.1375
.1810

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .392894E-01 + .777809E-01X$$

THE CORRELATION COEFFICIENT = .9990

$$r = 0.3827$$

$$COD = 0.1218''$$

$$CTOD = 0.03020''$$

WS-6
Pt. ①

OBSV.	X VALUE	Y VALUE
1	.0849	.0007
2	.1849	.0015
3	.2849	.0031
4	.9715	.0050
5	1.7600	.0130
6	1.0715	.0060
7	1.1715	.0072
8	1.2715	.0068

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .130304E-03 + .621370E-02X$$

THE CORRELATION COEFFICIENT = .9580

$$r = 0.0159 \quad P = 5.2K$$

$$COD = \Delta = .0068" \quad CTOD = 0.00013" = \delta$$

WS-6
Pt. ②

OBSV.	X VALUE	Y VALUE
1	.0849	.0014
2	.1849	.0040
3	.2849	.0052
4	.3849	.0064
5	.8715	.0116
6	.9715	.0113
7	1.0715	.0120
8	1.1715	.0137
9	1.2715	.0142
10	1.7600	.0215

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .150856E-02 + .107004E-01X$$

THE CORRELATION COEFFICIENT = .9900

$$r = 0.1068 \quad P = 9.0K$$

$$COD = \Delta = .0121" \quad CTOD = .00151" = \delta$$

WS-6
Pt. ③

OBSV.	X VALUE	Y VALUE
1	.0849	.0042
2	.1849	.0067
3	.2849	.0086
4	.3849	.0144
5	.8715	.0190
6	.9715	.0188
7	1.0715	.0208
8	1.1715	.0221
9	1.2715	.0240
10	1.7600	.0350

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .406598E-02 + .164997E-01X$$

THE CORRELATION COEFFICIENT = .9820

$$r = 0.2140 \quad P = 13.3K$$

$$COD = \Delta = .0209" \quad CTOD = \delta = .00407"$$

WS-6
pt. ④

THE LINEAR EQUATION FOR THIS CURVE IS

$Y = .636489E-02 + .197901E-01X$

THE CORRELATION COEFFICIENT = .7810

$r = 0.2437$ $P = 15.9^{\circ}$

$COD = \Delta = 0.0272''$, $C_{TOD} = \delta = 0.006364''$

ORSV.	X VALUE	Y VALUE
1	.0849	.0028
2	.1849	.0091
3	.2849	.0143
4	.3849	.0168
5	.8715	.0217
6	.9715	.0237
7	1.0715	.0271
8	1.1715	.0277
9	1.2715	.0299
10	1.7600	.0450

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THE LINEAR EQUATION FOR THIS CURVE IS

$Y = .800685E-02 + .271707E-01X$

THE CORRELATION COEFFICIENT = .9980

$r = 0.2232$ $P = 18.6^{\circ}$

$COD = \Delta = 0.0362''$, $C_{TOD} = \delta = 0.00001''$

ORSV.	X VALUE	Y VALUE
1	.0849	.0105
2	.1849	.0131
3	.2849	.0166
4	.3849	.0191
5	.9715	.0334
6	1.0715	.0361
7	1.1715	.0385
8	1.2715	.0420
9	1.7600	.0580

THE LINEAR EQUATION FOR THIS CURVE IS

$Y = .100839E-01 + .328481E-01X$

THE CORRELATION COEFFICIENT = .9970

$r = 0.2326$ $P = 20.2^{\circ}$

$\Delta = COD = 0.0445''$, $C_{TOD} = \delta = 0.01008''$

ORSV.	X VALUE	Y VALUE
1	.0849	.0128
2	.1849	.0167
3	.2849	.0206
4	.3849	.0237
5	.8715	.0373
6	.9715	.0410
7	1.0715	.0442
8	1.1715	.0470
9	1.2715	.0517
10	1.7600	.0705

WS-6
pt. ⑥

OBSV.

X VALUE

Y VALUE

WS-6

pt. ①

CRACK
EXT.

IMMINENT.

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .132599E-01 + .390712E-01X$$

THE CORRELATION COEFFICIENT = .9990

$$r = \text{0.2571} \quad P = 21.3^K$$

$$\Delta = 600 = 0.0547'' \quad , \quad CTOD = \delta = 0.01326''$$

OBSV.

