

Design and Repeatability Analysis of Desktop Tool for Rapid Pre-Cracking of Notched Ductile Plastic Fracture Specimens

Albert E. Patterson^{1,*}, Charul Chadha^{2,3}, Iwona M. Jasiuk^{2,3}, and James T. Allison^{1,2}

¹*Department of Industrial and Enterprise Systems Engineering*

²*Department of Aerospace Engineering*

³*Department of Mechanical Science and Engineering*

University of Illinois at Urbana-Champaign, Urbana, Illinois, USA, 61801

**Correspondence: pttrsuv2@illinois.edu*

Abstract

Fracture testing is a useful mechanical testing process to explore the properties and behavior of materials, one that has seen much development and refinement in recent decades. One of the most important steps in preparing samples for testing is the production of a sharp pre-crack to initiate crack propagation in a predictable way. While several methods have been developed for doing this, particularly for metals and brittle plastic materials, a quick and reliable method for more ductile materials is lacking. This technical note describes the design and verification of a simple desktop-sized pre-cracking device which safely uses a razor blade and hammer to quickly produce straight and sharp pre-cracks of consistent depth in ductile polymeric material samples. To verify its capability and consistency, a series of tests were performed using both molded and 3-D printed acrylonitrile butadiene styrene (ABS). First, a series of 40 notched 25 mm × 9.5 mm ABS bars were pre-cracked, and the distance under the crack measured on both sides of the bar. Several bars were then broken along the cracks to examine the quality of the pre-crack front. These tests were then repeated 20 times each for two print orientations of fused deposition modeling (FDM) ABS printed at 100% density. All 80 pre-cracks were found to be straight, sharp, and within 1% of the nominal distance under the crack for all samples. The consistency of the pre-cracks throughout the sample cross-section was also observed to be excellent, with all 80 tests showing less than 0.25 mm of deviation, even on the highly-anisotropic FDM samples.

Keywords: Fracture mechanics, polymer testing, pre-cracking

1. Introduction

To employ a standard plane-strain fracture theory to test materials which are not perfectly brittle, it is necessary to have the presence of a very sharp stress concentration in the test specimen [1, 2, 3]. Impact tests usually do not require such sharp cracks [4, 5, 6], but they are generally required for static tests such as 3-point and 4-point bending tests [7, 8, 9], notched tensile tests [10, 11], and crack tip opening displacement (CTOD) tests [12, 13]. The standard method for achieving this is to notch the specimens using a dedicated notch

cutter, milling machine, or other devices, and *pre-cracking* the specimens. This is typically done using fatigue cycling for metal and ceramic specimens [14], but for most polymer-based materials it requires actually cutting the sharp cracks [1, 15, 3]. It is essential that the area under the crack (the area between the bottom of the pre-crack and the bottom of the specimen) should be of a uniform length in order to perform a set of valid fracture experiments with the samples. It is also very important to avoid strain-hardening around the cracked area before the tests, as this may greatly distort the results of the fracture tests.

The standards typically followed for pre-cracking of polymeric materials, ASTM D5045 [16] and ISO 13586:2018 [17], suggest notching the samples and then sharpening the cracks by tapping or sawing the bottom of the crack using a new razor blade. ISO 13586:2018 provides a tolerance, where the length under the crack is required to be the same on all specimens within 0.5 mm. The report by Kuppusamy & Tomlinson [1] describes three methods (Figure 1) for accomplishing this for polymer-based samples, two of which use a traditional razor blade and another which applies carefully-controlled compressive loads on the samples to cause a local crack to grow in the material past the notch. Each method has its own advantages and disadvantages, primarily driven by the brittleness of the material under test. For very brittle polymer materials, the blade-base methods are generally best to avoid, as the pre-crack may continue to grow on its own, making precision-length cracks impossible and distorting fracture tests [18, 19].

