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Pre-Cracking techniques of polymeric materials: an overview

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Abstract. In fracture toughness tests, a number of notched specimens with identical artificial pre-cracks are essential to obtain accurate fracture parameters. The test results are critically depending on the initiation stage quality. Any slight variance in pre-cracks front shape, length and orientation could significantly affects the test results; therefore, producing identical pre-cracks is a critical issue to obtain accurate results. The pre-cracking technique should be selected carefully to fulfil controllably and repeatability requirements of the standard pre-cracks for a certain material while preserving the induced residual stresses at the crack tip at a minimal value. The notching and pre-cracking standards for metallic material have been well specified in ASTM E399. However, the case is more cumbersome for polymeric materials due their viscoelastic nature. ASTM D5045, ISO 13586:2000 and ASTM D6068 specified different procedures to prepare a sharp pre-crack for polymeric materials. Many pre-cracking techniques have been proposed in literature. The present work introduces an overview of the pre-cracking techniques for polymeric materials.

1. Introduction

Recent days, polymers are widely used in the industry due to their good properties against metals[1-3]. The usage of polymeric materials in critical applications makes the determination of accurate fracture toughness parameters an important issue especially when the structural integrity of the component is critical. For the fracture toughness tests, a sharp pre-crack must be introduced firstly. The pre-cracking of solid materials is investigated fairly and well specified in ASTM E399[4]. But polymeric materials still have some problems associated with obtaining a sharp pre-crack without developing residual stresses a head the crack tip especially for ductile polymers and sudden failure of brittle polymers. According to the standards, ASTM D5045 and ASTM D6068, a natural pre-crack can be initiatedin Compact Tension ***(CT)*** specimens or Single Edge Notch Bending ***(SENB)*** specimens using a razor blade by tapping in the centre of the notch with a new razor blade or sliding a new razor blade in either a sawing motion (side-to-side) or slicing repeatedly in a single direction. The standards warn against pressing a razor blade for ductile resins. ASTM D6068 provides fatigue pre-cracking standards requirements. Earlier problems associated with specimen preparation appeared since the labs use different techniques that lead to different results. Brown et al. [5]have investigated the effect of pre-cracking technique on the lifetime of polyethylene specimens and shows pressing a razor blade at a rate of 0.05 mm/min produced the fastest growing cracks. Dapp and Rimnac[6] investigated the effect of different pre-cracking techniqueson the results of J-R curve determination for Ultra High Molecular Weight Polyethylene resin, also indicating that the pressing of a razor blade at slow feed is the most accepted method since it introduced minimum residual stresses at the crack tip. Many investigations studied the different pre-cracking techniques of different polymeric material such as (PE- EPBC-PETG)[7-11] and it was reported that the fracture toughness results depend on the pre-cracking

methodology. New technique was introduced by Tamura [12];toinduce pre-crack controllable length in brittle polymeric materials by applying tension and compression load. Then, the technique was improved and optimized in[8]. Recently femto-laser is used to pre-crack polymeric materials. Many researches [13-15]investigate femto-laser as a promising pre-cracking technique against conventional techniques since femto-laser ablation causes minimum residual stresses ahead the crack tip .
This paper introduces an overview of pre-cracking techniques of polymeric materials, discusses the advantages and disadvantages of each technique, and highlights the recent developed techniques.

2. Notching

Prior to pre-cracking, a small machined notch is introduced firstly in a CT or SENB specimen according to standards as shown in Figure 1 (a). The notch can be produced either by conventional machining process such as hand saw, sawing machine, or rotary cutting machine. The effect of notch geometry (square or angular) ona single edge notched bending (SENB) specimen made of commercial Poly(Methyl Methacrylate)PMMA resin was investigated by Souza et al. [7]. Square and angular notches were produced by a sewing machine and rotary cutting device, respectively. The used rotary cutting device is supplied with cutting disk of 45 tip angle as shown in Figure 1 (b). The results of photoelasticity tests showeda slight perturbation of the patterns ahead the notch tip for the notch produced by rotary cutting device as shown inFigure 1 (c).The results indicated that the notch geometry has a very slight effect on the fracture toughness values; however, the angular sharp notch shape is preferred because it allows better control to direct the razor blade into a single point, thus insuring reproducibility of pre-cracks.

