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REVIEW OF SOME TECHNIQUES PRESENTED AT THE MEETING ABOUT "ENGINEERING FRACTURE TOUGHNESS TESTS (EFTT) ON FATIGUE PRECRACKED SPECIMENS ACCORDING TO FISSAD, NASA (ASTM) AND COMPARABLE PROCEDURES" HELD IN MILANO ON MAY 31-1979

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REVIEW OF SOME TECHNIQUES PRESENTED AT THE MEETING ABOUT "ENGINEERING FRACTURE TOUGHNESS TESTS (EFTT) ON FATIGUE PRECRACKED SPECIMENS ACCORDING TO FISSAD, NASA (ASTM) AND COMPARABLE PROCEDURES " HELD IN MILANO ON MAY 31 - 1979 "

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Abstract - A series of slow-bend tests and of impact-tests on "differentially precracked-Charpy-specimens" has been done on main steel grades for shafts and gear boxes (4340; 9310; Nitralloy).

For the main shaft steel (4340) different heat treatments have been tested.

In the impact-tests some basic physical phenomenon already evidenciated by Pellini with DT - tests are encountered in the present investigation.

Slow bend tests data were elaborated with original Ravez procedure and according to Witzke - NASA - procedure.

Summary

- Introduction and outline of the D.P.S. procedure (**)
- Experimental results
- Impact tests and flat-fractures:
  Comparison of the specific EC_o plot with the propagation resistance curve as determined by DT - tests.
- Slow bend tests:
  Comparison with NASA (ASTM) procedures (***)
- Conclusions

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EFTT Meeting Main References:

(*) based on works presented at the Engineering Fracture Toughness Tests, (EFTT), Meeting held in Milano on May 31, 79; organized by AIM, Associazione Italiana di Metallurgia, IGF, Italian Group of Fracture, and AIFA, Associazione Italiana per la Fatica in Aeronautica, and with the Sponsorship of AGARD.

(**) According the main peculiarity of the test, the Fissad procedure will be also defined "differentially precracked specimens" D.P.S. procedure see test (A.d.) and (B.d.) in the first paragraph (also ref.1)

(***) Succop, Bubsey, Jones and Brown, (2) also lectures at the EFTT Meeting. Witzke and others (3). The procedures presented in both papers are used in the following paragraphs.

Introduction and outline of the D.P.S. procedure

The research lines described in this work are basically the development of some ideas outlined in a previous paper [1].

At that time several points were considered of outstanding importance and worth of future development:

- the liason of the "differentially precracked specimens" and of the french spec. AIR 0814 (4), with the two main families of tests under specifications in USA regarding Charpy-V specimens, namely: slow bend and impact tests respectively (see following parts of this paragraph).
- the physical meaning and the trend of the specific rupture energy obtainable dividing the impact energy by the ligament surface for each specimen broken in each EC_0 determination according 0814.
- the use of a series of differentially precracked Charpy-V specimens for each test, (curves determined with different specimens).
- the parallel determination in slow and fast condition for precracked specimens of identical materials and treatment.

In this presentation the main goal is to illustrate in a deeper way these previous points also by means of experimental results obtained in a characterization of steels "consumable remelted" and specifically used in the geared-fan technology, because of the more stringent fatigue and fracture problems arising in this field as opposite to the normal turbo-fan technology.

The geared-fan technology is a short-flash definition given by Bamberger to the materials and engineering involvments of the HPDTS (High Power Density Turbo-Shaft).

Basic papers dealing with fracture parameters as obtained with Charpy-V specimens can be summarized as follows:

A) Dynamic tests on Charpy-V specimens, (impact tests A-a~~+~~d) :

(a) Charpy-V specimens subjected to impact bending (Barsom and Rolfe)[5]; cited also by Broek[6].
Purpose: First proposed correlation with K_{Ic} starting from the determination of total impact energy.
Notes: Total determination of brittle and shear energies, and consequently, difficulty in correlating - in a physical sense - K_{Ic} with the obtained values.

(b) Precracked Charpy-V specimens subjected to instrumented impact (Koppenaal)[7]; as a completation of Ronald work, see (B.a)
Purpose: Separation between brittle and shear contribution by recording force during impact failure.
Notes: Difficulty in evaluation of strain rate sensitivity in case of correlation with K_{Ic}. Possible experimental difficulties caused by frequencies which are typical of the system and of the specimen, especially in case of the brittle materials.

(c) Precracked Charpy-V specimens subjected to instrumented impact, by analogy with Koppenaal work (R.A. Wullaert, D.R. Ireland, A.S. Tetelman)(8)
Purpose: Introduction of the use of instrumented tests with Charpy-V precracked specimens, even for high toughness, low tensile strength steels, and correlation with Fracture Mechanics-
Notes: This test is recomended for low and medium strength steels as opposite to the normal impact on precracked specimens usefull for high strength steels. Substantial effects coming from strain rate, and differentiating K_{Ic} and K_{Id}.

(d) Standard dimensions Charpy-V specimens "differentially precracked" subjected to impact tests (9) (note the similitude with the slow bend test B.d)
Purpose: Qualitative and quantitative correlation of EC_0 and of specific energy from D.P.S., with K_{Ic}.
Notes: Standardization of specific energy values in order to determine shear contributions for control of constancy or-alternatively-of the variation between EC_0 and E_n where EC_0 is the extrapolated energy for the fatigue crack length tending towards 0 and E_n is the energy value for the effective flow length of each specimen. See (Table 1, step 3).
The impact measurements are made with a normal, not instrumented, pendulum

B) Static tests on Charpy-V specimens, (slow bend tests B-a÷d) :

(a) Precraked but not instrumented (subsize) Charpy-V specimens subjected to fracture by slow bending. Most reliable correlation with K_{Ic} values in respect of other test on Charpy-type specimens. (Ronald and others)(10)
Purpose: Optimization of engineering fracture toughness test by comparing different uses of Charpy-V specimens.
Notes: Difficulty in finding the right explanation in termsof physical model. Deviation between scheduled and calculated values for higher toughness materials.

(b) Charpy-V subsize (6,25 mm) precracked specimens subjected to slow bending (Succop, Bubsey, Jones and Brown).(2)
Purpose: Measurement of the specific energy for fracture through integration of the load-deflection curve or of schematization of it for correlation to K_{Ic}.
Notes: Use of calibration factors applied to the fracture energy values obtained with different models.

(c) Charpy-V subsize (6,25 mm) precracked specimens subjected to slow bending (Witzke and others).(3)
Purpose: Use of Ronald suggestion concerning slow bending but by calculating fracture energy values according the different procedures as checked by Succop in the cited paper, [test B.b].
Notes: use of calibration factors applied to energy values.

(d) Standard dimensions Charpy-V specimens, "differentially precracked" subjected to slow bending(9) (note the similitude with the impact test A.d)
Purpose: Determination of K_{Ic} from D.P.S. in analogy with ASTM E 399
Notes: A series of F-S curves for several precracked samples for determination of one K_{Ic} figure.

Experimental results

Specimens and testing equipment

- for tensile tests: round specimens (Ø 4 mm x 4 d) tested on Instron dynamic/static electro-hydraulic machine; using strain-gauge extensometer.
- for slow bend tests: Charpy-V specimens precracked on FISSAD facility, at predetermined crack depthes and tested on Instron dynamic/static electro-hydraulic machine using three-point-bend fixture and strain-gauge extensometer for plotting load vs. span.
- for impact tests: Charpy-V specimens precracked on FISSAD facility and tested on Charpy 300 J pendulum and on MANLABS pendulum; the choice of the pendulum depending on the hardness level.

Materials used

- SAE 4340-ESR Ø 20 mm spec.: STA 100-85-04
  (treated for 31÷34, 36÷39, 42÷45, 48÷50, 53÷55 HRC)
- SAE 9310-VAR Ø360 mm spec.: AMS 6265 (tr. 36÷39 HRC)
- Nitralloy -VAR Ø100 mm spec.: AMS 6470 (tr. 49÷51 HRC)
  (135 mod.)