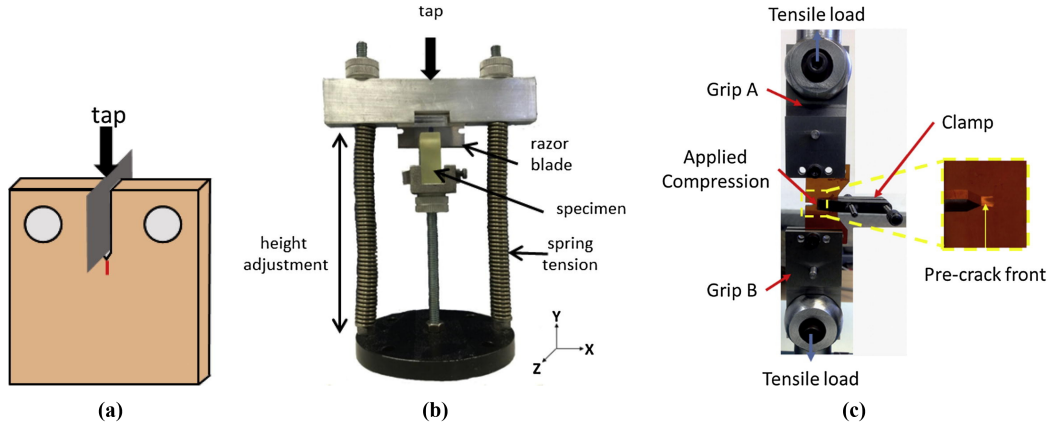


Figure 1: (a) Tapping/sawing with razor blade, (b) Hammered razor blade device, and (c) Tension/compression device developed by Kuppusamy & Tomlinson (All figures from [1], published under CC-BY 4.0 license)

In the first method, the ASTM and ISO standard recommendations are followed exactly and a razor blade is used to carefully sharpen the notch (Figure 1a). This method is easy to apply and requires no special equipment, but is not very precise and raises safety concerns around using hand-held razor blades. Extreme care must be taken to ensure that no hard sawing pressure or heat from friction are present between the razor blade and the crack, as this would harden the area around the crack tip and distort the fracture tests. The second method (Figure 1b) uses a device for more safely hammering a razor blade to form the pre-crack; as long as only one strike is made, sharp and consistent pre-cracks can be accomplished with this method. However, the precision of the pre-crack length and angle depend greatly

on the ability of the user to deliver consistent taps to the material [1]. This mechanism design is also relatively compliant and top-heavy. The method for changing samples also appears to be slow (requiring disassembly for each sample), so it is limited for large sample batches. The third method (Figure 1c), developed by Kuppusamy & Tomlinson [1], is to use a strategic tension-compression system to develop and grow a pre-crack in the material. As shown in their paper, it works best for brittle materials such as epoxy resin, for which the razor blade method is too hard to control. For more ductile materials, a variation of the razor blade method would be better to ensure a straight and consistent crack, one not subjected to obvious local plastic deformation that would result from the tension-compression system being used on a ductile material.

The device developed and demonstrated in this report is an improved version of the hammer-crack device described by Kuppusamy & Tomlinson (Method 2 above), with a more balanced and stiff design and adjustable end-stops to help ensure consistent crack length over numerous samples. Since the design allows pre-cracks to be made consistently with only a single tap or strike (depending on the needs of the user), the rate of work is much faster than other solutions available, offering a speed of about four specimens per minute for an experienced user. The specimen holder is also designed to be both stiff and facilitate rapid exchange of the samples during batch pre-cracking. A microscopic inspection station can easily be set up nearby to inspect and measure the cracks as they are made. The razor blade holder is designed for easy and regular changing of the blades to ensure good-quality pre-cracks.

To test the performance and reliability of the device, 80 tests were completed using molded and 3-D printed acrylonitrile butadiene styrene (ABS). A set of 40 molded ABS and 40 3-D printed bars ($25\text{ mm} \times 9.5\text{ mm}$) were notched and pre-cracked, followed by careful examination under a microscope to find the reliability and consistency of the device. After examination and measurement of the cracks, they were broken as a strategy to study the consistency and straightness of the crack fronts. The razor-blade was changed every 25 samples to ensure that the edge of the blade is sharp during cracking. The details and results are presented in Section 3; the results showed that method may be used reliably for any ductile or semi-ductile polymeric materials, including both molded and 3-D printed samples. Due to the use of the razor blade and hammer to make the pre-crack, it is not recommended that this technique be used for very brittle materials.

2. Tool Design

The tool described in this paper is designed to function in a similar way as the hammered razor blade device described by Kuppusamy & Tomlinson [1], with several improvements to make it suitable to produce fast and reliable pre-cracks for/in ductile materials. These include (in no particular order):

- The device is designed so that only a single strike from the hammer is used to create a pre-crack of the desired depth. This prevents the local strain hardening and crack non-verticality discussed in the ASTM and ISO standards.
- The center of gravity is made as low as possible to make it stable during hammer tapping (Figure 2a).

- 78 • The device is designed with long guide rods to allow pre-cracking of tall specimens if
79 needed, without disassembling the hardware (Figure 2a).
- 80 • The device is designed to use a 680-gram plastic dead-blow hammer for better operator
81 control (Figure 3b).
- 82 • The device is designed to be stiff to enable accurate and repeatable operations (Fig-
83 ures 2a and b).
- 84 • The device uses adjustable end-stops to ensure that the distance between the bottom
85 of the blade and the bottom of the sample remain at a constant height throughout the
86 tests (Figure 2a).
- 87 • The device can successfully use either a calibrated-weight balancing bar or adjustable
88 nuts on the guide rods to ensure that the razor blade is always kept vertical (in spite
89 of any wear or compliance in the moving parts), while also ensuring that the blade is
90 held just above the machined notch and without putting pressure on it (Figure 3d).
- 91 • The specimen holder was replaced by a machined slot in the base that was of the
92 same width as the specimens to be pre-cracked; this holds the samples more securely,
93 while also speeding up the exchange of samples significantly during batch-processing
94 (Figures 2a and b).
- 95 • An efficient system for exchanging the blades at periodic intervals is also developed
96 (Figure 3c).

