Assessment of Crack–Arrest Properties of Nuclear Pressure Vessel Steels by Means of Small Specimens

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Abstract.

Since 1982 ENEA started a program to assess the crack-arrest properties of pressure vessel steels in the framework of the italian nuclear power program.
SA533 gr. B Cl.1 and SA508 Cl.3 materials have been chosen for this purpose. The program has been conducted through two laboratories. CISE laboratory, in Milan, performed 99 tests on SA533 from 1982 to 1987, obtaining 92 propagations, while CASACCIA laboratory, in Rome, run 17 tests on SA508 starting in 1984 and up to 1988, with 15 propagations.
Two different specimens, WCA and CCA, have been used.
The main goal was to quantify materials crack-arrest toughness in a temperature range as large as possible, according to material linear elastic behaviour and specimen dimensions.
At the time the program started no recognized standard method existed for these tests therefore the proposed ASTM test method was adopted, as reference one, using a transverse loading arrangement.
Also important to the program was to check the validity of the ASME reference curve Kr and to look at the dependence of Ka on Ko.

Test specimens and crack initiation.

Fig.1 shows specimens geometry. A standard CCA specimen has been used as well as a WCA. This second specimen has been chosen because of the larger W/H ratio which allows longer crack propagations without invalidating the ASTM limitation on crack jump. It was analytically and experimentally calibrated as Crosley and Ripling (Crosley,1981) did for the standard CCA specimen. Fig.2 is a plot of the WCA calibration function compared to the ASTM one, valid for the CCA geometry.
Moreover using the friction method (Milella,1981) to derive the actual force N opening the specimen, it has been possible to infer an experimental calibration curve for the CCA test piece. Fig.3 shows the comparison between ENEA experimental and ASTM trend of compliances vs. crack depth for the standard CCA specimen.
The two kind of specimens were used to obtain a rapid run-arrest event through a transverse loading arrangement as shown in fig.4. Measuring the crack-mouth opening and the crack length at initiation and arrest it is possible to evaluate statically the stress intensity factor, right before initiation and a short time after arrest. If validity requirements are met, the stress intensity factor at arrest Ka is assumed to be the plane strain crack-arrest toughness.
The problem in this kind of test is to initiate the crack, mainly at high

temperature. In this program the crack starter has been obtained embrittling a small region beneath the notch, where a crack was introduced by EDM.

To embrittle the material at the notch a spot weld machine has been used. Two electrodes cause an electric current to pass either through the thickness or the ligament of the specimen, quenching the material. Hardness as high as 400-450 HV can be obtained and these values seem to be enough to have crack propagation at temperatures 70 C higher than the Reference Transition Temperature. Fig.5 shows the electrodes configuration and tab.1 presents some data relative to the embrittling process.

Test procedure and opening force determination.

A typical plot of wedge load vs. displacement is reported in fig.6. A cycling procedure has been adopted. It was originally proposed by Battelle (Rosenfield,1981) to get rid of all the plastic component of displacement prior to initiation of unstable fracture.

Researches are questioning whether or not that component should be considered in the evaluation of Ka since the strain energy stored in the plastic zone up to the last cycle could be recovered in time to influence the crack propagation. Another question is related to the sudden opening during propagation. The present ASTM procedure suggests to disregard the plastic displacement possibly experienced by the specimen in the first cycle and consider only half of the remaining plastic component till arrest takes place and half of the sudden final displacement increase.

At variance with ASTM, the present ENEA procedure does not consider at all the plastic component of displacement whereas takes complete account of the final jump. Indeed monitoring of the cross-head rod, at ENEA, has revealed that the wedge is further inserted in the specimen during crack propagation. This may be attributable to the volume expansion of the oil in the hydraulic actuator of the testing machine.

During the test no direct measurement of the force that opens the specimen is made. Using the friction method (Milella,1981),it is possible to derive this force from the plot of the wedge load vs. the specimen opening.

The knowledge of this force has been useful to infer an experimental calibration of the specimen as well as to check the results validity.

In fact, considering the last cycle, we can measure from the plot the compliance of the specimen at arrest. This measured compliance can be compared to the compliance calculated knowing the arrested crack length and the calibration function. Usually the measured compliance is less than the calculated one, due to the effects of the ligaments on the fracture surfaces. If this does not happen the result is disregarded as representative of a non linear-elastic condition.

Also ASTM standard introduces some validity requirements. In plane dimensions large enough to ensure a linear elastic behaviour of the specimen are required as well as a minimum specimen thickness for plane strain conditions.

Plane strain conditions are required in our procedure too.

Results will be presented in terms of valid data according to both ENEA and ASTM procedure.

In any case all the data obtained after an out of plane crack propagation or coming from specimens with large ligaments have been rejected.

Tests results.