Analysis

	C	Si	Mn	Ni	Cr	Mo	Al	Cu	S	P	V
4340 - ESR	0,40	0,33	0,78	1,73	0,82	0,26	-	-	0,006	0,010	0,11
9310 - VAR	0,09	0,30	0,47	3,33	1,36	0,13	-	-	0,002	0,010	-
Nitralloy-VAR (135 mod.)	0,41	0,40	0,61	-	1,69	0,35	1,02	0,14	0,001	0,007	-

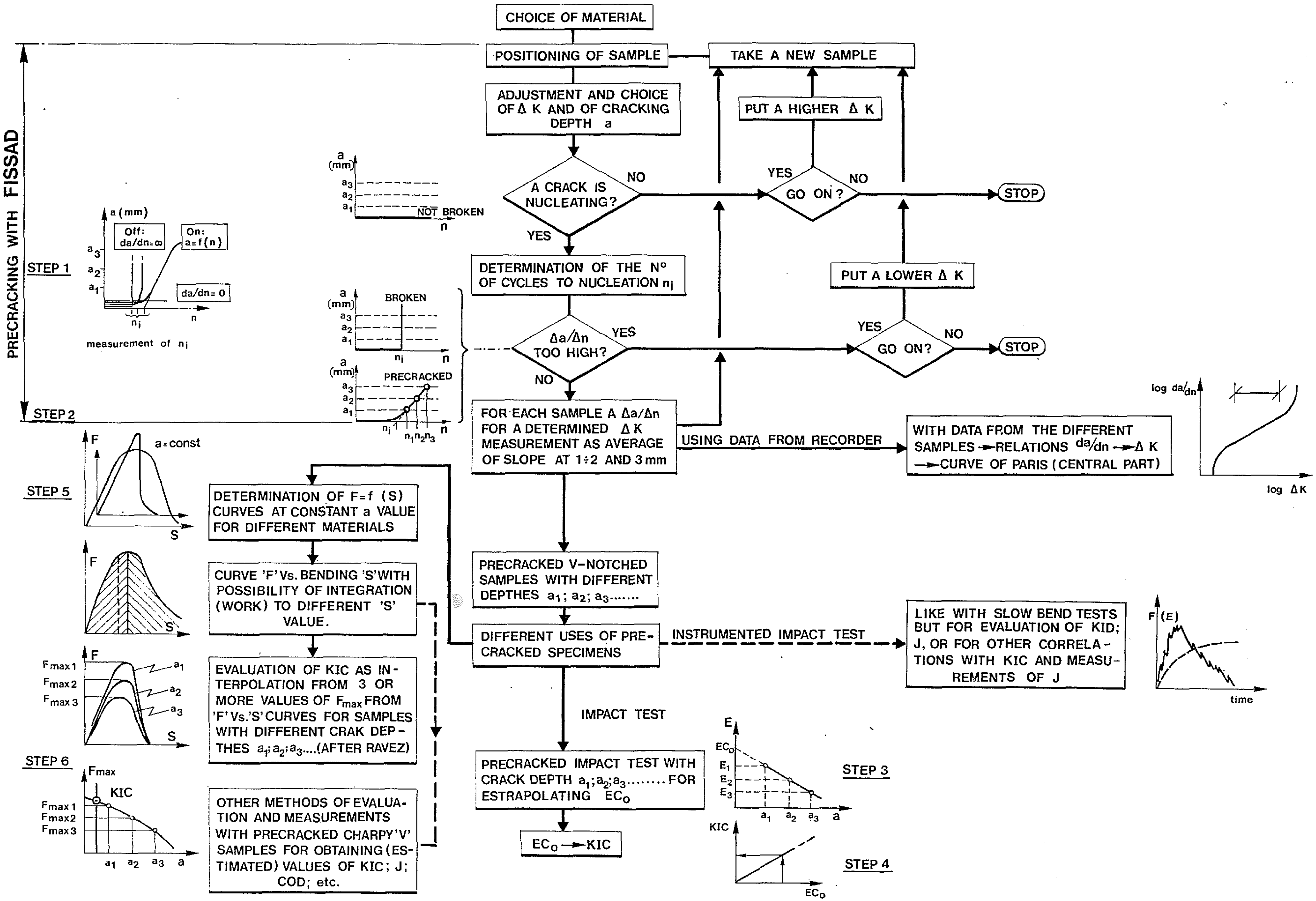
Data presented

The data presented can be summarized as follows:

- preliminary: figg. 1,2,3 and 4 are preliminary experimental evidences related to the "resistance - curve" approach to the EC_0 plot, according to the D.P.S. procedure.

TABLE 1

"FISSAD" AND D.P.S. SYSTEM FOR EVALUATION OR ESTIMATION OF FRACTURE TOUGHNESS PARAMETERS



. impact-tests:	figg. 5 and 6 are related to the systematic investigations by means of the EC_0 plots and of the "specific energy" version of the EC_0 plots, on 4340 - ESR steel grade.
. D.P.S. limits:	fig. 7 marks the actual limitation of the D.P.S. procedure (dynamic as well as static) when the aim is to obtain LEFM based parameters. (Outside of LEFM the EC_0 plot is very usefull as quality level indicator).*
. slow bend tests: (NASA procedures)	figg. 8 and 9 evidentiate the comparison between static D.P.S. results and data obtained from the identical load-deflection curves according two different NASA procedures.
. 4340 - ESR: (overall tensile and fracture characteristics)	in fig.10a summary is made for the tensile as well as for the static and dynamic D.P.S. figures obtained from 4340 - ESR Charpy-V specimens.
. 4340 - ESR: (overall Charpy-V fracture tests)	fig. 11 shows a comparison between the two D.P.S. procedures (static and dynamic) as well as for the two NASA procedures as used.
. Comparison between different steel grades:	Table 2 shows numerical data about tensile as well as fracture toughness for three main steel grades used in the geared - fan technology and experimented in this work.

* See, for example experimental data for the steel used in the pylon of the A 300 Airbus, in the paper of J. Odorico, EFTT, Meeting.