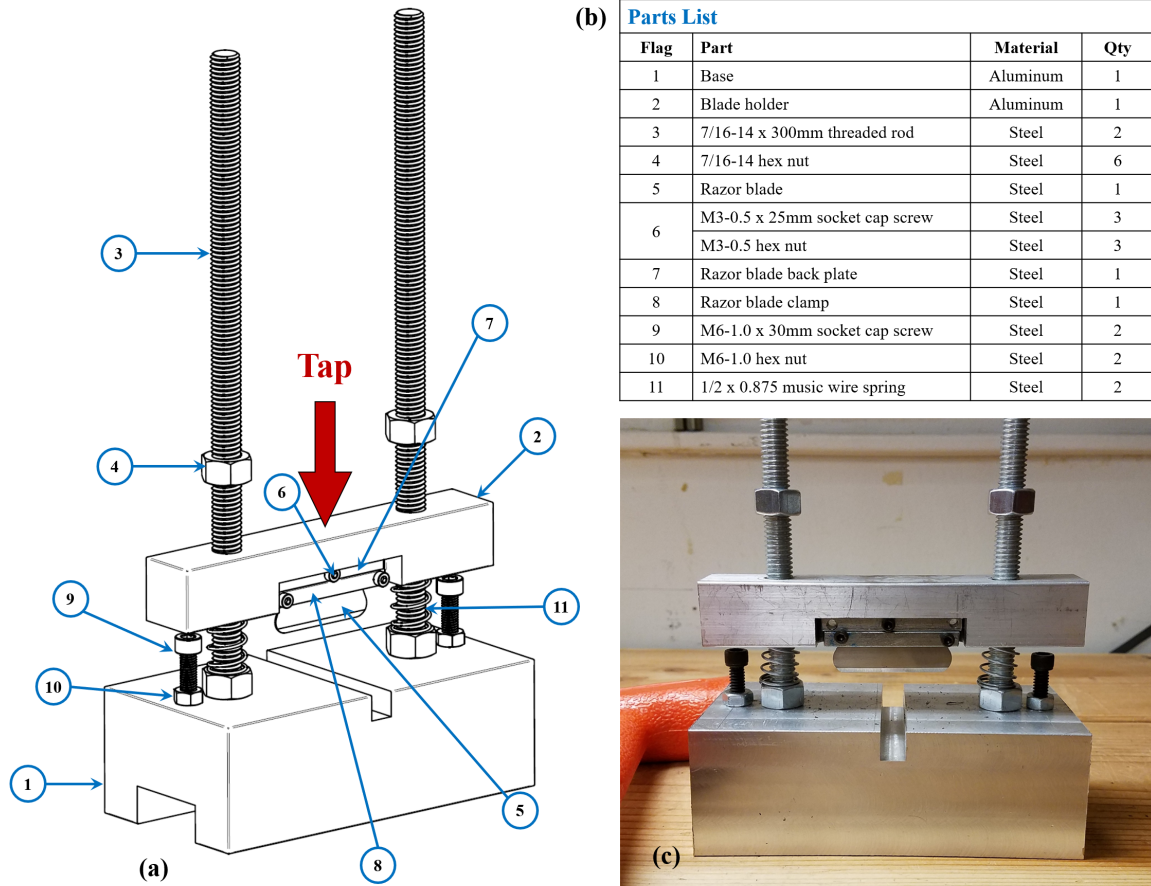


Figure 2: (a) Basic tool design with parts shown, (b) Parts list, and (c) Working prototype

The basic design of the tool is shown in Figure 2, along with a parts list. The tool consists of four main parts: the base, the blade holder, the balancing weight, and the dead-blow hammer. Figure 2c shows the working prototype of the device and all of its parts except for the dead blow hammer. The standard hardware (nuts, etc.) were purchased by the authors, with the rest fabricated from scratch. It was manufactured primarily out of scrap materials and required approximately six hours to machine, assemble, and tune at a cost of about \$35 US for materials. Those costs were primarily the springs, hammer, sliding rods/nuts, end-stop and blade-holder bolts, razor blades, and various drill bits and taps that were not already available in the lab tool set. Tools needed for production included a milling machine with a 3/8-inch TiN end mill, a drill press with bits, a tap-and-die set, pliers, and an Allen-key set.