Fig.7 shows valid tests according to ENEA procedure. Also reported is the ASME Kr curve. Data points are reduced from 107 to 54 because of validity requirements. If we consider ASTM procedure the number of valid tests reduces to 35 as reported in fig.8.

It is possible to observe that ENEA procedure leads to lower values of Ka

compared to ASTM. This fact leaves ENEA data trend well above the Kr curve at low temperatures crossing the reference curve at high temperatures. Using the ASTM procedure no data fall below the Kr curve.
If we consider also data marginally not valid (25% of not validity) we can go up to 63 data with the ENEA procedure and 45 with the ASTM procedure.
Fig.9 shows dependence of Ka on Ko for valid and marginally not valid results according to ENEA procedure.

Conclusions and recommendations.

Small CCA or WCA specimens are suitable to provide a large number of Ka data even if validity requirements may dramatically reduce the number of valid tests. Problems arise increasing the test temperature. ENEA procedure to generate a brittle starter seems to be effective also at 70 C over the Reference Transition Temperature, with three inches thick specimens.
The general Ka trend remains above the ASME, sec. XI, Kr curve at temperatures up to 70 C above the Transition Temperature where it seems to cross the ASME curve.
More data need to be generated at higher temperatures to fully assess the crack arrest properties of pressure vessel steels.
The crack arrest properties of the steel under investigation appear to be depending on the Ko at initiation. High Ko seems to lead to high Ka values. If one reflects over the fact that high Ko is possible mainly at high temperature, this finding may be revealing just the dependence of Ka on temperature. More data are needed.