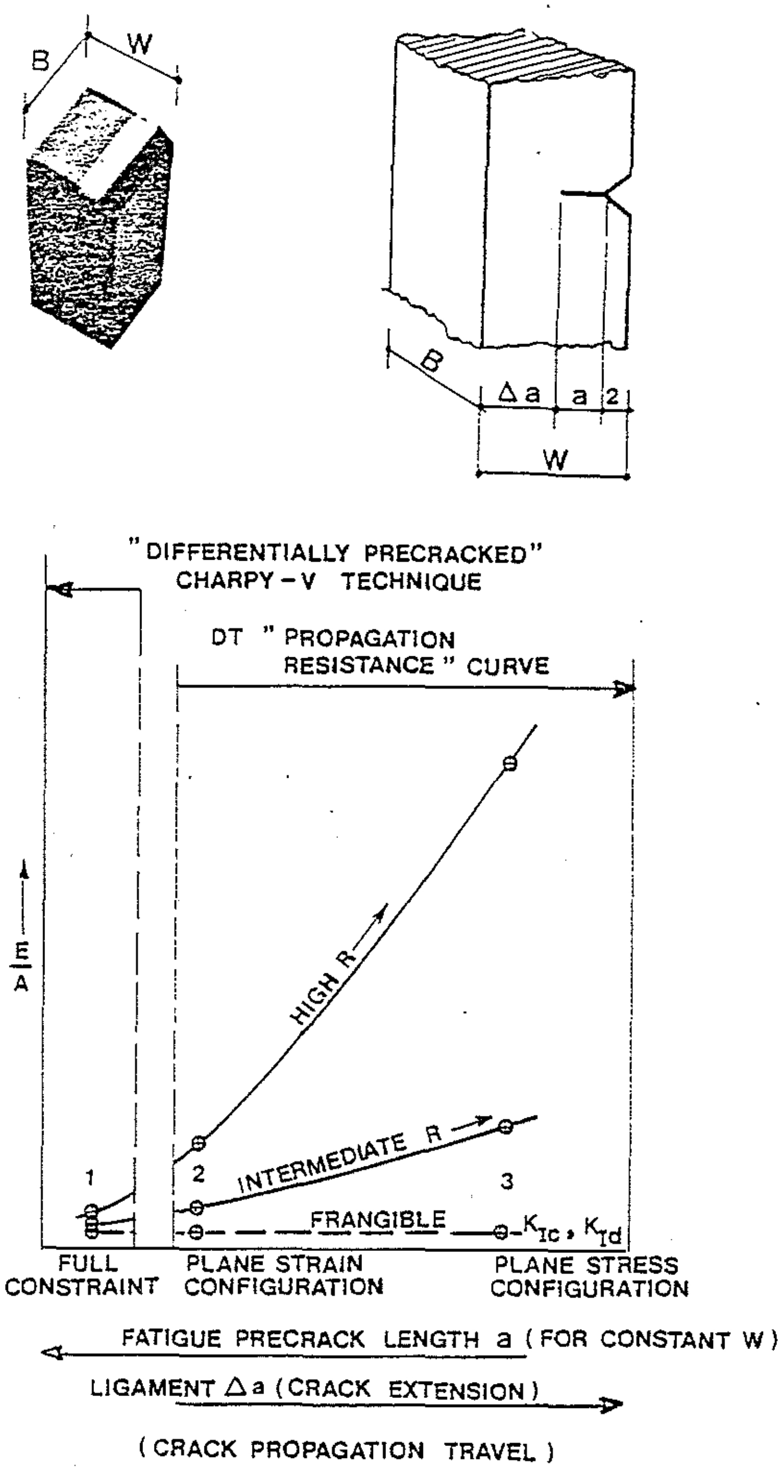


Fig. 1 Model for the propagation resistence curves determined either by recording specific energies as determined on Dynamic Tear specimens at increasing crack propagation values, Δa, or by recording impact specific energy on precracked Charpy at increasing precrack length a. The two systems for recording impact values are opposite in the diagram. The system with D.P.S. Charpy-V corresponds to the "specific" version of the EC_0 plot, (left side).
1 = high resistence; 2 = intermediate resistence; 3 = frangible.

Impact tests and flat - fractures .

Comparison of the specific EC_o plot with the propagation resistance curve as determined by DT-tests (fig. 1).

The main point for this comparison lies in the dynamic determination (step 3, table 1); the gross rupture energies applied in the original procedure are modified into specific rupture energy by dividing through the ligament surface to obtain a "specific" EC_o plot.

Apart the trivial fact that the specific energy vs. a (crack length) (see plots step 3) are opposite in trend in respect to the original Pellini, Goode and coworkers diagrams [11], it is clear that this type of representation for the specific energies of the differentially precracked specimens corresponds to the propagation resistance (R - curve) determination (apart the dimension of the specimens now involved) (see fig. 1).

Considering the Dynamic Tear propagation resistance method, severall points seem worth of note and comparable with specific energy version of the EC_o plot (differentially precracked specimens):

. the use of different impact values obtained from oversized Charpy specimens differentially notched or precracked in terms of variation of the ligament lenght, (Δ a, also defined as crack extension or crack propagation);

. the interpolation of a curve trough the experimental specific energy values and the consideration of the analytical form of this function;

. the assembly (on the same curve) of points with different physical meaning (with or without shear lips); transition from flat fracture to shear fracture;

After consideration of the formal analogies involved in the DT resistance - curve plot and the specific version of EC_o plot, these following differences can be evidentiated:

. the most important region of the DT resistance curve is the highest values portion (because the aim was to rationalise the behavior of the materials under plane-stress); on the contrary the energies obtained at medium and low levels of ligament (medium and high fatigue-precrack lengths) are foundamental for plotting the EC_o curve;

. the rationale of the DT resistance-curve is an higher order two parameters function taking into account the increasing slope, the influence of the two parameters thickness B and crack propagation Δ a, and describing the trend or the transition between plane stress and plane strain; on the contrary the EC_o- plot - points are interpolated with a simple line (originally a straight line) and EC_o is the extrapolated value to zero precracking;

. in the DT resistance-curve the experimental aim is to obtain the raising part of the propagation function; instead with EC_o plot the experimental aim is to extrapolate to a limit value(EC_o), corresponding to a maximum possible percentage of flat fracture;

• the main goal of the original DT propagation-resistance curve was to give a synthetic representation of the evolution speed of a sharp flat-fracture crack front into a smoothed 45° shear lips configuration, as essential for a valuable propagation damping; as opposite, the specific EC_0 function is a way to reduce shear lips contribution and to put in evidence the work for opening a standard defect, essentially under pseudo plane-strain conditions;

• in the DT resistance curves the embrittled notch is different in respect of the fatigue well defined notch of the EC_0 plot.

<u>The flat-fracture condition and the constancy or variation of specific energy in a "differentially precracked specimens" plot, (figg.2-3-4).</u>

• The series of flat fractures for different ligament lengthes as experienced in certain cases by Judy and Goode, in a previous LTS work, as well as during the actual program of tests, can be considered a typical physical phenomenon connected with the reduced extent of the propagation resistance as exhibited from different structural materials, at some hardness levels.

• This situation, in fact, can be explained either with the persisting absence of shear lips for all ligament conditions tested, or alternatively, (at least from the theoretical point of view) with the presence of constant percentage of shear contribution in all impact specimens tested for each family.

• This constancy in Charpy fatigue precracked specimens was at first time experienced during normal EC_0 (AIR 0814) test for three different steels [1] /figg. 2 and 3/.

• After a check on alternative impact measurements it was found that this flat trend for the propagation energy was also encountered from Judy and Goode either <u>in steels</u>[11] as in <u>aluminum</u> alloys [11].

• As a consequence of the first preliminary results found in differentially precracked Charpy-V specimens and in consequence of the two cited papers, a sistematic control of the specific energy for propagation, calculated on all Charpy specimen tested, was planned as a normal rule, combined with AIR 0814 specification.

• The simple control of the trend of the specific energy can allow two different and opposite type of results:
  - an additional indication giving warranty that flat-fractured Charpy specimens are really in conditions of elastic rupture, (see experimental results);
  - a rational description of the higher energy side of the D.P.S. Charpy-V impact plot (presently discriminated or less used) in term of propagation resistance prediction according the Judy and Goode suggestion for the much heavier DT tests; (see for the "parasitic contribution" in the EC_0 plot, as evidentiated by Ravez, fig. V of ref[9]).

• Activity on this second point is in progres with the aim of improving the correlation between EC_0 data and K_{Ic} values, at higher toughness, it means in the range where the correlation is now lacking (see next paragraphs).

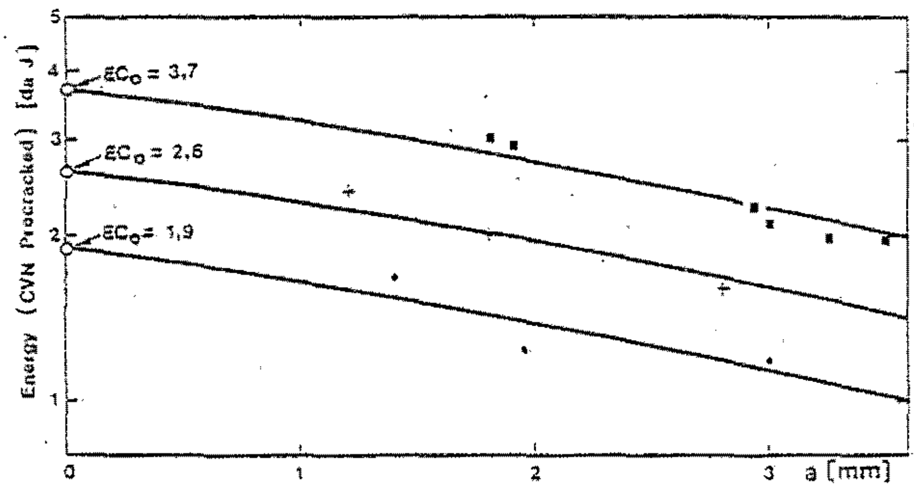


Fig. 2 Determination of EC_0 parameter for three different cases; • = ESR 4340 treated for 120–127 hbar, with abnormal grain size; ▪ = ESR 4340 treated for the same hardness level, with a standard procedure; + = 30 NCD 16 treated for 175 hbar; a = fatigue precrack length. From ref (1).

