

COST-EFFECTIVE PRECRACKING OF CHARPY V-NOTCH SPECIMENS FOR FRACTURE TOUGHNESS TESTING USING A PIEZO-ELECTRIC ACTUATOR

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ABSTRACT

The evolution in the ASTM standard to more stringent precracking requirements and the large amount of fracture toughness tests annually performed at SCK-CEN, was the motivation to search for novel techniques to gain more control over the precracking process and to reduce the precracking cost. A feasibility study identified the piezo-electric actuator as an excellent candidate for this purpose.

A dedicated precracking machine for Charpy V-notch specimens based on a piezo-electric actuator was developed. The high degree of automation allows full control over the precracking process in agreement with current or future standards. The low power consumption, high precracking frequency, low yield loss, low maintenance and minimum operator intervention significantly reduced the precracking cost. A second piezo-precracking was installed in a hotcell and is already providing a reliable service for several years.

Keywords: fracture toughness, fatigue cracking, piezo-electric actuator, precracked Charpy V-notch, PCCV, cost

Introduction

History proved that the presence of cracks in structural components can lead to catastrophic failure. In 1954 for example, the Havilland Comet - the world's first jet airliner - broke apart in mid-flight. The riveting of the square windows created cracks in the plane's fuselage, which eventually led to fatigue failure under the enormous landing and take-off stresses. Because cracks in structural components can lead to disaster with severe environmental and economic impact, injuries and deadly accidents, the detection and monitoring of cracks is taken very seriously and integrated in many safety regulations and inspections. Boeing for example recently reported to have found 'cracks' in factory Dreamliner planes [1]. Two Belgian nuclear power plants (Doel 3 and Tihange 2) were shutdown after the discovery of cracks in the reactor pressure vessel by a new ultrasonic measurement technique [2].

The property which describes the ability of a material containing a crack to resist further fracture is called "fracture toughness". Experience has shown that it is practically impossible to obtain a reproducible sharp, narrow notch using conventional manufacturing techniques that will simulate a natural crack well enough to provide a satisfactory fracture toughness result. Hence, all specimens have to be precracked in fatigue. To avoid biasing of the test result, the maximum stress intensity during precracking must be kept well below the material fracture toughness measured during the subsequent test. In consequence the precracking requirements described in ASTM and ISO standards may differ mutually and over the years became more stringent [8]. Demanding a flexible, user definable and more accurate control of the precracking process.

The fatigue precracking is generally performed on a servo-hydraulic tensile testbench. Which is available in most mechanical testing laboratories. The fairly low operating frequency of about 30 Hz and the high power consumption of the hydraulic power

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unit makes this the least economic solution. The precracking cost is more favorable on a fatigue resonant machine but requires an additional investment.

The stringent precracking conditions, the differences between the standards and the large amount of fracture toughness tests annually performed at SCK•CEN was the motivation to search for novel techniques to gain more control over the precracking process and to further reduce the precracking cost. The high operating frequency, compact size, fairly low cost, reliable operation, low power consumption and low maintenance made the piezo-electric actuator an excellent candidate for this purpose. A dedicated, fully automated precracking apparatus for precracked Charpy V-notch (PCCV) specimens based on a piezo-electric actuator was developed – the SCK•CEN "Piezomatic".

Specimens made from a typical RPV (reactor pressure vessel) steel, were precracked conform the ASTM E1921-13 standard. The obtained fatigue crack was measured for the plane-sided and side grooved condition and verified with the requirements set by the standard.

After an extensive evaluation period, a second piezo-precracking machine was constructed and installed in a hotcell. Where it is providing a reliable precracking service for several years.

Precracking requirements

The basic strategy behind most precracking procedures is to start with high fatigue loading for fast precracking and to reduce the force levels near the final cracklength to avoid biasing of the subsequent test results. This philosophy is found in earlier versions of most standards.

In the ASTM E1820-99 version, a maximum initial force is defined for the first precracking step. Which is reduced to 70% of the maximum force expected during testing, at 50% of the precrack extension or 1.3 mm, whichever is less [3]. This simple load based scheme however failed to provide sufficient guarantee on the actual stress intensity and refinement was necessary. In the latest version of this standard [4], the maximum initial stress intensity is defined as function of the yield stress at precracking and test temperature. For the final precracking step, the stress intensity is limited to 60% of the stress intensity of the test, times the ratio between the yield stress at precracking and test temperature. The minimum finish sharpening length is 1.3 mm for wide notch specimens but reduced to 0.6 mm for the narrow notch.