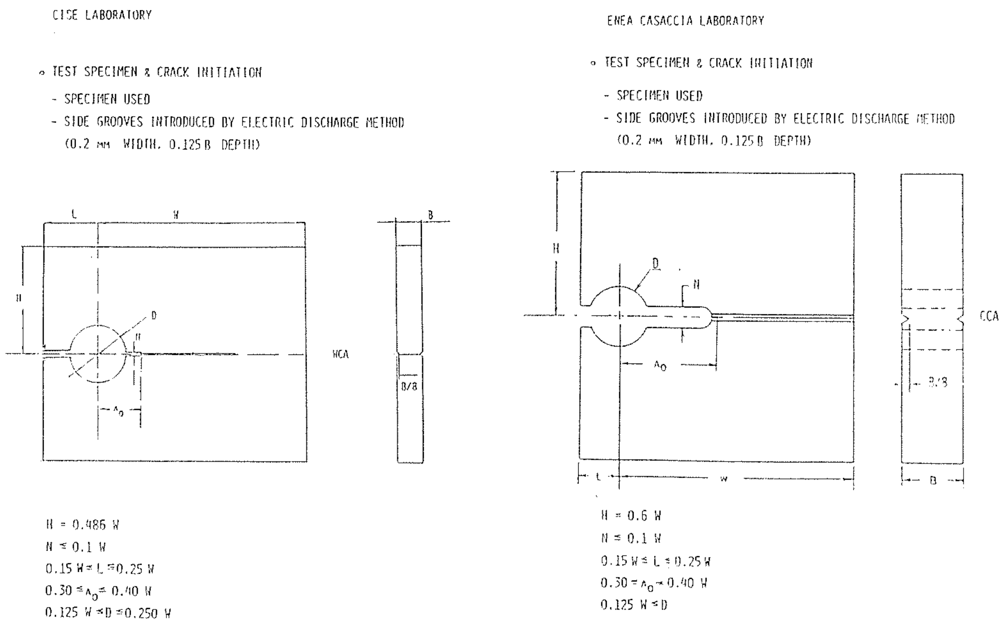

Fig.1 - Specimens geometries

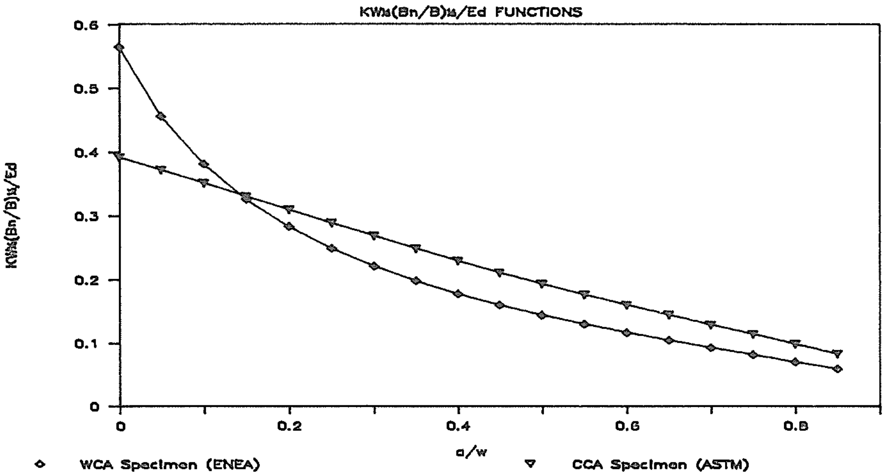

Fig.2 - Calibration functions for ASTM and ENEA specimen

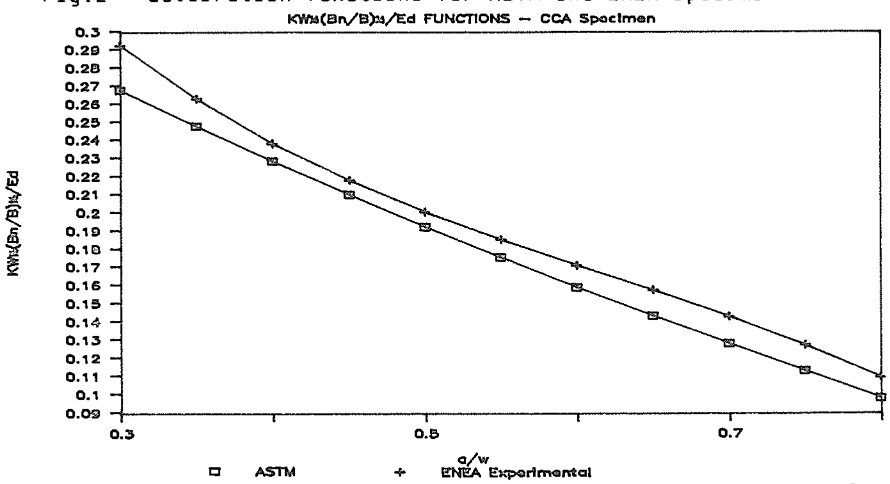

Fig.3 - Comparison between ASTM and ENEA experimental calibration functions

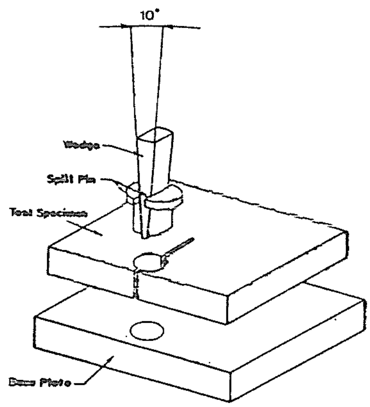

Fig.4 - Transverse loading arrangement

TABLE 1 - Used spot weld machines

Spec.	Power (KVA)	Discharge Time (s)	Force on Electrodes (kN)	Contact Area (mm^2)	Electrode
1WCA1/50	260	4	30	490	Pastil
2WCA1/9	300	8	30	490	"
2WCA10/30	350	16	30	1020	Prism
3WCA1/32	350	16	30	1020	"
A4/8	260	4	30	490	Pastil
B1/5	20	90	/	33	Cylinder
BK1/6	20	90	/	33	"