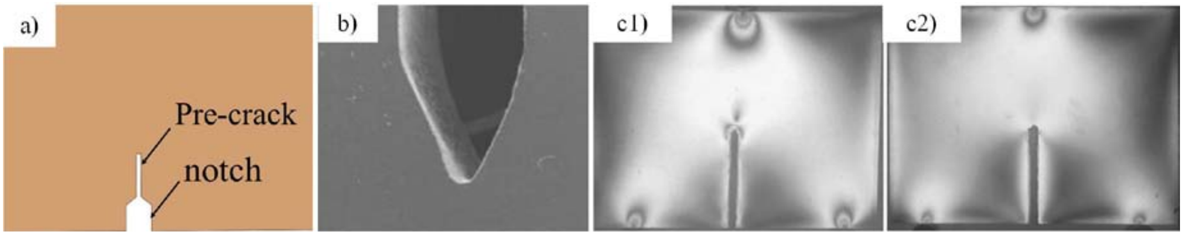

Figure 1 a) Notch and pre-crack; b) Example of notch root, produced by the rotating disk in the PMMA[7]; c) Examples of Moiré patterns for notch produced by (1) rotary cutting device, (2) sawing[7]

3. Pre-cracking Techniques

It is known that fatigue tests of ductile polymers are long term testing [16-18]; as it could take days or weeks at room temperature. Many attempts to obtain stable slow crack propagation at room temperature for such polymers in short time testing were induced using different pre-cracking techniques. The results showed that the pre-cracking technique has a critical role for obtaining stable propagation in a short time testing. Also, the fracture toughness test results of polymeric materials are sensitive to pre-cracking method since pre-cracking introduce large residual stresses at the crack tip for ductile polymers. And pre-cracks need very little energy to propagate for brittle polymers. The pre-cracking techniques can be classified into two categories conventional techniques and un conventional techniques as shown in Figure *2*.**Error! Reference source not found.**represents a summary of the pre-cracking techniques.

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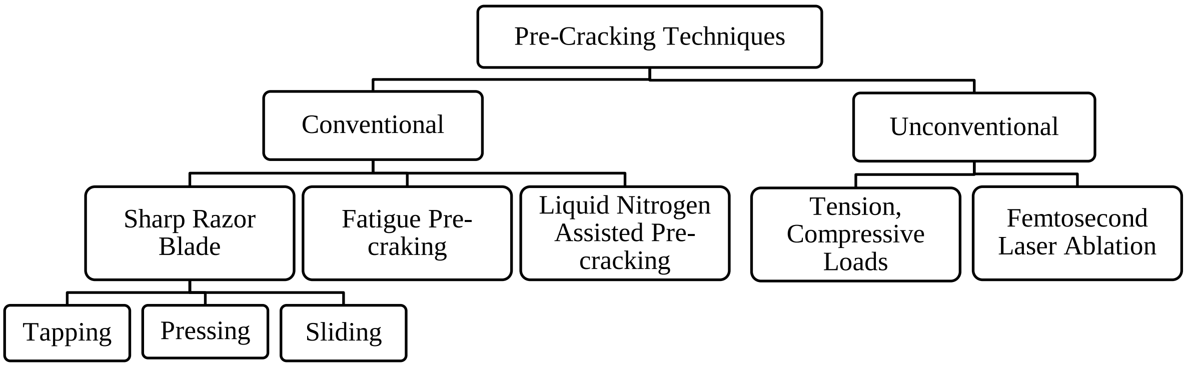

Figure 2. Classification of thePre-Cracking Techniques.

Table 1. Summary of Pre-Cracking Techniques.