The history behind the precracking requirements of the ASTM E1921 standard is quite similar. The E1921-97 version specifies a maximum initial stress intensity as function of the Young modulus. Finish sharpening is started at least 0.6 mm before the final crack length with a maximum stress intensity of about 0.7 times the initial stress intensity, corrected for the difference in fatigue cracking and testing temperature [5]. In the most recent version [6], the maximum initial stress intensity is set to $25 \text{ MPa}\sqrt{\text{m}}$. When the subsequent test is performed at a temperature equal or above the precracking temperature, the maximum stress intensity during finish sharpening is $20 \text{ MPa}\sqrt{\text{m}}$, otherwise $15 \text{ MPa}\sqrt{\text{m}}$. The stress intensity is gradually decreased from the initial to the final stress intensity in the onset to finish sharpening. The minimum value for the load shedding crack extension defines the condition where the leading edge of the plastic zone remains stationary as the stress intensity decrease. The finish sharpening length is further reduced to a minimum of 0.2 mm.

The evolution to more stringent precracking requirements, lower stress intensities, shorter finish sharpening lengths and the difference between standards demands an accurate and flexibility process control. This requires a high degree of instrumentation and automation of the precracking equipment.

Piezo-prec cracking apparatus

Introduction to piezo-mechanics

The piezo-electric effect, where electrical charges are produced in certain ceramics upon application of a mechanical stress, has been known for a very long time². Examples of materials exhibiting piezo-electric properties are: quartz, tourmaline, Rochelle salt, PZT³, etc. The reverse effect, where ceramics deform when exposed to an electrical field, can be used to generate motion and/or forces and is often referred to as piezo-mechanics.

A basic piezo-actuator is constructed by coating the ceramic with a top and bottom electrode. From its construction a piezo-actuator's response is mainly capacitive. The application of a potential difference between the two electrodes causes the ceramic to deform under the influence of the induced electrical field. In order to keep the required driving potential within reasonable proportions, the thickness of the ceramic is limited. A longer total stroke is obtained by stacking several layers towards a multilayer structure (Figure 1); placing each layer electrically in parallel. The incorporation of piezo stacks into a metal casing generally improves reliability and stability. The casing provides protection against mechanical impact and deteriorating environmental effects (corrosion). Very often, a preload mechanism is included to keep the stack in compression, as a piezo-ceramic is extremely vulnerable to tensile stresses.