X VALUE

Y VALUE

WS-6

pt. ②

CRACK
EXTENSION

$$RS = 0.0043''$$

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .174343E-01 + .439807E-01X$$

THE CORRELATION COEFFICIENT = .9980

$$r = 0.3003 \quad P = 22.0^K$$

$$COD = \Delta = 0.0638'' \quad , \quad CTOD = \delta = 0.01743''$$

$$(\delta = \delta - RS = 0.01700'')$$

WS-7
pt. ①

OBSV.	X VALUE	Y VALUE
1	.0849	.0007
2	.1849	.0027
3	.2849	.0034
4	.3849	.0052
5	.8900	.0058
6	.9900	.0064
7	1.0900	.0072
8	1.1900	.0079
9	1.2900	.0099
10	1.7600	.0135

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .105465E-02 + .639951E-02X$$

THE CORRELATION COEFFICIENT = .9620

$$r = \text{0.1248} \quad P = 6.0 \text{ KPS}$$

$$\Delta = .0071'' \quad \delta = .00105''$$

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WS-7
pt. ②

OBSV.	X VALUE	Y VALUE
1	.0849	.0025
2	.1849	.0041
3	.2849	.0058
4	.3900	.0110
5	.9900	.0110
6	1.0900	.0117
7	1.1900	.0132
8	1.2900	.0106
9	1.7600	.0210

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .202581E-02 + .935872E-02X$$

THE CORRELATION COEFFICIENT = .9570

$$r = 0.1640 \quad P = 9.0 \text{ K}$$

$$\Delta = .0116'' \quad \delta = .00203''$$

WS-7
pt. ③

OBSV.	X VALUE	Y VALUE
1	.0849	.0035
2	.1849	.0058
3	.2849	.0073
4	.3849	.0099
5	.8900	.0146
6	.9900	.0135
7	1.0900	.0183
8	1.1900	.0201
9	1.2900	.0214
10	1.7600	.0310

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .241943E-02 + .148726E-01X$$

THE CORRELATION COEFFICIENT = .9810

$$r = 0.1232 \quad P = 12.3 \text{ K}$$

$$\Delta = 0.0182'' \quad \delta = 0.00242''$$

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .336259E-02 + .197769E-01X$$

THE CORRELATION COEFFICIENT = .9960

$r = 0.1288$ $P = 15.1^{\circ}$

$\Delta = 0.0237''$ $\delta = 0.00336''$

OBSV.	X VALUE	Y VALUE
1	.0849	.0067
2	.1849	.0070
3	.2849	.0086
4	.3849	.0112
5	.8900	.0200
6	.9900	.0220
7	1.0900	.0239
8	1.1900	.0264
9	1.2900	.0290
10	1.7600	.0400

WS-7
pt. ④

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .600742E-02 + .237817E-01X$$

THE CORRELATION COEFFICIENT = .9960

$r = 0.1914$ $P = 17.5^{\circ}$

$\Delta = 0.0302''$ $\delta = 0.00601''$

OBSV.	X VALUE	Y VALUE
1	.0849	.0081
2	.1849	.0109
3	.2849	.0128
4	.3849	.0166
5	.8900	.0266
6	.9900	.0285
7	1.0900	.0304
8	1.1900	.0333
9	1.7600	.0500

WS-7
pt. ⑤

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .817584E-02 + .281680E-01X$$

THE CORRELATION COEFFICIENT = .9940

$r = 0.2199$ $P = 19.5^{\circ}$

$\Delta = 0.0370''$ $\delta = 0.00816''$

OBSV.	X VALUE	Y VALUE
1	.0849	.0112
2	.1849	.0139
3	.2849	.0174
4	.3849	.0200
5	.8900	.0308
6	.9900	.0343
7	1.0900	.0373
8	1.1900	.0409
9	1.2900	.0445
10	1.7600	.0610

WS-7
pt. ⑥

WS-7
Pt. ⑦

THE LINEAR EQUATION FOR THIS CURVE IS
 $Y = .102071E-01 + .339461E-01X$

THE CORRELATION COEFFICIENT = .9970
 $r = 0.9997 \cdot 2278$ $P = 24.0^\circ$
 $\Delta = 0.0450''$ $\delta = 0.01021''$