Pre-Cracking Techniques			***machine***	***tool***	***International Standard***	***Standard size of Specimen***	***Material recommended***
Conventional	*Using Sharp Razor Blade*	*Pressing*	*Special pressing machine*	*Razor Blade*	*ASTM D5045 and ASTM D6068*	*Compact Tension **CT** or Single Edge Notch Bending **SENB***	-
		Tapping	*Manual*				*Ductile polymers*
		Sliding	*Sawing machine or manual*				-
	Fatigue Pre-Cracking		*Universal Testing Machine*	-	*ASTM D6068*		-
	Liquid Nitrogen Assisted Pre-Cracking		-	*Razor Blade*	-		-
Unconventional	*Tension – Compression Loads Application*		*Universal Testing Machine*	*Clamps*	-		*Brittle polymers*
	Femto-Second Laser Ablation		*Laser Machine*	-	-		*Both Brittle and Ductile Polymers*

3.1 Pre-cracking via Fresh Razor Blade
Pre-cracking via fresh razor blade is one of the most popular techniques according to ASTM D6068 and ASTM D5045. In this technique sharp cracks are produced either by tapping in the center of the notch with a fresh razor blade, pressing a fresh razor blade perpendicularly into specimen at very slow feed, sliding a new razor blade in a sawing motion (side-to-side) or slicing repeatedly in a single direction. Although razor blades are used in a wide range of applications, it has many problems. It is very difficult to obtain identical pre-cracks via razor blades, beside safety concerns.

3.1.1.Pressing a Fresh Razor Blade. Sharp pre-cracks are produced by pressing a fresh razor blade perpendicularly into a specimen at very slow feed to avoid deformation and minimizing the residual stresses at the crack tip using a suitable pressing machine. This technique is firstly developed by Brown et al. [19-23] to prepare fracture toughness specimens. The influence of pre-cracking by pressing a fresh razor blade at feed of (0.05 mm/min) on the test results for a tough polyethylene is discussed in [5]. The results showed an appropriate failure time. Although this technique provides high controllable pre-cracks lengths and orientations, the standards warn against pressing a razor blade for ductile resins since it introduces a residual stress at the crack tip as shown in Figure 2(a). Souza et al. [7] have studied the effect of inserting a fresh razor blade on PMMA as a pre-cracking technique; and concluded that this technique produces non-planar propagation of the unstable crack started from the center of the pre-cracksince the resultant propagation show concentric lines initiated from the center as shown in figure 2 (b). The photo elasticity tests show a perturbed stress state at the crack tip as shown in Figure 2(c) leading to high K_{Ic} values.

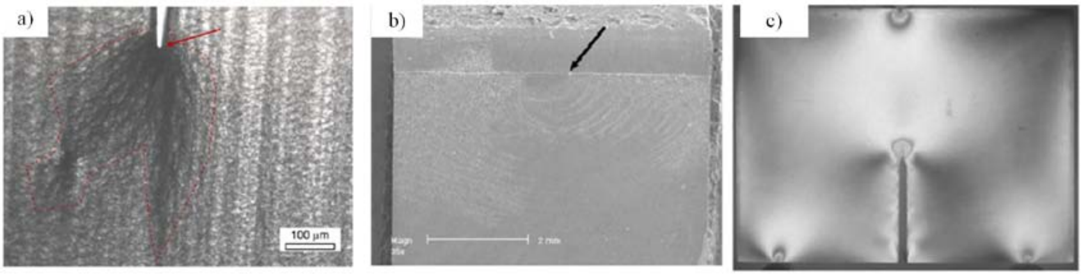

Figure 3. a) Residual stresses developed by inserting a razor blade[14]; b) Morphology for the case in which the pre-crack was produced by inserting a razor blade[7]; c) Moiré patterns produced in samples pre-cracked by inserting a razor blade[7]

3.1.2.Tapping a Fresh Razor Blade. Tapping a fresh razor blade manually in a center of the notch to produce pre-cracks as shown in Figure 3 (a) is acceptable technique according to the standards(ASTM D5045 and ASTM D6068). Souza et al. [7]have investigated the effect of tapping a fresh razor blade on PMMA; and concluded that this technique is very acceptable compared to inserting a fresh blade technique for PMMA since it produces planar propagation of the crack started from the root line of the pre-crack as show in Figure 3 (b).The frac to graphic patternshow less disturbed stresses at the crack tip as shown in figure 3 (c) which leads to lower K_{Ic} values. But this technique is very poor since it is depending on the operator skills. Positioning and orientation of razor blade, tapping force and pre-cracks lengths are very sensitive to the operator so there producibility of pre-cracks is impossible[9]. Some of the problems associated with the operator are highly eliminated by the pre-crack rig that introduced by Kuppusamy and Tomlinson [8]. The pre-crack rig is designed to control the length and the orientation of the produced pre-cracks by guide springs as shown in Figure 3 (d).Although many problems of this technique are eliminated by using the pre-crack rig, but the tapping force is still sensitive to operator skills and specimen material, blade usage is very risky, and tapping is not suitable for brittle polymers.