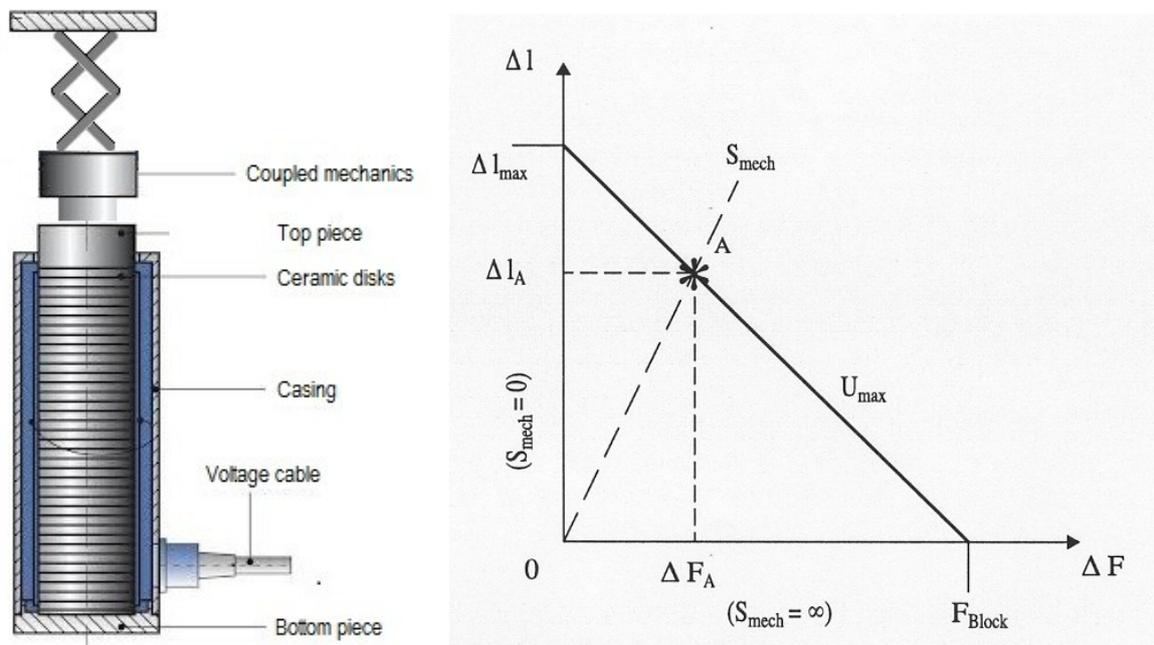


Figure 1: Stacked piezo-actuator with coupled mechanics (left) – Stroke-force diagram (right)

A piezo-actuator converts electrical energy into motion and/or force of the coupled mechanical system. This mechanical interaction is ruled by the stiffness (S) of the two system parts: the actuator and the actuated mechanics. To characterize the actuator's stroke and force generation capability, two basic experiments are carried out: the 'voltage-stroke' and 'voltage-blocking force' characteristic. In the first case, the actuator's stroke is recorded as function of the applied voltage (U), under the condition that the coupled mechanical system has zero stiffness ($S_{\text{mech}}=0$, freely moving actuator). In the second case, the actuator is prevented from generating any stroke ($S_{\text{mech}}=\infty$, fully blocked actuator). The force generated by the actuator as function of the applied voltage is recorded. By combining the 'voltage-stroke' and 'voltage-blocking force' data, the stroke (Δl) versus blocking force (ΔF) characteristic of a piezo-actuator is obtained (Figure 1). In practice, piezo-actuators interact

² The piezo-electric effect was discovered by Jacques and Pierre Curie in 1880.

³ Lead(Pb) Zirconate (Z) Titanate (Ti)

with mechanical systems having an intermediate stiffness ($0 < S_{\text{mech}} < \infty$). The actuator distributes its 'activity' partially into the generation of stroke and partially into the generation of force. Where 'partially' depends on the quantitative relation between the stiffness of the actuator and the coupled mechanics. The achievable force-stroke in a real system is determined by the combined characteristics of the actuator and the attached mechanics. This is defined by the intersection of the line connecting the maximum stroke of the actuator with its maximum blocking force, and a line starting from the origin with a slope equal to the stiffness of the coupled system (Point A, Figure 1). Notice that in a stroke-force diagram, a slope represents 'compliance', the inverse of stiffness.

Design constraints

The high operating frequency, compact size, fairly low cost, reliable operation, low power consumption and low maintenance makes the piezo-electric actuator an excellent candidate for fast fatigue precracking. The limited stroke (range 100 μm) of commercially available actuators and an actual system performance depending on the combined characteristics of the actuator and the attached mechanics however pose a real design challenge. The supporting frame has to be very stiff! The low thermal conductivity of the PZT and the airgap between the stack and casing is responsible for very poor heat-sinking. This can give rise to overheating especially at high frequencies. Good thermal management has to be incorporated in the design to avoid severe limitations of the maximum operating frequency. The brittle nature of PZT material makes it extremely vulnerable to tensile stresses. Only PCCV specimens are considered in the design as they are precracked solely in compression. Crack propagation is monitored by the 'compliance method'. The specimen compliance is measured at regular intervals in the course of the precracking process. The cracklength is inferred from the compliance-cracklength relation as found in the ASTM E1820 standard [4]. A high degree of automation is essential for accurate control of the precracking process and minimization of the operator cost.

Basic operation

The basic operation of the piezo-precracking machine is depicted in Figure 2. The operator fills the cartridge with PCCV specimens from the top. The cartridge is replaceable to accommodate for specimens with different dimensions.

