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Master curve description of crack arrest toughness of 350WT steel

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Master Curve Description of the Crack Arrest Toughness of 350WT Steel

by

J. Morrison[1], L. N. Pussegoda[2], R. B. Nethercott[3], and J.D. Sumpter[4]

[1]DREA Dockyard Laboratory (Pacific), Victoria, BC, Canada.
[2]Fleet Technology Ltd, Kanata, ON, Canada
[3]Aeronautical and Maritime Research Laboratory, Melbourne, Australia
[4]DERA, Rosyth, United Kingdom

Abstract

The measurement of crack arrest fracture toughness is difficult and expensive, particularly if a representative structural element is to be tested, and the underlying theory is controversial. Small specimen test methods have been developed, but applying these to ship plate presents special challenges, primarily because the limited thickness precludes plane strain conditions in the specimen. A collaborative Operating Assignment under TTCP MAT Group Panel 1 (Metallic Materials and Processes) has recently assessed a small specimen crack arrest test method for ship plate.

As part of this assignment the crack arrest toughness of 15 mm thick CSA 350WT plate has been determined using a full thickness compact specimen test procedure. A crack arrest master curve has been calculated from this data, and provided a good description of the data scatter. Comparisons were made between the crack arrest reference temperature T_{Ka}, and the crack arrest temperature estimated from NDTT. The data have also been analyzed using expected service loading for a simple structural detail.

The results suggest that the proposed procedures can be used to generate useful data from ship plate for structural integrity assessment, although the technique will always require careful optimization of specimen design and testing conditions.

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9th CF/DRDC Meeting on Naval Applications of Materials Technology

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The measurement of crack arrest fracture toughness is difficult and expensive, particularly if a representative structural element is to be tested, and the underlying theory is also controversial Small specimen test methods have been developed, but applying these to ship plate presents special challenges, primarily because the limited thickness precludes plane strain conditions in the specimen A collaborative Operating Assignment under TTCP MAT Group Panel 1 (Metallic Materials and Processes) has recently assessed the suitability of small specimen crack arrest test methods when applied to ship plate A key part of this assignment involved determination of the crack arrest toughness of a 15 mm thick CSA 350WT plate shared between the participants using a full thickness compact specimen test procedure proposed by Crosley and Ripling (1990)

A brief description of the test procedure and calculations is provided, including the difficulties encountered by the different laboratories These centre on the difficulty of optimizing starter notch brittleness, and the relatively low success rates for suitably arrested cracks Comparisons are made between Canadian and Australian data and crack arrest master curves and reference temperatures have been calculated from this data, using a recent formulation (Wallin 2000) for multi-temperature analysis This provided a good description of the data scatter for results considered valid according to the test procedure requirements There were discrepancies between results from different laboratories, but these were within the 90% master curve scatterband

An assessment has been made of the results using published correlations Comparisons have been made between the crack arrest reference temperature T_{Ka} and the crack arrest temperature estimated from NDTT The data have also been analyzed using expected service loading for a simple structural detail using a scenario due to Sumpter (1991) T_{Ka} was also found to be 10-20 °C higher than the dynamic initiation reference temperature for the same plate orientation The results suggest that the proposed procedures can be used to generate useful data from ship plate, although the technique will always require careful optimization of specimen design and testing conditions This particular steel plate has good crack arrest toughness

TTCP Operating Assignment on Crack Arrest Toughness of Ship Plate

Contributors

J. Morrison (Focus Officer)
DREA/DL(P)
Victoria, BC, Canada

J.D. Sumpter
DERA
Rosyth, Scotland

R. Nethercott
AMRL
Melbourne, Australia

N Pussegoda
Fleet Technology Ltd
Kanata, ON, Canada

Overview

- Background/program.
- Material properties.
- Crack arrest test procedure/problems.
- K_a* master curve.
- Crack Arrest Master Curve/Correlations.
- Structural Implications.
- Conclusions.

Background

- Limited thickness invalidates K_{Ia} tests.
- Is it possible to measure a useful crack arrest toughness under non plane strain conditions?
- How well would the master curve describe the crack arrest data?
- Would the results be useful for material selection and structural integrity assessment?