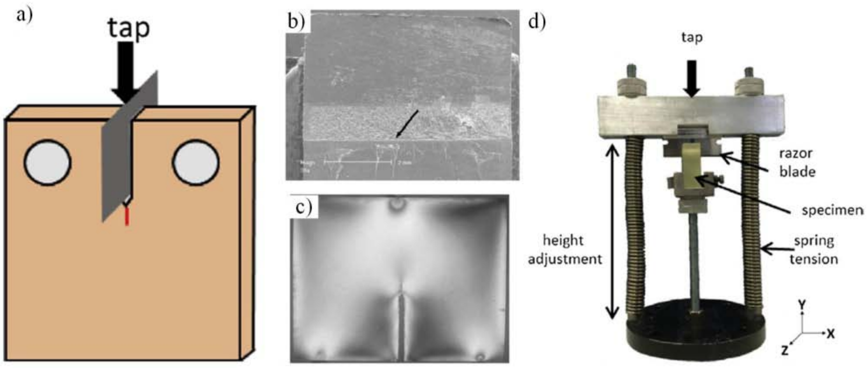

Figure 4. a) Pre-cracking by tapping[8]; b) Morphology for the case in which the pre-crack was produced by tapping on a razor blade[7]; C) Moiré patterns produced in samples pre-cracked by tapping on a razor blade[7]; d)pre-cracking rig[8].

3.1.3.Sliding a Fresh Razor Blade. According to the standard(ASTM D5045 and ASTM D6068), pre-cracks can be obtained either by sliding a new razor blade in a sawing motion (side-to-side) or slicing repeatedly in a single direction manually or using a suitable machine. Although this technique is allowed by standards, it is uncommon technique and is rarely used.

3.2.Fatigue Pre-Cracking

Fatigue pre-cracking is a common used technique especially for metals pre-cracking using a fatigue testing machine but it is restricted for polymers since it has the following limitations: it is very time-consuming technique, producing unstable crack growth, and it is very difficult to crack the brittle material without failure [8]. Moreover, the loading frequency must be lower than 4 Hz to minimize the residual stresses at the crack tip that introduced by the hydrostatic heating [24]. An attempt was performed to grow a pre-crack by fatigue in polyethylene [5]; the results showed the same trend as that obtained by standard razor blade[6].Moreover, it was reported that the damage developed ahead the crack tip is more than that developed by pressing razor blade leading to high fracture resistance.

3.3.Liquid Nitrogen Assisted Pre-Cracking

A very sharp pre-cracks can be obtained via pressing or tapping on razor blade after immersing the polymer in liquid nitrogen for a period of time. As known that the freezing process embrittle the polymers. Brown et al. [5]have investigated producing pre-cracks for tough polyethylene using liquid nitrogen by two methods. First method, initial notch is produced prior immersing the specimen into liquid nitrogen then additional notch is produced. Second method, after producing the initial notch the specimen is loaded during cooling process. After pre-cracking the specimens are tested at 80 ºcunder maximum stress of 2.4 MPa. The results indicated that both methods have a slight effect on the failure time. Another attempt was conducted by [11]to study the influence of pre-crack technique on K_{Ic} for medium density polyethylene (MDPE) with cryogenic conditions. K_{Ic} test is conducted after pre-cracking and cooling the specimen in liquid nitrogen (-196 ºc). The pre-cracking was produced by two techniques (inserting and tapping) fresh razor blade. The results showed that freezing the polymer in liquid nitrogen is a good method to obtain proper K_{Ic} values.