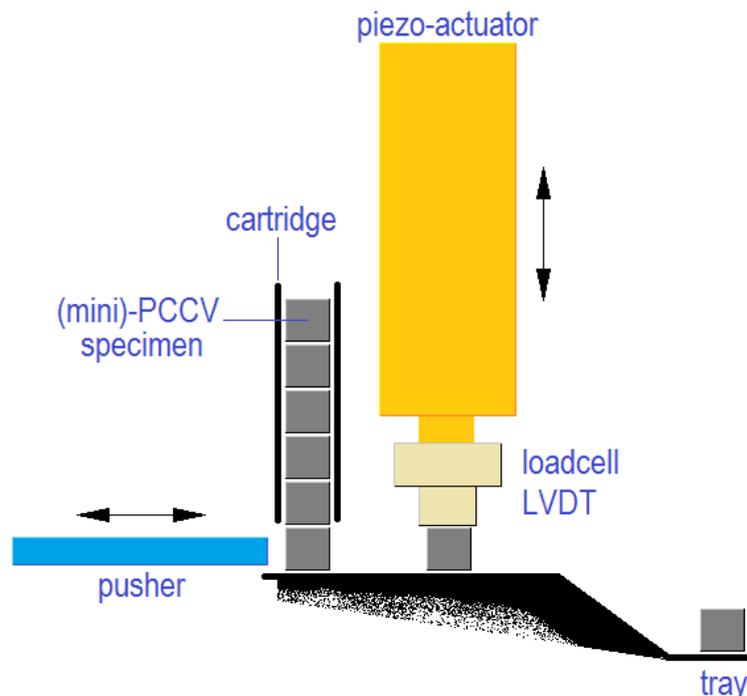


Figure 2: Basic operation piezo-precracking apparatus

The bottom specimen is positioned underneath the piezo-actuator by the pusher. After the actuator is brought in contact with the specimen, the precracking process is started. The applied load is monitored in real-time and adjusted if necessary. The fatigue cycling is interrupted at regular intervals to measure the specimen compliance from which the actual crack length is inferred. Specimen loading is adjusted conform the selected standard. When the final crack length is reached, the actuator is lifted and the specimen is pushed forward into the tray. The pusher is retracted and when it reaches its original position, the next specimen in the stack drops down; ready to be precracked.

Validation

The apparatus is validated by precracking a number of PCCV specimens made from a typical RPV steel, DIN 20NiMoCr2. The specimens are precracked conform the ASTM E1921-13 standard; the most stringent one. After precracking, the specimen is broken to expose the crack. The physical crack size is measured optically for the plane-sided and side grooved condition. The average crack size and individual data points are evaluated according the ASTM E1820-11 and ISO 12135-2002 [7] standard. The repeatability and accuracy of the precracking process is assessed by statistical analysis of the average cracklength and actual final stress intensity of each batch. The effect of specimen geometry is evaluated by precracking reconstituted and mini-PCCV specimens. The reconstitution method of stud welding and subsequent machining is responsible for lower dimensional accuracy, warping and torsion of the specimen. Voids and gaps at the welds also weaken the specimen locally. Introducing an additional uncertainty of the measured compliance and real cracklength during precracking. The fatigue loading of mini-PCCV specimens is about 5 times lower than for PCCVs. Enabling to test the performance of the machine at the lower force boundary. The precracking conditions for the different specimen types are listed in Table 1.

Table 1: Precracking conditions

Type	PCCV	PCCV (recon)	mini-PCCV	
B	10	10	3	mm
W	10	10	4	mm
a_N	3	3	1	mm
Material	20NiMoCr2	20NiMoCr2	20NiMoCr2	
Amount	12	8	7	

Standard	E1921-13	E1921-13	E1921-13	
a_f	5	5	2	Mm
K_i	17.5	17.5	18	MPa√m
K_f	18	18	18	MPa√m
f_i	75	75	150	Hz
f_f	100	100	200	Hz

Twelve PCCV specimens with a typical width (W) and thickness (B) of 10 mm and a notch depth (a_N) of 3 mm are precracked conform the ASTM 1921-13 standard. The desired cracklength (a_f) is set to 5 mm. The initial stress intensity (K_i) is 17.5 MPa√m due to the force limitations of the actuator. Because the specimens are part of a test campaign, the final stress intensity (K_f) is set to 18 instead of the usual 20 MPa√m, just to be on the safe side. The maximum output current of the wavegenerator limits the initial precracking frequency (f_i) to 75 Hz. As the crack extension progresses, the required specimen loading and hence driving power decreases. By gradually increasing the cycling frequency during precracking to

a final frequency (f_f) of 100 Hz the wavegenerator is used in the most economical way. The reconstituted specimens are precracked under the same conditions. Seven mini-PCCV specimens with a typical width of 4 mm, thickness of 3 mm and a notch depth of 1 mm are precracked. The desired cracklength is set to 2 mm. The initial stress intensity is set to 18 and the final stress intensity 18 MPa \sqrt{m} . The initial frequency is 150 Hz which is gradually increased to a final value of 200 Hz. The validation of the obtained crackfront is summarized in Table 2.