OBSV.	X VALUE	Y VALUE
1	.0849	.0136
2	.1849	.0168
3	.2849	.0204
4	.3849	.0243
5	.9900	.0422
6	1.0900	.0453
7	1.1900	.0494
8	1.2900	.0533
9	1.7600	.0730

WS-7
Pt. ⑧

THE LINEAR EQUATION FOR THIS CURVE IS
 $Y = .129861E-01 + .394896E-01X$

THE CORRELATION COEFFICIENT = .9980
 $P = 22.2^\circ$ $r = 0.9997 \cdot 0.2491$
 $\Delta = 0.0542''$ $\delta = 0.01299''$

OBSV.	X VALUE	Y VALUE
1	.0849	.0171
2	.1849	.0212
3	.2849	.0248
4	.8900	.0468
5	.9900	.0505
6	1.0900	.0546
7	1.1900	.0598
8	1.2900	.0637
9	1.7600	.0850

WS-7
Pt. ⑨

THE LINEAR EQUATION FOR THIS CURVE IS
 $Y = .172668E-01 + .462862E-01X$

THE CORRELATION COEFFICIENT = .9980
 $P = 22.7^\circ$ $r = 0.9997 \cdot 0.2826$
 $\Delta = 0.0658''$ $\delta = 0.01727''$

OBSV.	X VALUE	Y VALUE
1	.0849	.0231
2	.1849	.0265
3	.2849	.0306
4	.8900	.0563
5	.9900	.0617
6	1.0900	.0662
7	1.1900	.0717
8	1.2900	.0767
9	1.7600	.1020

ORSV.	X VALUE	Y VALUE
1	.0849	.0282
2	.1849	.0337
3	.2849	.0392
4	.3849	.0439
5	.8900	.0681
6	.9900	.0729
7	1.0900	.0790
8	1.1900	.0849
9	1.7600	.1160

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .236691E-01 + .514430E-01X$$

THE CORRELATION COEFFICIENT = .9990

$$r = 0.3486 \quad P = 21.7^K$$

$$\Delta = 0.0784" \quad \delta = 0.02367"$$

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FOLLOWING IS YOUR INPUT

Pt. ①

THE LINEAR EQUATION FOR THIS CURVE IS

OBSV.	X VALUE	Y VALUE
1	.0849	.0026
2	.1849	.0033
3	.8790	.0080
4	.9790	.0090
5	1.0790	.0094
6	1.1790	.0095
7	1.2790	.0122
8	1.7600	.0170

$$Y = .132537E-02 + .813450E-02X$$

THE CORRELATION COEFFICIENT = .9820

$$r = .1234$$

$$COD = .0094 \quad CTOD = .001325$$

WS-69

Pt. ①

OBSV.	X VALUE	Y VALUE
1	.0849	.0033
2	.1849	.0060
3	.2849	.0077
4	.3849	.0082
5	.9790	.0160
6	1.0790	.0179
7	1.1790	.0178
8	1.2790	.0210
9	1.7600	.0285

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .277988E-02 + .140502E-01X$$

THE CORRELATION COEFFICIENT = .9950

$$r = 0.1499$$

$$COD = 0.0179 \quad CTOD = 0.00278$$

C23

WS-69

Pt. ②

OBSV.	X VALUE	Y VALUE
1	.0849	.0078
2	.1849	.0096
3	.2849	.0112
4	.3849	.0126
5	.9790	.0239
6	1.0790	.0260
7	1.1790	.0268
8	1.2790	.0301
9	1.7600	.0405

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .563151E-02 + .190997E-01X$$

THE CORRELATION COEFFICIENT = .9980

$$r = 0.2230$$

$$COD = 0.0260 \quad CTOD = 0.00563$$

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Pt. ③

WS-69

FOLLOWING IS YOUR INPUT

Pt. ①

THE LINEAR EQUATION FOR THIS CURVE IS

OBSV.	X VALUE	Y VALUE
1	.0849	.0026
2	.1849	.0033
3	.8790	.0080
4	.9790	.0090
5	1.0790	.0094
6	1.1790	.0095
7	1.2790	.0122
8	1.7600	.0170

$$Y = .132537E-02 + .813450E-02X$$

THE CORRELATION COEFFICIENT = .9820

$$r = .1234$$

$$COD = .0094 \quad CTOD = .001325$$

OBSV.	X VALUE	Y VALUE
1	.0849	.0033
2	.1849	.0060
3	.2849	.0077
4	.3849	.0082
5	.9790	.0160
6	1.0790	.0179
7	1.1790	.0178
8	1.2790	.0210
9	1.7600	.0285