3.4.Unconventional Procedures

3.4.1.Tension and Compression loads. Tamura et al. [12] have developed a technique to grow a pre-crack in brittle polymeric materials. This technique depends on applying load in two directions as shown in Figure 4 (a). A tension load is applied in the direction of crack opening causing crack growth. And compression load is applied in the transverse direction, ahead of the notch causing crack arrest at the required crack length. Although this technique introduced a safe manner to produce pre-cracks, it has some problems to obtain repeatable pre-cracks front shape. Pre-cracks front shape problem that that induced by Tamura technique have been treated in Kuppusamy and Tomlinson [8]. In that investigation, the effect of contact area type between the specimen surfaces and clamping that apply the compressive load on pre-crack front shape for Arcan-type specimens [25] made from an untoughened epoxy resin used in aerospace composites has been explored as shown in Figure 4 (b)The results showed that the rectangular contact provided by (T clamp) type generate a very straight crack front whereas ball contact (G clamp) generate a curved crack front. Kuppusamy and Tomlinson [8]. have determined the optimum compressive load required to produce a pre-crack of a known length for untoughened epoxy modified Arcan specimen using a slipper torque wrench on (T clamp). If the compressive load is insufficient the pre-crack will be larger than the desired length. if the compressive load is large the pre-crack will travel along the axis then grow perpendicular to the pre-crack axis. The results show that the optimum compressive and tensile loads required to grow a pre-crack for a 4mm thickness specimen are 300 N. This technique shows high repeatable, controllable pre-crack lengths and shapes with minimum residual stresses at the crack tip. As shown in Figure 4-d-f, T-clamp method did not introduce any residual stresses at the crack tip.

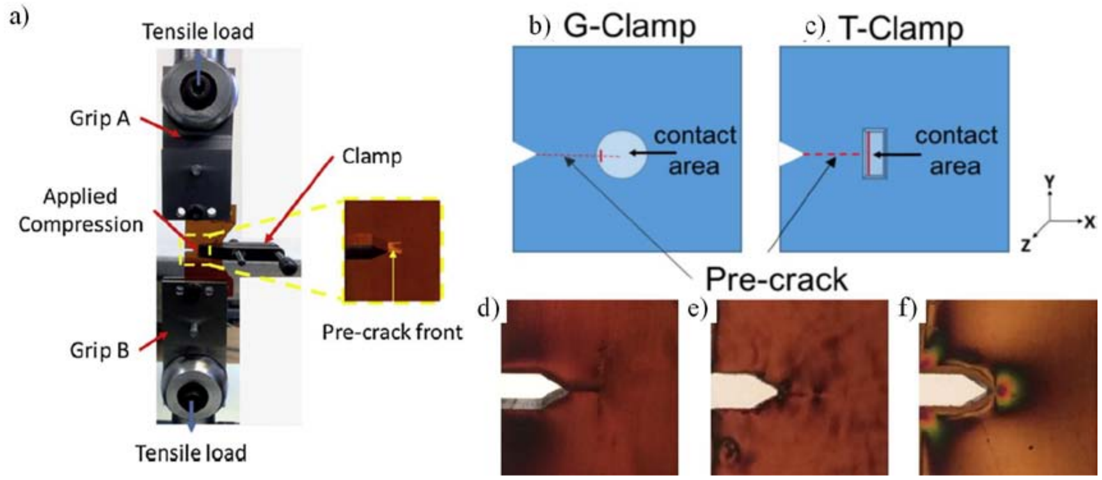

Figure 5. a) Pre-cracking technique without using a blade; b)Compressive load contact area (G clamp); c) Compressive load contact area (T clamp);(d-f)Showing residual strain CNC-machined specimens with a crack introduced (d) using the T-clamp method; (e) using razor tapping; and (f) a specimen with a notch only [8].