Table 2: Validation of obtained crackfront

Criterion	PCCV		PCCV (recon)		mini-PCCV
	Plane-sided	Side grooved	Plane-sided	Side grooved	Plane-sided
$0.45 \leq a/W \leq 0.55$	OK	OK	OK	OK	OK
a_f [mm]	5.046	5.115	5.126	5.207	1.917
σ	0.060	0.0887	0.071	0.084	0.057
$ a_i - a \leq 0.05 B$ ⁽¹⁾	1 fail (a_9)	OK	3 fail (a_1, a_9)	OK	7 fail (a_1, a_9)
$ a_i - a \leq 0.1 a$ ⁽²⁾	OK	OK	OK	OK	1 fail
K_f [MPa \sqrt{m}]	18.43		18.79		16.66
σ	0.606		0.408		0.435

(1) ASTM E1820-11, $|a_i - a| \leq 0.05 B$, for $i = 1, 2, \dots, 9$

(2) ISO 12135-2002, $|a_i - a| \leq 0.1 a$, for $i = 1, 2, \dots, 8$ with $a_1 = (a_1 + a_9)/2$

All cracks fall within the $0.45 \leq a/W \leq 0.55$ validity range. The average plane-sided cracklength exceeds the desired value of 5 mm only by 1% for the PCCV specimens and 2.5% for the reconstituted ones. The cracklength of the mini-PCCV specimens is retarded by 4%. The increase in cracklength after side grooving was expected as this action removes the area of crack retardation near the surface, yielding a higher average. The mini-PCCVs are not side grooved due to their small size. From the standard deviation on the average cracksize it is clearly demonstrated that the piezo-precracking machine is capable of producing the desired cracklength within the specified limits for the PCCV specimens (process capability index $C_p = (USL - LSL)/6\sigma > 2$) [9]. A yield loss of about 1 out of 370 is expected for the mini-PCCVs ($C_p = 1.16$).

An additional requirement is that the difference between each measured point on the crackfront and the average cracklength is less than 0.05 times the specimen thickness for the ASTM E1820 standard. The retarded crackgrowth near the surface is often the reason why this criterion is not met. This is the reason why a slightly different criterion is found in the ISO 12135 standard. The 7 points in the centre and the average of the 2 outer points must be within $\pm 10\%$ of the average cracklength. When applying the ASTM criterion 1 PCCV, 3 reconstituted PCCVs and all mini-PCCVs failed for the plane-sided condition. All attributed to the surface points. After side grooving, all PCCV specimens meet the requirement. When applying the ISO method, all specimens pass for the plain-sided as well as side grooved condition. The fail of the mini-specimen was due to a material defect and cannot be attributed to the equipment itself.

The actual final stress intensity is larger than the desired value for the PCCV sized specimens and smaller for the mini-PCCVs. As the stress intensity is related to the cracklength, an obvious outcome. From the standard deviation on the stress intensity it is concluded that the actual stress intensity stays within the allowable envelope [6] when the desired stress intensity is lowered by a value of 3σ , or about 1.5 MPa \sqrt{m} .

Installation in hotcell

The installation of a piezo-precracking machine in hotcell was already taken into account at the design phase. Aspects like ease-of-operation and low maintenance were integrated in the conceptual design from the beginning. The high level of automation

minimizes the machine operation to the loading of the cartridge with new specimens and the removal of precracked specimens from the tray (Figure 3); tasks easily done with a telemanipulator. The overall maintenance cost is kept to a minimum by placing all radiation sensitive devices (electronics), serviceable and adjustable parts outside the hotcell. In case of component failure, the Piezomatic can be fold up (Figure 4) and taken out of the hotcell through a port with a minimum diameter of 250 mm; avoiding high intervention costs. The compact size of 20 x 50 x 50 cm (BxDxH) promotes an efficient and economic use of hotcell space. An additional weight reduction of the hotcell version is accomplished by the removal of excess material. The light weight version can be easily moved in the hotcell with the manipulator. The Piezomatic installed in the hotcell is shown in Figure 3. Where it is providing a reliable precracking service for several years.