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .277988E-02 + .140502E-01X$$

THE CORRELATION COEFFICIENT = .9950

$$r = 0.1499$$

$$COD = 0.0179 \quad CTOD = 0.00278$$

C23

OBSV.	X VALUE	Y VALUE
1	.0849	.0078
2	.1849	.0096
3	.2849	.0112
4	.3849	.0126
5	.9790	.0239
6	1.0790	.0260
7	1.1790	.0268
8	1.2790	.0301
9	1.7600	.0405

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .563151E-02 + .190997E-01X$$

THE CORRELATION COEFFICIENT = .9980

$$r = 0.2234$$

$$COD = 0.0260 \quad CTOD = 0.00563$$

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Pt. ③

WS-69
Pt. ②

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .645033E-02 + .244109E-01X$$

THE CORRELATION COEFFICIENT = .9980

$$r = 0.9902$$

$$C.D. = 0.0327" \quad C.T.D. = 0.00645"$$

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .874725E-02 + .315305E-01X$$

THE CORRELATION COEFFICIENT = .9980

$$r = 0.2102$$

$$C.D. = 0.0423" \quad C.T.D. = 0.008747"$$

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .127194E-01 + .376801E-01X$$

THE CORRELATION COEFFICIENT = .9960

$$r = 0.2557$$

$$C.D. = 0.0516" \quad C.T.D. = 0.01272"$$

OBSV.	X VALUE	Y VALUE
1	.0849	.0087
2	.1849	.0119
3	.2849	.0137
4	.3849	.0152
5	.8790	.0273
6	.9790	.0303
7	1.0790	.0327
8	1.1790	.0337
9	1.2790	.0381
10	1.7600	.0505

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pt. ④

OBSV.	X VALUE	Y VALUE
1	.0849	.0120
2	.1849	.0151
3	.2849	.0186
4	.3849	.0204
5	.8790	.0353
6	.9790	.0391
7	1.0790	.0423
8	1.1790	.0446
9	1.2790	.0493
10	1.7600	.0660

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pt. ⑤

OBSV.	X VALUE	Y VALUE
1	.0849	.0168
2	.1849	.0207
3	.2849	.0242
4	.3849	.0269
5	.8790	.0436
6	.9790	.0513
7	1.0790	.0516
8	1.1790	.0551
9	1.2790	.0595
10	1.7600	.0825

WS-69

pt. ⑥

OBSV.	X VALUE	Y VALUE
1	.0849	.0206
2	.1849	.0252
3	.2849	.0298
4	.8790	.0599
5	.9790	.0650
6	1.0790	.0653
7	1.1790	.0698
8	1.2790	.0760
9	1.7600	.0970

WS-69

Pt. ⑦

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .172825E-01 + .457941E-01X$$

THE CORRELATION COEFFICIENT = .9990

$$r = 0.2854$$

$$COD = 0.0653 \quad CTOD = 0.01728$$

OBSV.	X VALUE	Y VALUE
1	.0849	.0237
2	.1849	.0327
3	.2849	.0374
4	.3849	.0421
5	.8790	.0707
6	.9790	.0713
7	1.0790	.0768
8	1.1790	.0812
9	1.2790	.0882
10	1.7600	.1150

WS-69

Pt. ⑧

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .215187E-01 + .523698E-01X$$

THE CORRELATION COEFFICIENT = .9980

$$r = 0.3113$$

$$COD = 0.0768 \quad CTOD = 0.02152$$

OBSV.	X VALUE	Y VALUE
1	.0849	.0312
2	.1849	.0368
3	.2849	.0434
4	.8790	.0825
5	.9790	.0831
6	1.0790	.0892
7	1.1790	.0945
8	1.2790	.1013
9	1.7600	.1325

WS-69

Pt. ⑨

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .261184E-01 + .595918E-01X$$

THE CORRELATION COEFFICIENT = .9990

$$r = 0.3320$$

$$COD = 0.0892 \quad CTOD = 0.02612$$

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WS-10
Pt. ①

OBSV.	X VALUE	Y VALUE
1	.0849	.0017
2	.1849	.0012
3	.2849	.0014
4	.3849	.0015
5	.8772	.0066
6	.9772	.0080
7	1.0772	.0079
8	1.1772	.0086
9	1.2772	.0086
10	1.7600	.0125

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .429886E-03 + .488893E-02X$$

THE CORRELATION COEFFICIENT = .9890

$$r^2 = 0.004727$$

$$COD = .0079" \quad CTOD = .00043"$$

OBSV.