Program

Australia.
- Compact crack arrest (CCA) specimen testing (plate).
- Low temperature tensile properties.
- Efffect of prestrain on crack initiation.

Canada
- Characterization of steel plate.
- CCA specimen testing (plate plus HAZ).
- Evaluation of different brittle weld crack starters.

United Kingdom
- Review of crack arrest theory and application.
- Dynamic crack initiation tests.
- Crack arrest trials using both wedge and pin loaded specimens.

15 mm 350WT plate

Chemical Composition (wt %)							
C	Mn	Si	S	P	Ni	V	Al
0.16	1.38	0 28	0 005	0.009	0 21	0 07	0.036

Mechanical Properties		
	T-L	L-T
0.2% Proof Stress (MPa)	450 (T)	447 (L)
UTS (MPa)	590	587
Elongation (%)	26	27
Charpy V-notch @ -40°C (J)	38	120
DT @ -20°C (J)	355	1285
CTOD δ_m @ -20°C (mm)	0 42	0 55
NDTT (°C)	-40	-40

350WT Weld

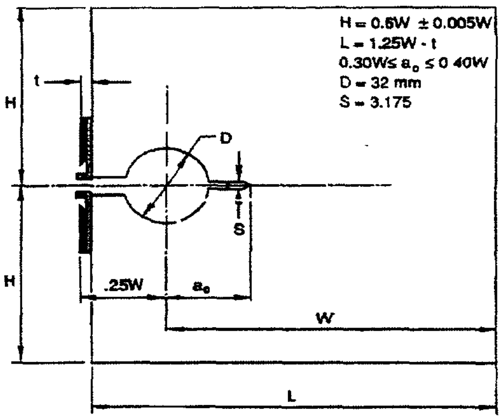
Submerged Arc Welded 15 mm plate
Orientation: transverse.
Butt weld with one straight edge.
Lincoln LA75 wire Lincoln 880M flux
6 passes, Travel speed 435 mm/min
Min. preheat 20°C, max. interpass 200°C
Heat input 3.4 kJ/mm
VHN Hardness: Plate-198,
CGHAZ-221
Weld-209

Heat Affected Zone Properties

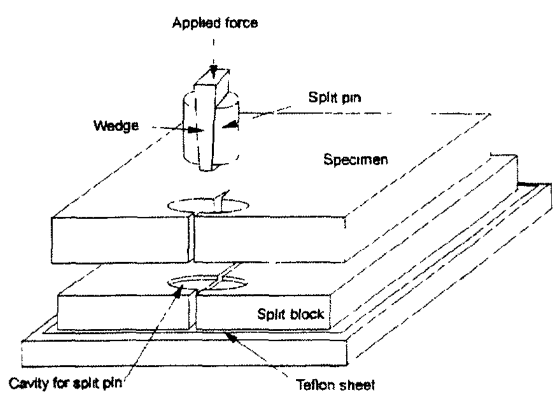
Charpy V (J)	140J @ -25°C	
	138J @ -35°C	
	95J @ -40°C	
	50J @ -45°C	
CTOD mm	0.55 @ -5°C	SD = 0.40
	0.79 @ -15°C	SD = 0.47

Crack arrest test procedure

- Tests carried out by FTL and AMRL.
- ASTM E1221 requires plane strain.
- Followed Crosley and Ripling (1990) procedure for specimens with full product thickness.



Wedge and split pin loading



Crack arrest test parameters

- Modified compact specimen W=150 to 300mm.
- Brittle crack starter.
  Brittle weld deposit or strain aged embrittled.
- Test temperature range -10°C to -30°C.
- K_a* considered "valid" if crack runs and arrests within defined CMOD and a/W limits.