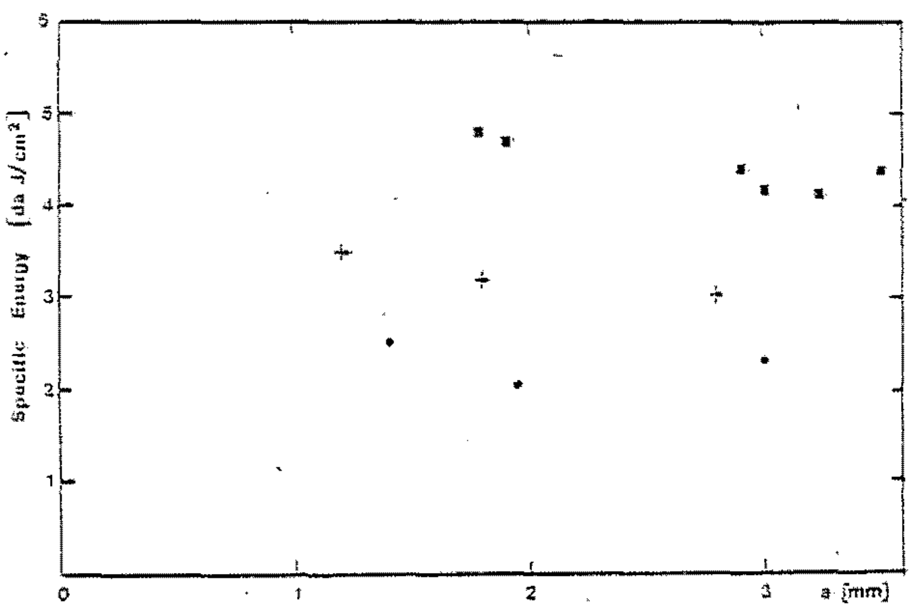
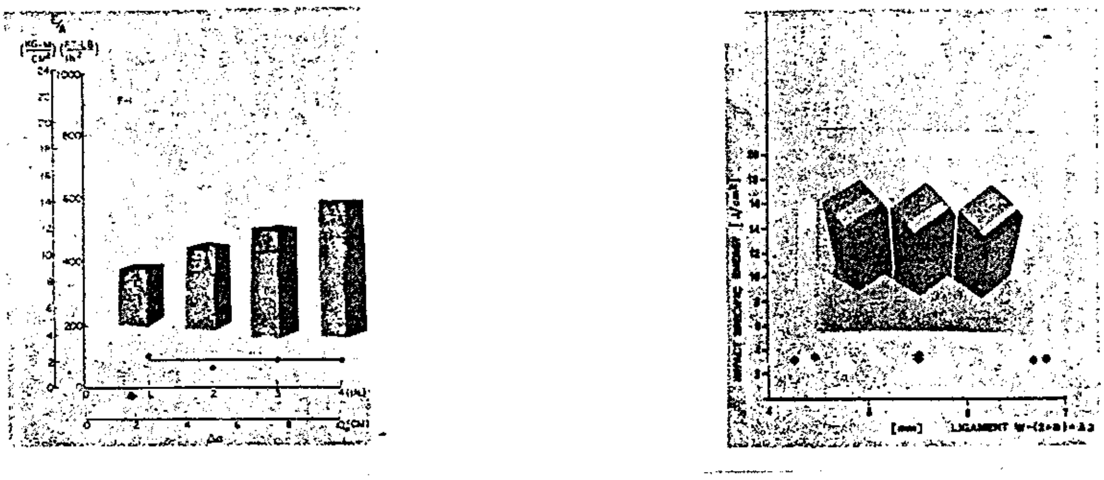


Fig. 3 Specific energy values calculated according to the points of fig.2 This is a specific EC_0 plot: specific impact values are plotted as a fuction of the precrack length like in the original 0814 Spec., instead as a function of the ligament Δ a (R-curves).
For the most brittle material (4340 abnormal grain size; • points) the specific impact energy is nearly constant in function of the precracking length a, for the other two cases (+, ▪) there is a small variation of specific energy in function of a, ref (1).



D.T. specimens
(with different ligaments)

D.P. specimens
(with different fatigue precracks)

Fig. 4 Typical examples of constancy of the specific impact energy values (in case of flat-fractures) obtained either with DT specimens (11) and with D.P.S. Charpy-V specimens subjected to impact. The D.P.S. flat-fractures were obtained during systematic work on 4340 ESR steel described in the next figures (5,6).

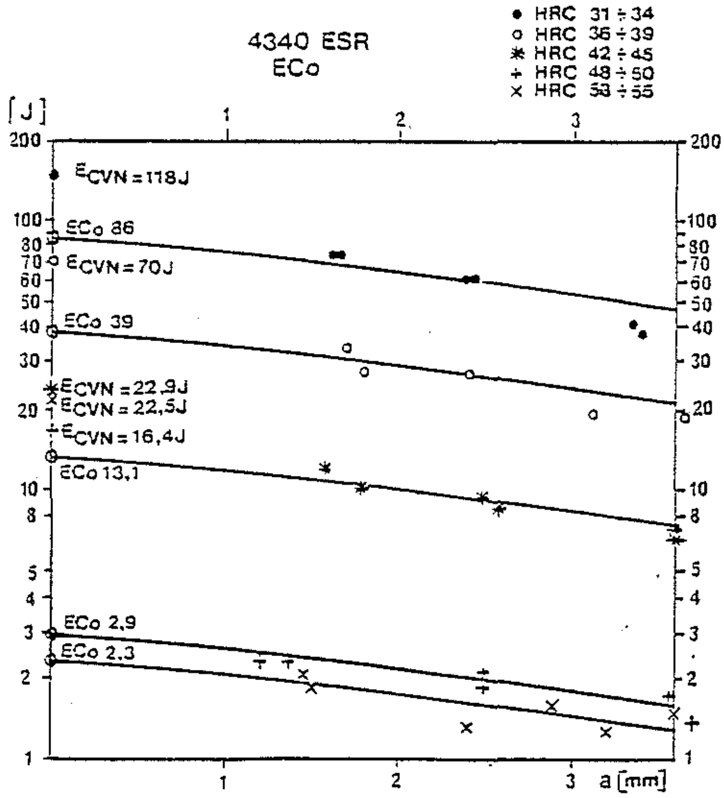


Fig. 5 EC_0 plots for the five families of Charpy specimens, machined from an identical bar of 4340 ESR and treated for different hardness levels.