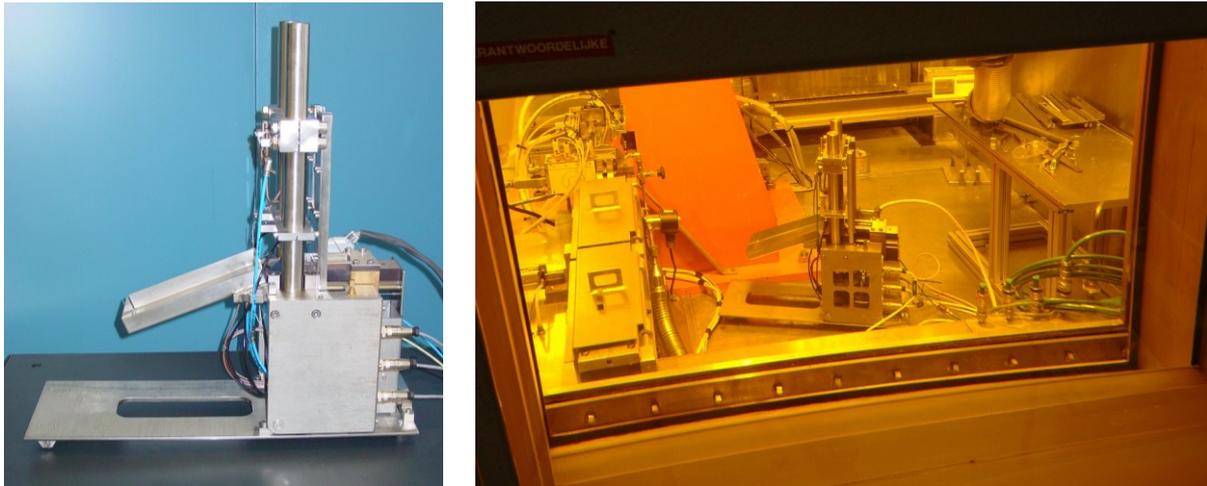


Figure 3: Piezomatic in cold lab (left) and hotcell (right)



Figure 4: Piezomatic in fold up position

Precracking cost

Because the cost analysis is based on incomplete data⁴ and assumptions, the obtained figures are rather guestimates but are very helpful for general decision making. A comparison of the cost-per-specimen when precracked on a servo-hydraulic tensile testbench, a resonant fatigue machine or the SCK•CEN piezo-precracking apparatus – the Piezomatic – is shown in Table 3. The total cost is subdivided in a fixed and variable cost. All expenses related to the purchase, installation, personnel training, etc. of the equipment are amortized over a period of 10 year and further refined to come to an equipment cost per hour. In the same manner, an infrastructure cost per m² is calculated from the amortisation, maintenance, lighting, heating, etc. of the building. For the variable cost, only the energy and labour cost is taken into account.

⁴ General overhead is not included in this analysis.

Table 3: Comparison precracking cost per specimen

Fixed cost	Hydraulic testbench	Resonant machine	Piezomatic
Equipment	29.03	4.97	3.87
Infrastructure	3.37	0.43	0.27
Variable cost			
Electricity	27.00	0.18	0.09
Labour [min]	15	10	1
Total [€]^(*)	59.40	5.58	4.23

(*) Labour not included

From Table 3 it is clear that the precracking cost per specimen is the highest for the servo-hydraulic tensile testbench and the lowest for the Piezomatic. Precracking on a resonant fatigue machine is about 5 times cheaper than on a hydraulic testbench. The Piezomatic cuts the cost by a factor 14.

The high cost for the servo-hydraulic testbench is attributed to 1) the higher equipment cost in combination with a longer use due to the lower cycling frequency, 2) the higher infrastructure cost as a result of the large footprint for testbench and power pack and 3) the high energy consumption of the hydraulic power unit. The low equipment cost, small footprint, low energy consumption and the possibility to precrack in batch mode makes the Piezomatic the most economical solution.

Conclusions

The use of a piezo-electric actuator for fatigue precracking of Charpy V-notch fracture toughness specimens has numerous advantages.

- The equipment can be kept very compact.
- Cycling frequencies in the range of 100 to 200 Hz are easily obtainable.
- The replaceable cartridge accommodates for various specimen sizes.
- The high degree of automation provides the necessary flexibility to meet the requirements of current and future standards.
- High accuracy and reproducibility of the desired crack length and stress intensity.
- The low maintenance, reliability and ease-of-operation makes it very suited for use in a hotcell environment.

Concluding that a precracking apparatus based on a piezo-actuator has a low cost-of-ownership and offers a very economical solution.

Acknowledgments

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