Crack arrest expressions

- Specimens dimensions:

$$W \geq 2.83(K_v/\sigma_{ys})^2$$

where K_v is a starting estimate of toughness

- CMOD limits:

$$\delta = K_v\sqrt{W}/E\ f(a/W)$$

for a/W = 0.525 (min.) and 0.8 (max.)

f(a/W) is same as in ASTM 1221

- Preliminary toughness:

$$K_a = \delta\ E\ f(a/W)/\sqrt{W}$$

- Plasticity correction:

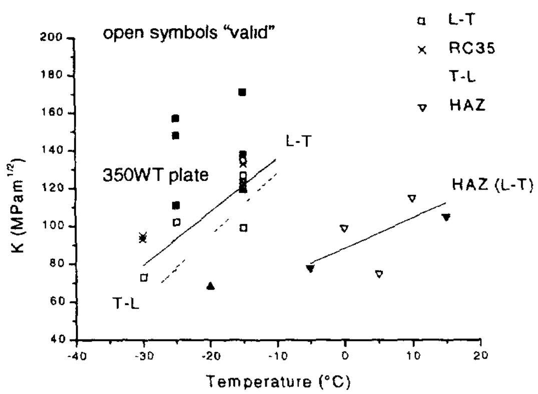
$$K_a^* = K_a[1 - 0.105\phi^2(1 - (a/W)^{0.5})]$$

where $\phi = E\delta/1.5\sigma_{ys}W$

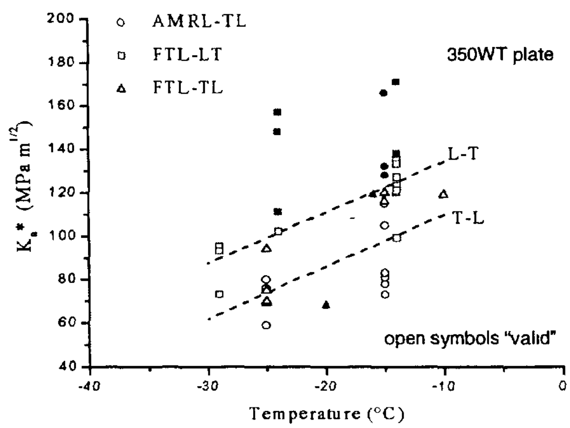
Problems in crack arrest testing

- Requires large specimens.
- Low to moderate success rates. Method originally conceived for quality assurance.
- Difficult to optimize brittle starter for specimen toughness and test temperature.
- Monotonic vs. repeated loading?
- Plasticity corrections.

FTL results



Combined AMRL and FTL K_a* results

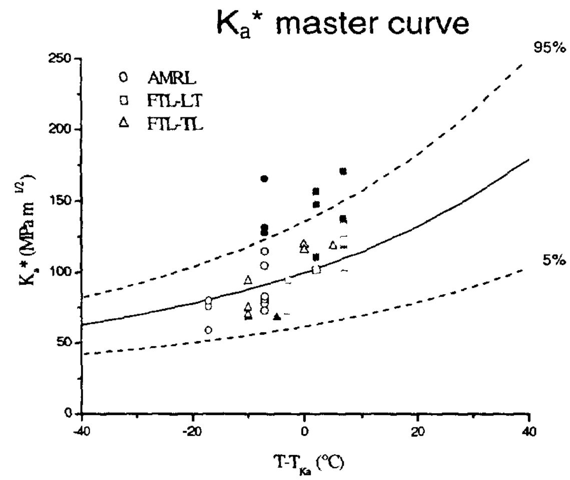


Reference temperature fit for T_{Ka} (Wallin 2000)

- K_a does not follow the Weibull distribution used for K_{Jc} (slope=4, K_{min}= 20 MPa√m). Need alternative algorithm (Wallin 2000).
- If K_a distribution is log normal, the multi-temperature fit for plane strain K_{Ia} is given by:

$$\sum_{i=1}^{n} \frac{\ln K_{Ia_i} \cdot \exp\{0.019 \cdot [T_i - TK_{Ia}]\}}{30+70 \cdot \exp\{0.019\,[T_i - TK_{Ia}]\}} -$$

$$\sum_{i=1}^{n} \frac{\ln(30+70 \cdot \exp\{0.019 \cdot [T_i - TK_{Ia}]\}) \cdot \exp\{0.019\,[T_i - TK_{Ia}]\}}{30+70\,\exp\{0.019 \cdot [T_i - TK_{Ia}]\}} = 0$$



Crack arrest reference temperatures

Orientation	Source	T_{Ka} (°C)
L-T	FTL	-27
T-L	AMRL	4
	FTL	-15
	Combined	-3

(multi-temperature analysis)

Are these K_a^* values sensible?