WS-10
Pt. ②

OBSV.	X VALUE	Y VALUE
1	.0849	.0020
2	.1849	.0031
3	.2849	.0034
4	.3849	.0056
5	.8772	.0095
6	.9772	.0108
7	1.0772	.0124
8	1.1772	.0139
9	1.2772	.0137
10	1.7600	.0190

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .108614E-02 + .102081E-01X$$

THE CORRELATION COEFFICIENT = .9970

$$r^2 = 0.08061$$

$$COD = .0124" \quad CTOD = .001091$$

OBSV.

WS-10
Pt. ③

OBSV.	X VALUE	Y VALUE
1	.0849	.0045
2	.1849	.0042
3	.2849	.0049
4	.3849	.0076
5	.8772	.0141
6	.9772	.0149
7	1.0772	.0164
8	1.1772	.0178
9	1.2772	.0202
10	1.7600	.0275

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .184169E-02 + .140599E-01X$$

THE CORRELATION COEFFICIENT = .9950

$$r^2 = 0.09926$$

$$COD = .0164" \quad CTOD = .00184"$$

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .178078E-02 + .188474E-01X$$

THE CORRELATION COEFFICIENT = .9950

$$r = 0.071858$$

$$COD = 0.0239''$$

$$CTOD = 0.0078''$$

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .563405E-02 + .234193E-01X$$

THE CORRELATION COEFFICIENT = .9950

$$r = 0.0823$$

$$COD = 0.0310''$$

$$CTOD = 0.00563''$$

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .799889E-02 + .278780E-01X$$

THE CORRELATION COEFFICIENT = .9960

$$r = 0.2174$$

$$COD = 0.0372''$$

$$CTOD = 0.00800''$$

OBSV.	X VALUE	Y VALUE
1	.0849	.0052
2	.1849	.0057
3	.2849	.0062
4	.3849	.0083
5	.8772	.0176
6	.9772	.0189
7	1.0772	.0228
8	1.1772	.0239
9	1.2772	.0256
10	1.7600	.0360

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pt. ④

OBSV.	X VALUE	Y VALUE
1	.0849	.0108
2	.1849	.0092
3	.2849	.0107
4	.3849	.0139
5	.8772	.0253
6	.9772	.0283
7	1.0772	.0310
8	1.1772	.0333
9	1.2772	.0357
10	1.7600	.0475

WS-10

pt. ⑤

OBSV.	X VALUE	Y VALUE
1	.0849	.0136
2	.1849	.0128
3	.2849	.0148
4	.3849	.0181
5	.8772	.0317
6	.9772	.0342
7	1.0772	.0372
8	1.1772	.0402
9	1.2772	.0438
10	1.7600	.0590

WS-10

pt. ⑥

WS-10
pt ⑦

ORSV.	X VALUE	Y VALUE
1	.0849	.0179
2	.1849	.0172
3	.2849	.0198
4	.3849	.0231
5	.8772	.0414
6	.9772	.0457
7	1.0772	.0500
8	1.1772	.0532
9	1.2772	.0557
10	1.7600	.0730

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .114949E-01 + .348831E-01X$$

THE CORRELATION COEFFICIENT = .9970

$$r = 0.2496$$

$$C00 = 0.0500 \quad C700 = 0.01149$$

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pt ⑧

ORSV.	X VALUE	Y VALUE
1	.0849	.0249
2	.1849	.0255
3	.2849	.0276
4	.3849	.0234
5	.8772	.0535
6	.9772	.0584
7	1.0772	.0639
8	1.1772	.0673
9	1.2772	.0716
10	1.7600	.0935

THE LINEAR EQUATION FOR THIS CURVE IS

$$Y = .177844E-01 + .422647E-01X$$

THE CORRELATION COEFFICIENT = .9980

$$r = 0.3188$$

$$C00 = 0.0639 \quad C700 = 0.01779$$

END

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