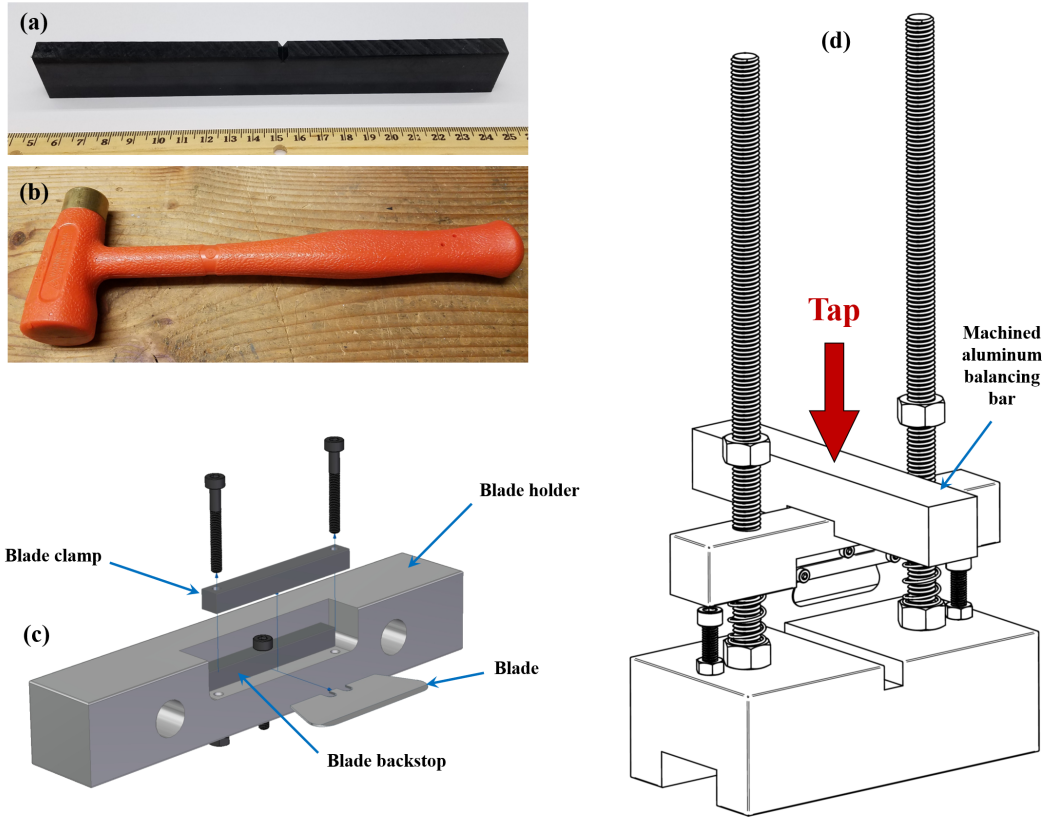


Figure 3: (a) Typical specimen example, (b) Dead blow hammer, (c) Operation of the blade holder, and (d) System with stabilizer bar mass installed

The razor blade holder was designed to facilitate steady and consistent pre-cracking of samples, while also allowing fast and easy changing of the blades with minimal recalibration requirements. It was noted in preliminary tests that the steel razor blades wore into the aluminum sample holder, distorting the results over time and damaging the holder. This was solved by installing a 6 mm steel back plate (Figure 3c) for the blade to rest against during operation and blade changes, with the blade clamp then being installed over the blade. This provided a strong base for the blades and allowed fast blade exchange without needing to recalibrate the end stops for the holder. The backstop and clamp should be M6 square steel stock cut to fit into the cut groove and to hold the hole pattern as shown in the drawing. The technical drawings of the rig can be obtained upon request by contacting corresponding author.

It was also noted that there was some compliance in the device, especially between the blade holder and its guide rods, which could result in the blade not being applied perfectly vertical during the hammering. While this was addressed primarily by adjusting the guide rod nuts, as shown above; this was found to be relatively slow. It was discovered, after several iterations of the design, that a balancing mass (Figure 3d) did an excellent job of preventing this, as it kept the moving parts centered and levelled during the operation and absorbed vibration in the system. Note that this required the use of stiffer springs, as it

increased the mass of the blade holder. The mass was calibrated so that the blade sat above the base of the sample notches without directly putting pressure on them, as required by the ASTM and ISO standards. The design presented here is very flexible and can be modified as needed without changing the fundamental design. For example,

- The guide rods selected were 7/16 *in* threaded rods, but these may be exchanged for any size that is appropriate for the desired testing abilities of the device. Smooth rods may be used as well, but they will likely be more difficult to install and calibrate.
- The machined-groove sample holder was made for samples of a certain size, but the groove can be cut to be any size desired by the experimenter (both width and depth of cut). It should be noted, however, that efforts should be made to ensure that the milling is precise and that the groove is not wider than the sample, as this will result in less stability for the samples. The depth selected for the prototype shown here was 10 *mm*, but it could have been made deeper; it is not recommended that less than 25% of the sample be in the groove, but it is also important to expose as much material as possible to the blade.
- Different types of hammer, springs, and razor blade are all usable with this design, but it is recommended that the ones shown here be used.
- The amount of strike or tap force on the sample is dependent on the material used, the strength of the operator, and the desired precrack depth. Effort should be made to make the pre-crack using only one strike or tap, so this should be taken into account when selecting the force to use.
- The frequency of blade changes is a user decision and dependent on the material used.