1. T_{ka} and Crack Arrest Temperature (CAT).

CAT estimation e.g. Wiesner & Hayes (1996)

$$CAT = [NDTT+10] + [\ln\sigma/0.046-105] + [1.53(B-5)^{1/13}-190]$$

applied stress correction thickness correction

at 450 MPa yield stress & B = 15 mm

$$CAT \sim NDTT + 30°C \sim -10°C$$

taking an average T_{ka} of -15°C for T-L and L-T
median $K_a^* \sim 107$ MPa√m at CAT

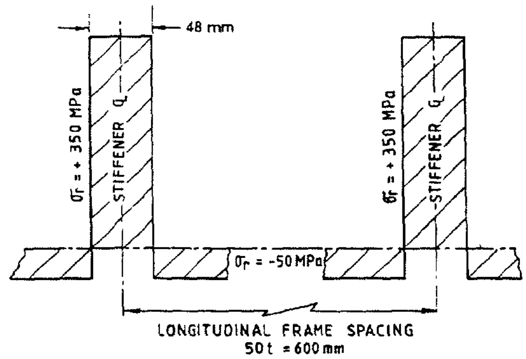
2. Normalization to dynamic yield stress.
e.g. Sumpter (1986)

At NDTT:

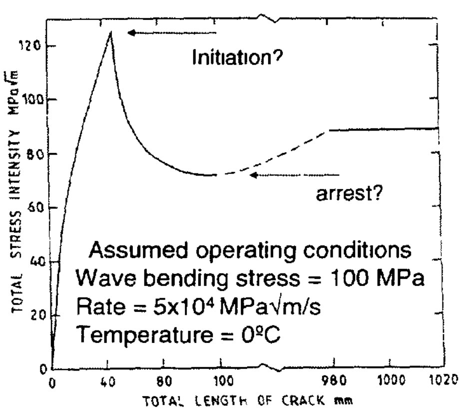
$$0.075 \leq K_{Ia}/\sigma_{yd} \leq 0.118\ \sqrt{m}$$

for $K_a^* = 74$ MPa√m and $\sigma_{yd} = 630$ MPa

$$K_a^*/\sigma_{yd} = 0.117\ \sqrt{m}$$

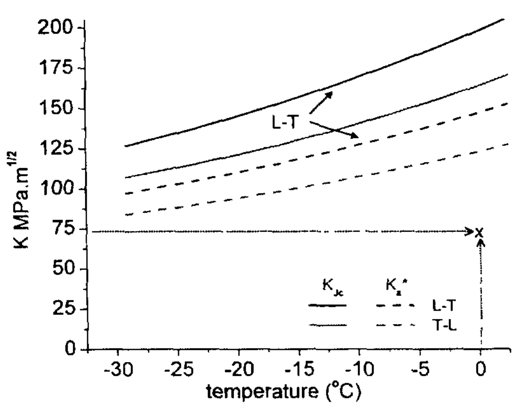


Longitudinal stiffener detail (Sumpter (1991))



Stress intensity distribution

- For T_{ka} = -15°C (average of T-L and L-T),
  K_a^* = 70 MPa√m at -44°C.
- NDTT is -40°C.
- At 0°C 70 MPa√m is on 4% tolerance bound.



Conclusions

- A full thickness specimen procedure was used to characterize the crack arrest toughness of a ship plate.
- The master curve provided a reasonable description of K_a* data.
- T_{ka}* was 10-20°C higher than a dynamic T_o, and is roughly equal to a CAT predicted from NDTT.
- 350WT steel should have a high resistance to cleavage crack propagation under ship operating conditions.