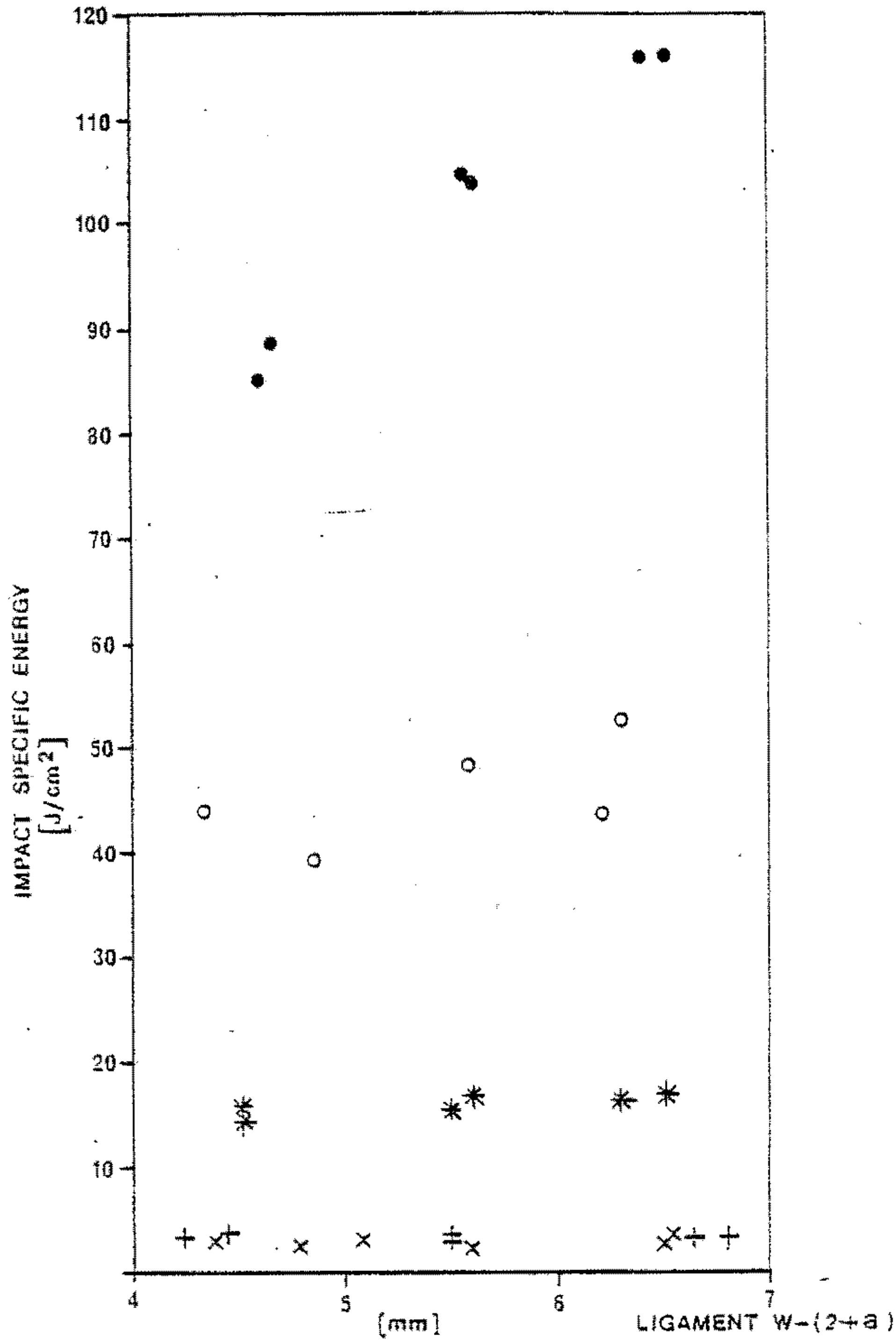


Fig. 6 Propagation resistance curves as obtained from data of Fig. 5.
Note the constancy of the specific energy for three families(*, +, x)
In this specific energy representation the points corresponding to
(*, +, x) present a flat propagation resistance curve. In this case
the K_{Ic} values obtained by EC_0 correlation are in agreement with the
values obtained in slow bend tests with D.P.S. or with NASA procedures.

Comparison with NASA (ASTM) procedures (*) (figg. 7,8,9)

In this comparison the step 5 and 6 of the differentially precracked specimens technique are to be considered (see table 1).

In fig. 7 an internal check of the self-consistency of two D.P.S. procedures (static, and dynamic) is carried out on the Charpy-V specimens coming from the same 4340 steel bar. The experimental points were carried out at the same UTS level used for the remainig parts of this work.
This figure evidentiates the main limitations of the D.P.S. tests (either slow bend or dynamic): the values of the static tests are well below the correlation line (double arrows) and the dynamic test values are increasingly in excess on the right of the dotted-line (single arrows). In a previous work, with less tough steels, the limit of the K_{Ic} vs EC_0 correlation range was extimated at abaut 30 /J/ (1).

Due to the above mentioned limitations the F vs S curve already used for the determination of the "small sample" K_{Ic} values according the D.P.S. procedure were subjected to the calculations according to the two NASA systems (equivalent energy and $\overline{w}/A$ to F_{max}) (3). Data obtained from static D.P.S. were compared either with the "equivalent energy" data and with the "$\overline{w}/A$ till F_{max}" data; the comparisons reported in fig. 8 and 9 respectively show a fair agreement in a typical aerospace range and present for the D.P.S. technique a systematic drop at high toughness levels.

The different considerations can be divided in two groups, namely:
-comments from the point of view of methodology;
-comments from the point of view of numerical reliability (for example in term of value obtainable according the original ASTM standard).

As for "the methodology" the two main comments are: 1) the D.P.S. technique (using for the slow bend determination load values read on testing machine) is one of the most easy experimental technique permitting to reach fracture parameters in the most straight way; 2) the D.P.S. technique is also dependable because of the peculiar use of the nomograph. On the opposite the NASA(Witzke)(3) techniques are less straight forward because of the calculations imposed by the procedures.

As for the "numerical reliability" the price of the procedural simplicity is (at least for our experimental tests) partially paid by a loss of maximum load because of plastic deformation, starting from the region of medium toughness.

According to the simplest way of application of the D.P.S. technique (as originally proposed) the after-yelding fracture tendency typical of small specimens seems to penalize the medium and high toughness tests (see experimental results) in sense of giving always conservative values, at high toughness.

This main trend evidentiated for the slow bend figures made following the D.P.S. technique is one of the main explanations for the pronounced deviation (on the low side from straight line correlation) between the K_{Ic} slow bend and the corresponding EC_0 values; (fig.7).

- This can emphasise once more the two main reasons of deviation of the values determined following engineering fracture tuoghness tests (in respect of the original ASTM standards) as made according first proposals, (see introduction).

(*) see test (B.c) of first paragraph.

- In case of small specimens bending tests in which the maximum load is recorded (and used without taking in due account the actual behaviour of the plastic zone) this value gives normally K_{Ic} (it would be better to say K_{EFTT}) lower than valid K_{Ic}; on the contrary in case of small specimen subjected to bend for recording (integrated) fracture energy value, this value as whole is normally the origin for too high fracture toughness determination (for very well known reasons).
- The first tendency (negative deviation of K_{EFTT} in respect of valid K_{Ic}) for medium or high toughness D.P.S. slow bend is very well illustrated by the different cases studied by RAVEZ. The original D.P.S. slow bend technique having choosen the most restrictive load determination (instead of passing trough the complete energy integration) is consistently on the conservative side.

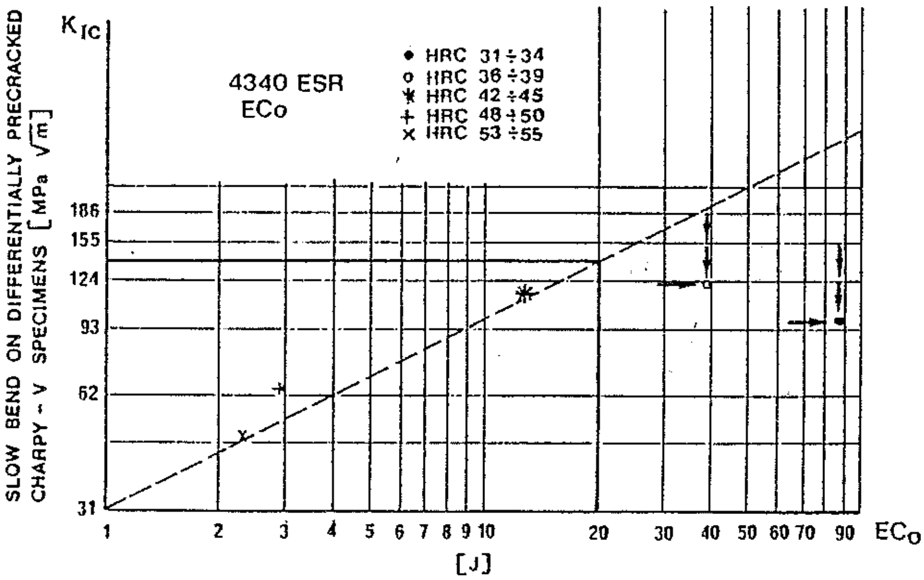


Fig. 7 Cross check between static and dynamic D.P.S. tests on identical Charpy-V specimens, machined from identical 4340 ESR bar, (see also experimental results).
This example evidentiates the main limitations of D.P.S. figures (dropping values over 20 [J]) and consequently the opportunity of alternative procedures for medium-high toughness levels (see in experimental results data calculated according NASA procedures).
The dashed line corresponds to the original Ravez correlation line for steels. The experimental points are carried out at the identical UTS levels of figg. 5,6 and following.