3. Height Adjustment and Setup

The height of the end stops should be calculated prior to any use to ensure that they are adjusted to the correct height. The height can be measured with blocks or calipers, as desired by the user. Referring to the measurements shown in Figure 4, the heights should be calculated in order to properly adjust the end-stop screws.

- The height of the material under the machined notch (non-cracked) is represented by D . The proper establishment of this measurement should be done by adjusting the springs and balancing mass.
- The height of the blade is represented by B . Any standard blade can be used, but the height protruding from the holder should be known and recorded.
- The height of the sample holder is represented by C and should be known to the user before testing
- A represents the height of the retaining nuts above the end stop screws. To ensure efficient operation of the device, this should be set high enough to allow the rapid exchange of samples while also being low enough to maintain a low center of mass. If

the nuts are used for each sample, their end height can be set to speed up the operation; if the nuts are not used and the balancing bar is, the nuts may be set in a fixed location that will ensure fast operation while preventing the blade holder from flying off. This setting of this is subjective and up to the user.

- Finally, H represents the needed height adjustment for a particular material length under the pre-crack, and $C + H$ represents the length under the crack.
- The length L of the pre-crack itself can be calculated by $L = D - (C + H)$
- If the parameters are known, the machine can be tuned for a particular notch height Z (from the base of the sample to the bottom of the machined notch) by calculating $Z = D + B - H$

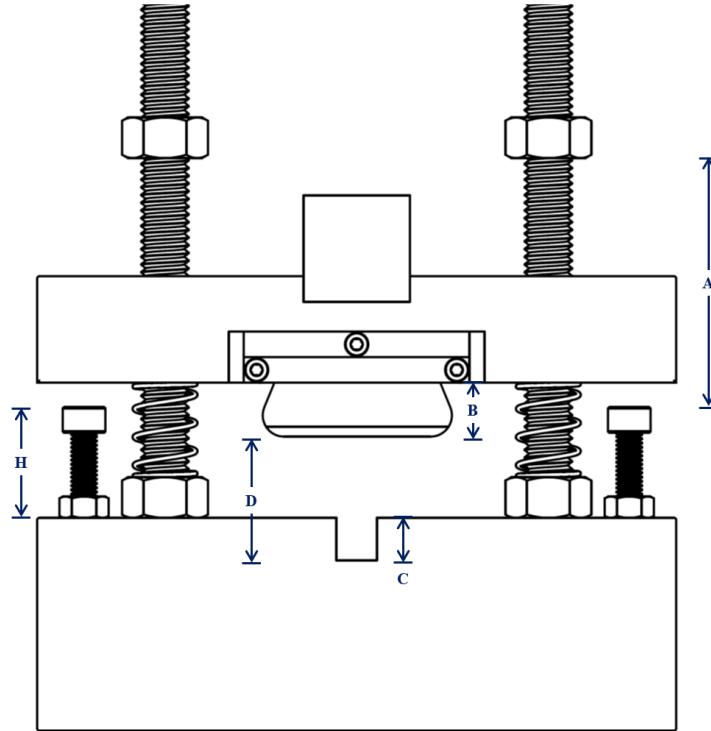


Figure 4: Setup and height adjustments to be made before operation (shown with balancing bar, but nuts can be used as well to ensure straight and effective operation)

4. Repeatability Analysis

When assessing the performance of pre-cracking devices, there are four essential evaluations that must be made. These are presented in this study to demonstrate the value and usefulness of this device. These are, in no particular order:

1. Consistency of the crack length or length of material under the crack between the two sides of the sample; in a perfectly-tuned machine, they should be identical, but

there will always be some variability. Compliance with the requirements of ISO 13586:2018 is typically considered sufficient in practice.

2. How straight the cracks are relative to the side view of the sample (viewed parallel to the blade)
3. The consistency of the crack front inside of the material; the straighter the crack front, the more reliable the test is from a theoretical fracture mechanics perspective.