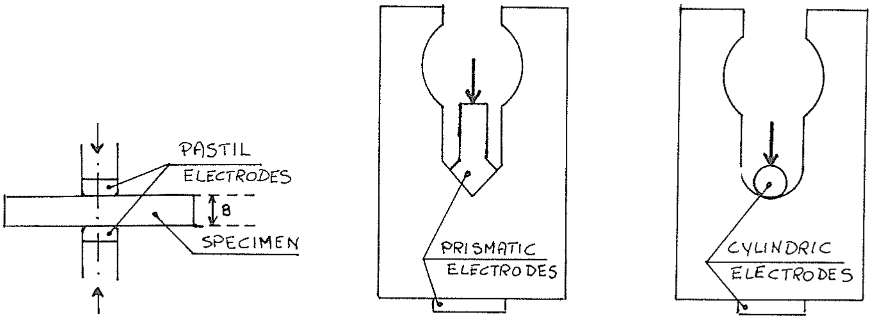

Fig.5 - Electrodes Configurations

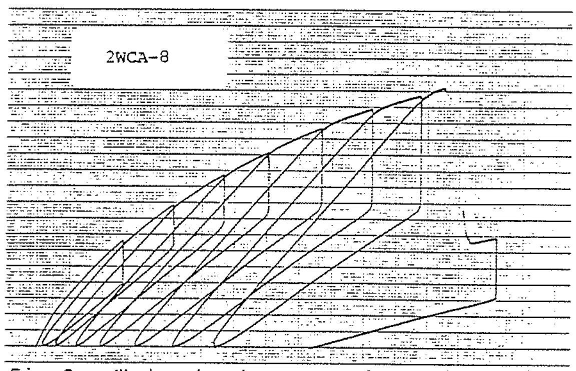

Fig.6 - Wedge load vs. crack mouth opening

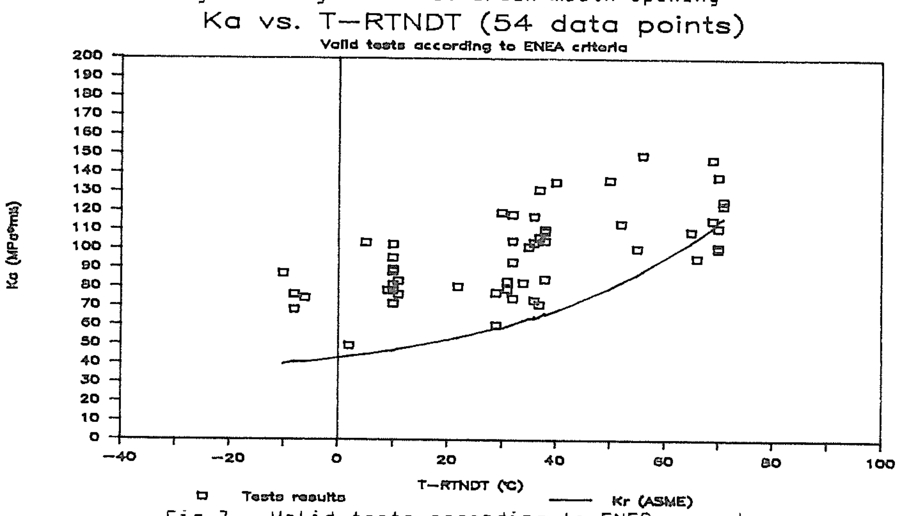

Fig.7 - Valid tests according to ENEA procedure

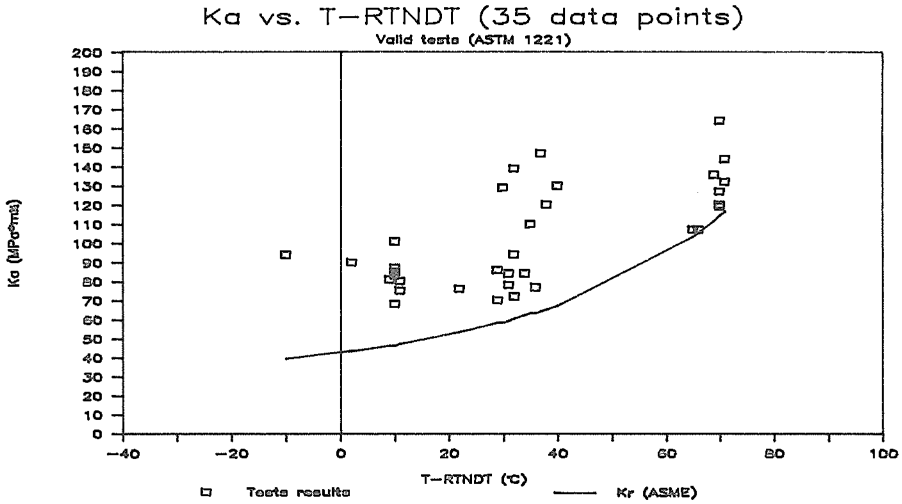

Fig.8 - Valid tests according to ASTM procedure

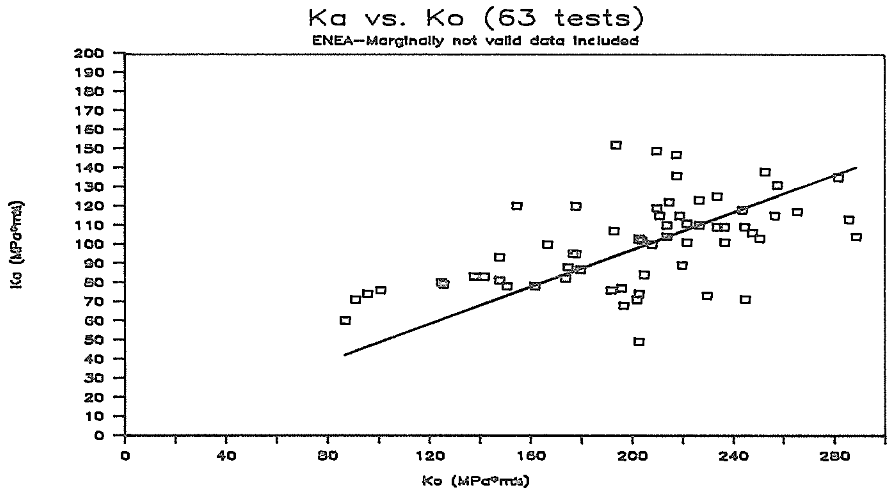

Fig.9 - Ka vs. Ko for ENEA procedure including marginally valid tests

References.

Crosley,P.B., and Ripling E.J., " Development of a Standard Test for Measuring KIa with a Modified Compact Specimen ", NUREG/cr-2294 (ORNL/Sub-81/7755/1), MRL, Glenwood, Illinois (August 1981).

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