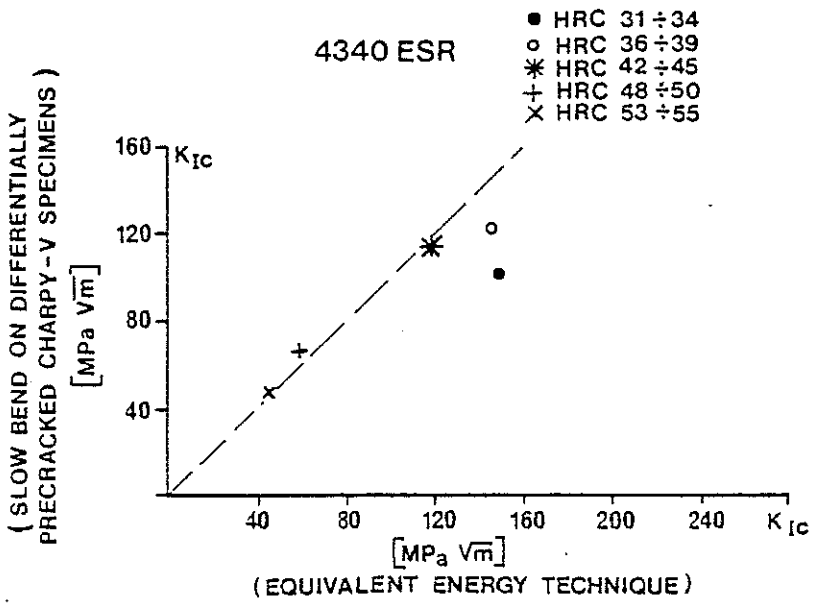


Fig. 8 Cross check of one to one correspondence between slow bend D.P.S. original procedure and K_{Ic} obtained from equivalent energy technique (WITZKE, NASA).
The congruence is maintained in the typical aerospace material range.

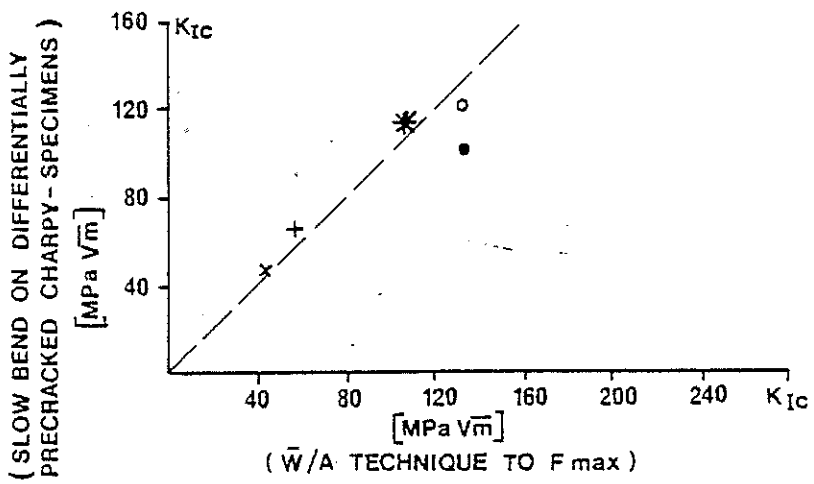


Fig. 9 Cross check between D.P.S. procedure and K_{Ic} obtained from $\bar{w}/A$ technique to F_{max} (WITZKE, NASA).
The congruence is maintained in the typical aerospace material range.
The divergency of EC_o values in the range of $K_{Ic} >$ 120 MPa $\sqrt{m}$ disappears because of truncation at F_{max} of the energy integral (as foreseen by the NASA procedure).

Conclusions

In fig. 10 (overall mechanical characteristics, tensile as well as fracture data) the congruence between the trend of the "small sample" K_{Ic} (from D.P.S.), E_{cvn} and EC_o for hardnesses higher than about 40 HRC , is worth of note. The largest difference between E_{cvn} and EC_o is obviously at the minimum reported hardness. At minimum hardness the trend of the static D.P.S. K_{Ic} is misleading for the loss of maximum load because of plastic deformation. Fig. 11 (4340-ESR, fracture data obtained with different evaluation techniques) shows that in the YTS range 1600 ÷ 1300 MPa, the two D.P.S. procedures as well as the two NASA procedures are in mutual agreement.
In the 1300 ÷ 1000 MPa range only the static D.P.S. procedure is in agreement with the two NASA procedures. At lower level only the two NASA procedure remain in fair agreement.
The data obtained with the two "small sample" approaches, in the range of mutual agreement, can be compared with an indipendent source of data (fig.12).

Conclusions can be summarized as follows:

a) Slow bend on precracked Charpy-V specimens: mutual and "cross check" relia bility of the different procedures as discussed in this presentation.

b) Impact tests on precracked Charpy-V specimens: main steps of evolution for the plain impact measurements (without possible comparison with other procedures of comparable simplicity).

c) Some additional peculiarities of D.P.S. test worth of future development. Limitations of plain - strain tests.

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a) According the experimetal results obtained in this work with aircraft mate rials, it is possible to give confidence to fracture toughness parameters as determined either by D.P.S. slow bend Charpy-V procedure or by the two NASA procedures used. The different types of approach are giving results in agreement in a range essential for the aircraft industry. The validity range of the D.P.S. procedure (as already evidentiated by Ravez)is limited to 120 ÷ 130 kg/mm^2 and is therefore smaller than the NASA ranges.

   The advantage of the D.P.S. application is the higher simplicity. In case of higher toughness it is advisable to use the NASA procedures with the related calculations.

b) Concerning the straight plain impact measurements it is possibile to conclude that after the first suggestion to correlate the bare impact energy to K_{Ic} as proposed by Barsom and Rolfe[5], two additional main steps have been put in evidence now (one consolidated and one in progress):

   - <u>the French specimens issue of AIR 0814 for the impact test on precracked Charpy-V</u>, allowing to correlate K_{Ic} with EC_o (and not with E_{cvn} energy), by reducing gross plastic contribution by means of differential precrack ing;

   - the deeper discrimination of the shear energy contributions to EC_o (even on medium - high toughness materials) by taking into account the variance of specific rupture energy. One of the basic intrinsic assumption for the "non plastic" EC_o value extrapolation should be the constancy of the specific impact energy. See for example pag. 1 of Ravez[4].

c) Finally another point definitively on an opposite field in respect of the linear elastic fracture mechanics is the analysis of the whole specific energy curves, for the determination of the propagation resistance, as a function of the crack depth. In this case there is to check if and at what extent the form used by Pellini can be used, for smaller impact specimen.