To address the first two points, a series of 80 trials was completed. No sample replacement was performed and every pre-crack specimen was counted, ensuring that a true dataset could be found. A set of 40 molded ABS samples with a cross section of $25\text{ mm} \times 9.5\text{ mm}$ was used, as well as a set of 20 FDM-printed samples printed in a horizontal orientation and 20 printed in a flat orientation (Figure 5a). The FDM samples were printed from Hatchbox Blue ABS using an XYZ Printing Da Vinci Pro machine (with full enclosure) with a 0.4 mm steel nozzle, a layer height of 0.2 mm , nozzle temperature of 230°C , and a print speed of 50 mm/s . The printing was completed on 3.5 mm epoxy-coated tempered glass sheets heated to a temperature of 90°C . Notching was done for all samples using a milling machine with a 60° V-groove router bit with a 0.2 mm tip. Only one strike was used for each sample, ensuring that the surface would not be strain-hardened by pressure, heat, or multiple hits. As previously suggested, the blades were exchanged every 25 samples.

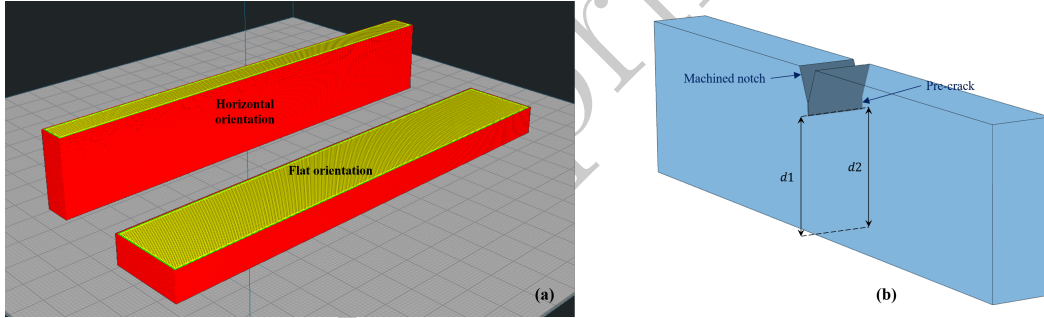
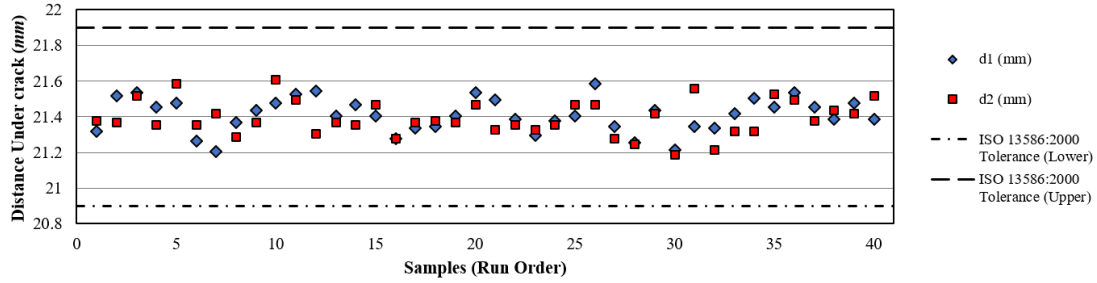


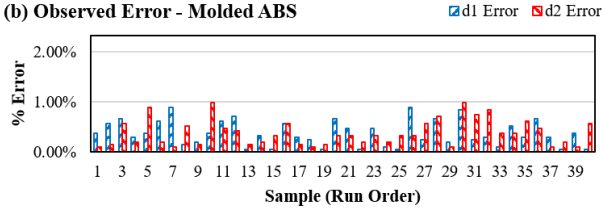
Figure 5: (a) Print orientation of the FDM samples and (b) the notching and cracking configuration, shown with measurement points

The results are shown in Figures 6 and 7. The basic configuration of the samples is shown in Figure 5b, including the location and configuration of the notch and the measurement location. Note that the actual depth of the pre-cracks varied somewhat, as there was some variability in the height of the raw samples; therefore, the distance under the crack was measured for consistency. Figures 6a and 6b demonstrate the results of the molded ABS samples, showing the measured values of $d1$ and $d2$, as well as the percent error. The FDM printed ABS samples behaved in a very similar way, as shown by Figures 6c through 6f. Finally, Figure 6g presents a comparison between the three types of samples based on the mean crack distance (i.e., the average of $d1$ and $d2$). Note that, even though the FDM samples were highly anisotropic, there was very similar variation between them and the molded samples. All errors were observed to be less than 1%, well within the 2.33% error allowed by ISO 13586:2018.

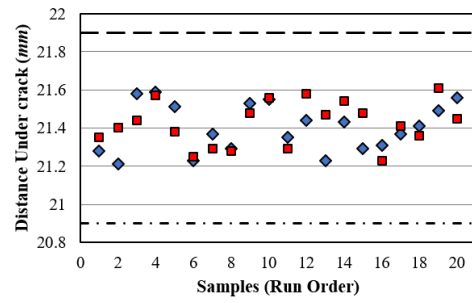
(a) Repeatability - Molded ABS



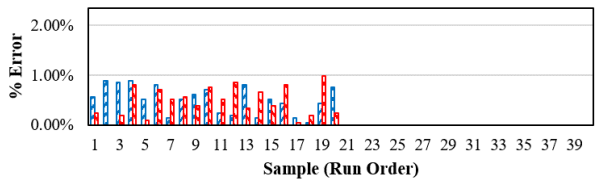
(b) Observed Error - Molded ABS



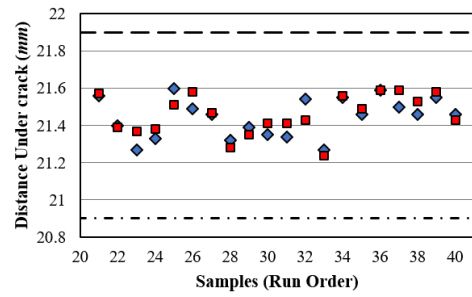
(c) Repeatability - FDM (Flat Print) ABS



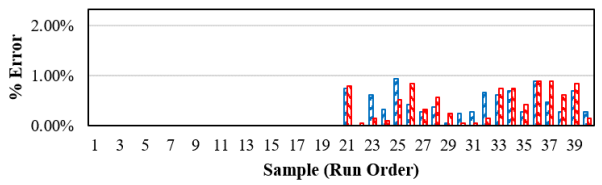
(d) Observed Error - FDM (Flat Print) ABS



(e) Repeatability - FDM (Horizontal Print) ABS



(f) Observed Error - FDM (Horizontal Print) ABS



(g) Repeatability - Comparison of Data Means

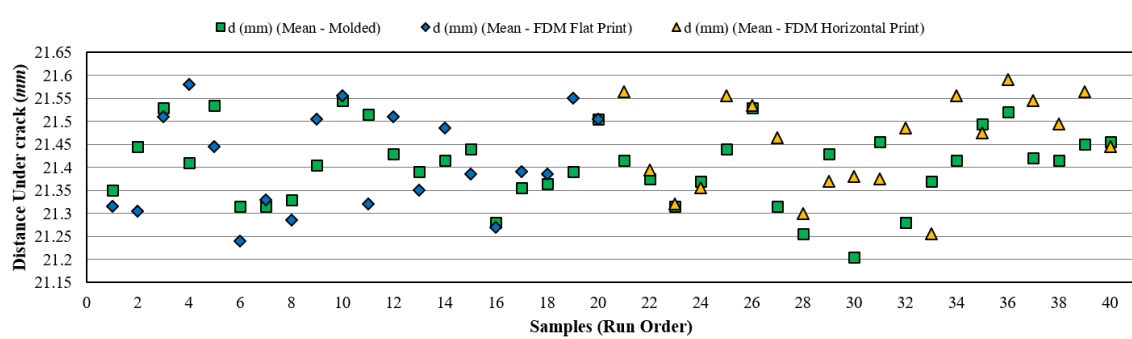


Figure 6: Collected repeatability analysis data for (a) molded ABS, (c) flat print FDM ABS, (e) horizontal print FDM ABS, along with observed percent errors for (b) molded ABS, (d) flat print FDM ABS, and (f) horizontal print FDM ABS and (g) comparison of the mean under-crack length for the cases (average of both side measurement points). All observed error in the length under the notch was well within the 2.33% error allowed by ISO 13586:2018

To examine the straightness of the cracks, the series of cracks from the three sets of samples were examined under a microscope. Typical examples of cracks in the molded ABS (Figure 7a), the flat-printed ABS (Figure 7b), and horizontally-printed ABS (Figure 7c) are shown below. Note the sharpness of the cracks and that they did not branch off after the strike. This behavior is expected only in ductile or semi-ductile materials however, as these kinds of cracks may continue to grow uncontrollably in a more brittle material. Most of the other cracks studied look very similar and it was observed that none of the cracks deviated from the vertical by more than 1° . Therefore, it is clear that the presented device generates straight and reliable pre-cracks.