Concerning the steel behavior in plane stress it is necessary to compare in table 2 (reporting tensile and fracture data for the three different grades) the two grades 4340 and Nitralloy at the same YTS level (1500 ± 10 MPa). Even if the "small sample" K_{Ic} and the EC_o figures for the two steels can be compared, the sole consideration of El, ROA and E_{cvn} should suggest the choice of the 4340-ESR instead of the Nitralloy, even for nitrided parts. This is one of the main reason for recording the fracture parameters as quality level indicator; even far outside of the range of valid correlation of "small sample" K_{Ic} values.
A complete judgement about the merit of the two grades (both consumable remelted) should considare the comparable K_{Ic} level, as a necessary but not sufficient condition. In case of materials with a comparable fracture toughness (the K_{Ic} value is related to the fracture initiation) the final choice should tend to the material with the better propagation resistence behaviour.

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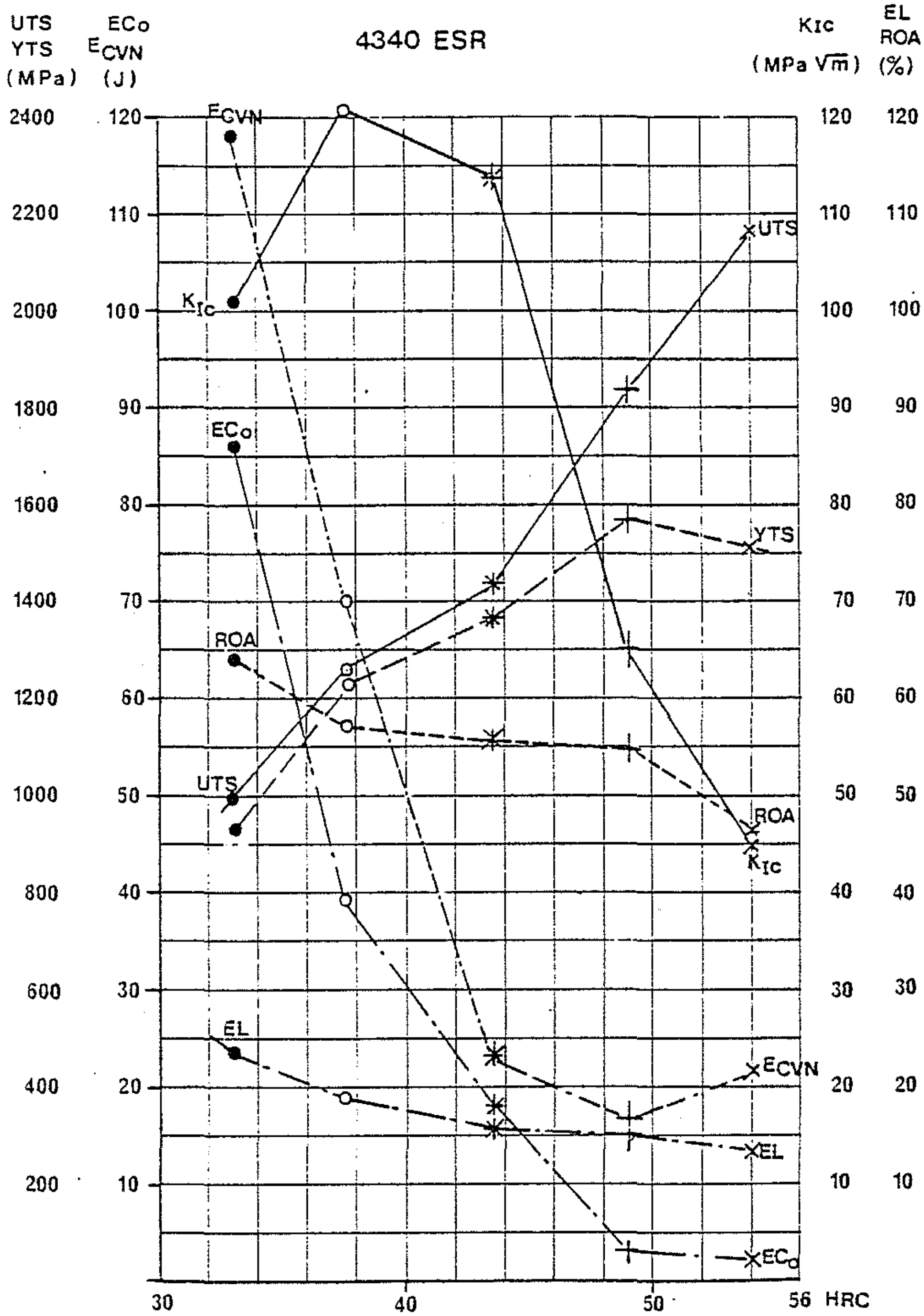

Fig.10 Mechanical characteristics for 4340 ESR treated for five hardness levels. The following points are worth of note:
- the congruence of the trend of K_{Ic}, EC_o, plain impact Ecvn, in the typical range for aerospace application (UTS > 1300 Mpa).
- the K_{Ic} (slow bend D.P.S.) values (as obtained with the original D.P.S. technique) evidentiates a misleading falling trend at UTS < 1300 MPa.
- at high hardness level, the competitivity of RoA and El values in respect of the lower hardness ones.

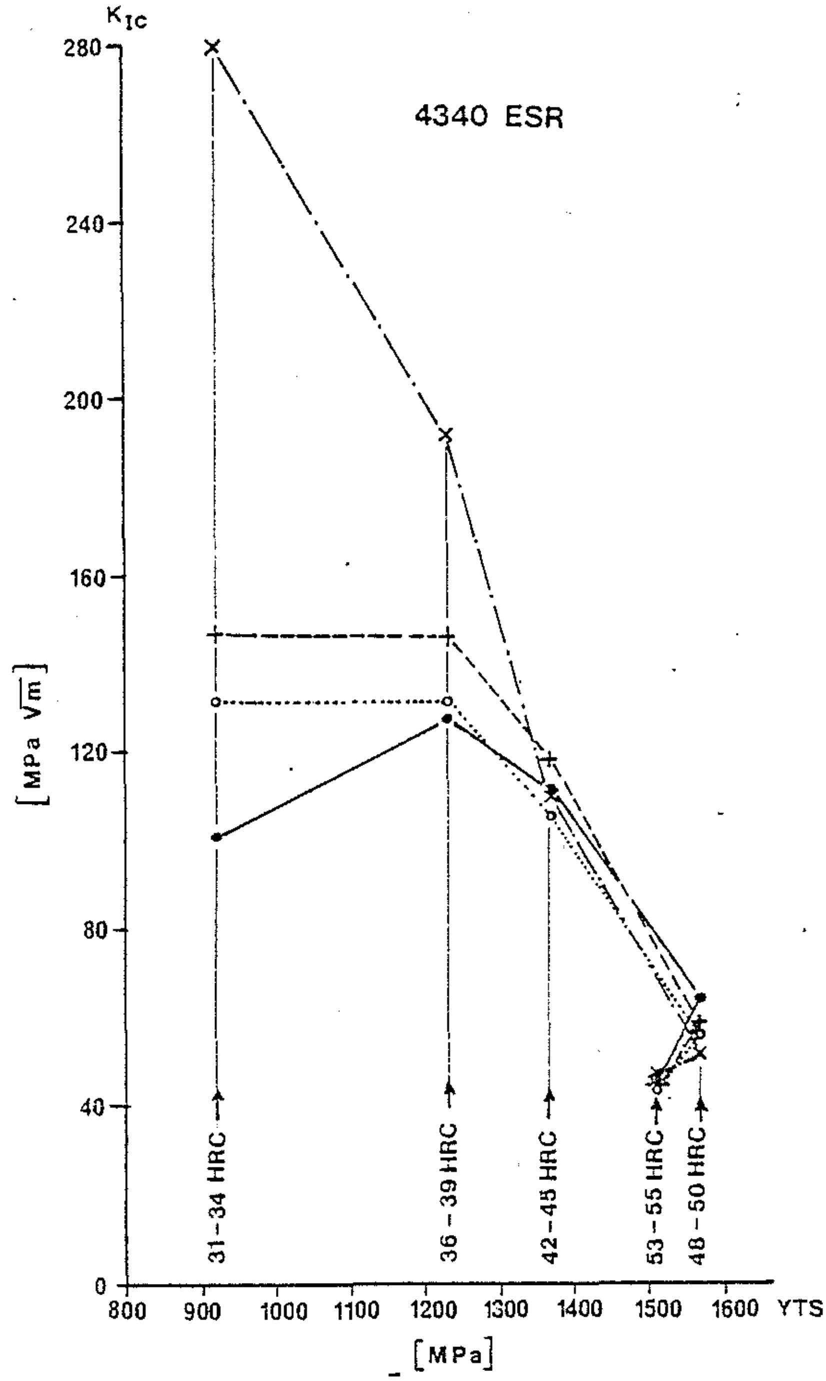

Fig.11 K_{Ic} vs YTS, by using different techniques for K_{Ic} evaluation

X = EC_o; + = equivalent energy; 0 = integration to F_{max};

● = slow bend D.P.S.