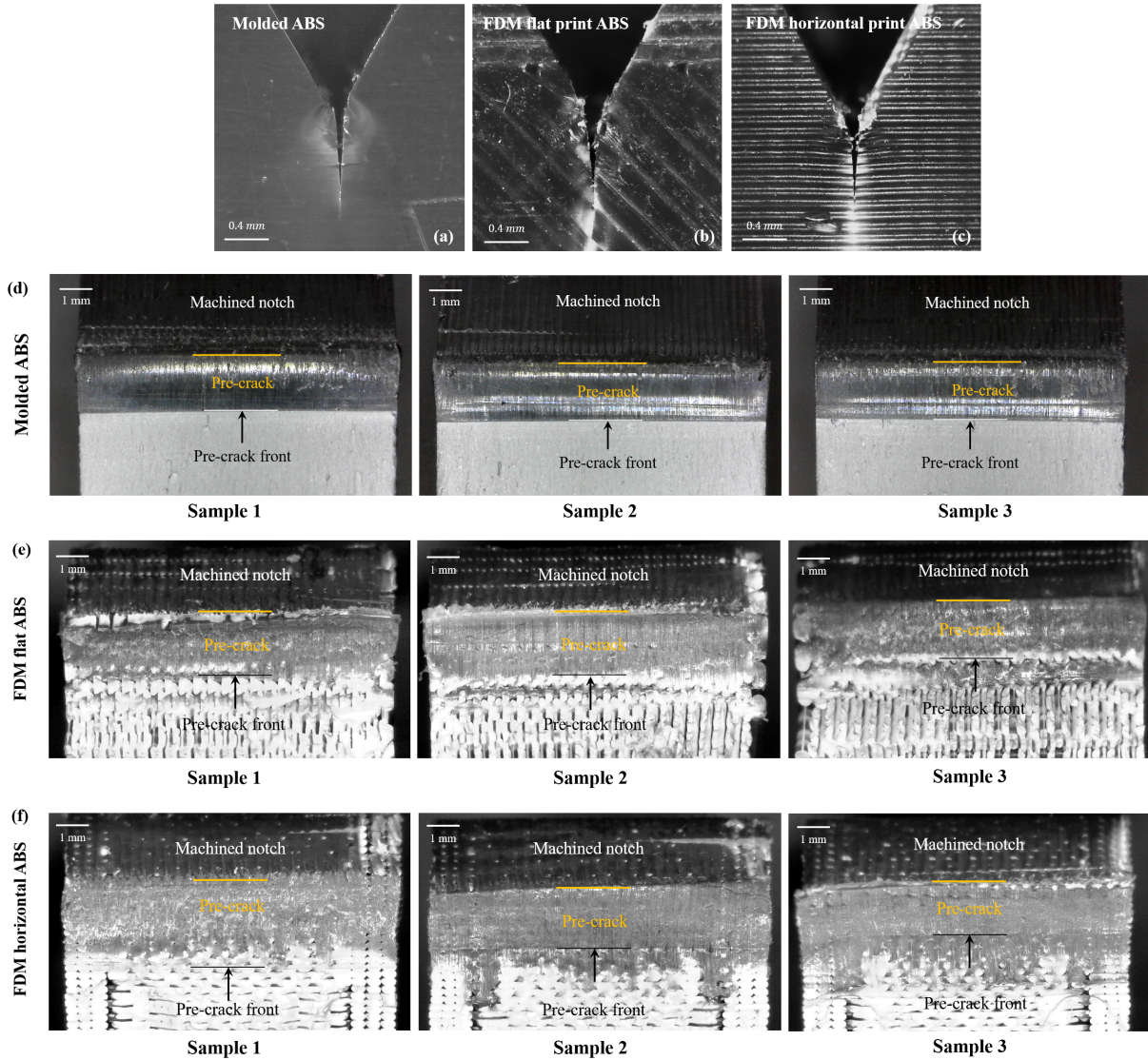


Figure 7: Randomly selected ABS samples showing pre-crack front after breaking (crack front locations and precision determined by examination under a microscope)

Finally, three of the pre-crack samples from each of the cases (nine samples total) were selected randomly, clamped, and broken. This was done to expose the inside of the specimens

and examine the straightness of the crack fronts. While it was expected that there would be some variance on how well-behaved the crack fronts were within the material, all were observed to be straight and well-defined. The molded ABS crack fronts were extremely straight and uniform (Figure 7d), as expected for an isotropic material. Those for the FDM samples (Figure 7e and Figure 7f) were less well-defined, but still far superior to those observed in previous work for plastic materials (e.g., those shown in [1] and [20]). The crack fronts were easily observable and any deviation was localized and predictable based on the obviously anisotropic structure of the material. This indicates that the presented method is very reliable for pre-cracking of ductile and semi-ductile polymeric materials.

5. Conclusions

In this technical report, the design and consistency verification were completed on a simple, desktop device to rapidly and consistently pre-crack notched ductile plastic fracture testing samples. A series of 80 tests were completed with it, showing that it did an excellent job of producing consistent and straight cracks in both molded ABS and two orientations of 3-D printed ABS. This device will be useful in a commercial or lab setting where many fracture testing specimens are needed for static and dynamic fracture tests requiring pre-cracks. The production of good-quality pre-cracks in ductile materials will also help to generate more consistent and reliable fracture testing results for these materials. Design details were provided so that the device can be further tested, reproduced, and improved in future research efforts. The design is very flexible and can be adapted for a variety of environments and materials.

Acknowledgments, Conflicts of Interest, and Funding

All opinions and conclusions offered in this report are solely those of the authors. No external funding was used in the production of this device, its testing, or the publication of this technical note.

Technical Drawings and Data

The raw data from the repeatability tests and all technical drawings and specifications for the described device are archived and available upon request from the corresponding author.

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