The lines follow the hardness from lower to higher values.
All techniques feature comparable figures of K_{Ic} for YTS > 1300 MPa.
In the divergengy range (YTS < 1200 MPa) the higher values are given by the EC_0 whilst the lower values are given by the slow bend D.P.S. The two NASA procedures, in fair agreement lies in the middle range for K_{Ic}.

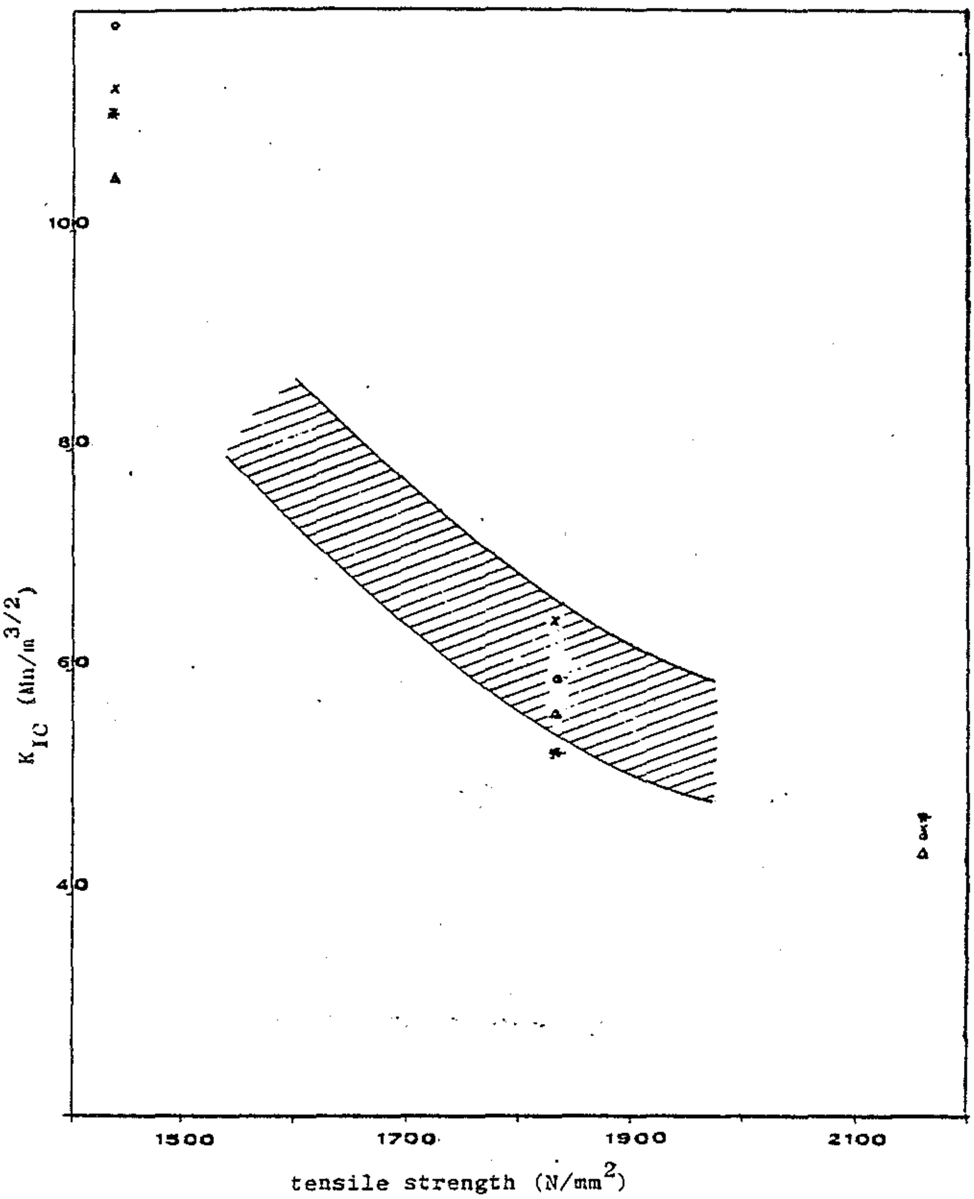

Fig.12 Comparison of K_{Ic} values as obtained by dynamic D.P.S. system, by slow bend D.P.S., and by two NASA procedures for slow bend, with most recent data from Imrie for fracture toughness of 4340 for aircraft primary applications.

TABLE 2

Material	Fibre direction	Hardness (HRC)	UTS (MPa)	YTS (MPa)	El (%)	ROA (%)	E_{OVN} (J)	ECo (J)	K_{1C} from ECo ($MPa\sqrt{m}$)	K_{1C} from D.P.S. ($MPa\sqrt{m}$)	K_{1C} from F max ($MPa\sqrt{m}$)	K_{1C} from F eq. ($MPa\sqrt{m}$)	$2.5(\frac{K_{Ic-F.eq.}}{YTS})^2$ (mm)
4340 E.S.R.	L	53 ÷ 55	2160 ± 0.1%	1510 ± 1.29%	13	46.1 ± 8.1%	21.5 ± 5.98%	2.3	47.1	46.1	44.1	45.6	2.28
	L	48 ÷ 50	1830 ± 0.38	1567 ± 0.92	14.7 ± 6.81	54.6 ± 0.66	16.4 ± 3.04	2.9	52.7	64.8	56.4	59.6	3.62
	L	42 ÷ 45	1435 ± 0.44	1368 ± 0.66	15.6 ± 6.3	55.4 ± 1.54	22.9 ± 3.75	13.1	111.7	113.8	105.3	118.7	18.82
	L	36 ÷ 39	1276 ± 0.4	1230 ± 0.51	18.9 ± 5.2	57.3 ± 2.02	70	39	192.4	120.8	132.7	146.6	35.48
	L	31 ÷ 34	995 ± 0.26	921 ± 2.96	23.5 ± 1.9	64.4 ± 0.3	118 ± 5.5	86	280.8	101.2	132.7	147.3	63.96
9310 V.A.R.	Le	36 ÷ 38	1217 ± 0.65	964 ± 1.01	16.7 ± 4.23	71 ± 1.07	133 ± 8.5	69	254.5	107.8			
	Li	36 ÷ 38	1224 ± 0.28	970 ± 1.31	17 ± 5.85	69.4 ± 1.43	110.5 ± 8.3	69	254.5	110.7			
	T	36 ÷ 38	1214 ± 0.09	967 ± 0.78	17.5 ± 3.56	69.8 ± 2.93	106.5 ± 13.9	65	248.2	110.7			
NITRALLOY	L	49 ÷ 51	1763 ± 0.25	1486 ± 0.66	4.2 ± 18.5	9.9 ± 27.5	4.84 ± 6.1	2.55	49.6	78.7			
	T	49 ÷ 51	1723 ± 0.05	1447 ± 0.23	4.1 ± 25.4	12.3 ± 16	5.09 ± 12.7	2.6	50.2	77.4			

L = Longitudinal

Li = Long. intern.

Le = Long. extern.

T = Transverse

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