3.4.2.Noncontact Technique (Femtosecond Laser Ablation). Femtosecond laser pulses [26] are used to ablate polymers since 1994 [27]. Many researchers studied the effect of femtosecond laser pulses on polymers [28]and polymer based composites [29]and show minimum thermal damage around the ablation area. Recently Femto-laser technique is used to prepare specimens of fracture toughness tests since it produces very sharp pre-cracks with a very small crack tip radius as shown in Figure 6 (a)and minimum residual stresses a head the crack tip leading to accurate determination of K_{Ic} and G_{Ic}[13]and [14].Thermoplastic polymers such as (semi-crystalline multi-phase ethylene–propylene block copolymer and an amorphous polycarbonate) are better to pre-cracked by femto-laser techniques since very small crack tip can be achieved resulting in proper fracture toughness values that can be explained that the plastic deformation developed at the crack tip is very small compared to the damage resulted from the conventional techniques [10]. Also, femto-laser technique produces a well-defined pre-crack that are independent on the dimensions of specimens, on the contrary of the conventional techniques in which the higher specimen width the more damage introduced at the crack tip [15].. The influence of different pre-cracking techniques (contact conventional techniques such as razor blade tapping, sliding, pressing, broaching opposite recent non-contact techniques such as femto-laser ablation) on the fracture parameters have been analyzed for SENB specimen made of poly (ethylene terephthalate) modified glycol (PETG)by Martínez et al.[30]. As shown in figure 6 (b),sharp pre-cracks with 0.5 µm tip radii can be obtained via the non-contact femto-laser technique, leading to the low values of fracture toughness. But the conventional tapping on razor blade technique generated large crack tip resulted in higher values of fracture toughness. Broaching and pressing razor blade techniques produced smaller crack tip radii compared to pre-cracks produced by razor tapping, and hence leading to intermediate values of fracture toughness.

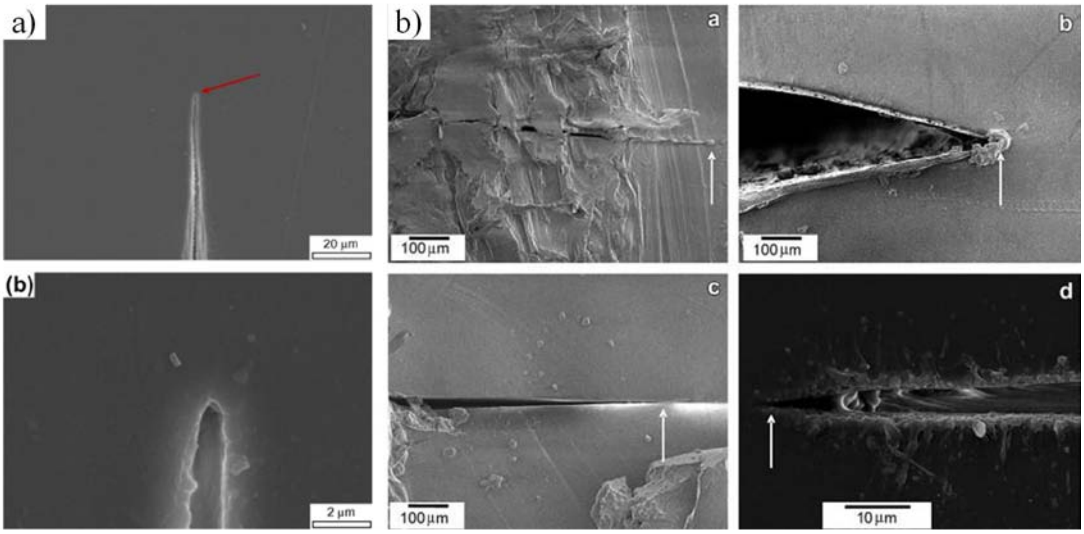

Figure 6 a) Crack tip produced by femto-laser[10]; b) SEM micrographs of non-tested specimens (a) by Tapping, (b) by sharp tool (c) by Pressing, (d) by femto-laser. The arrow points out the end[9].

4. Conclusion
Fracture toughness and initiation stage of the long-term fatigue tests results of polymeric materials are very sensitive to the pre-cracking methodology. Conventional techniques (tapping on, pressing, slicing by) a fresh razor blade that specified in the standards procedures are insufficient and unsuitable for all polymers and need more study since resulted large damage at the pre-crack tip is observed leading to variance in test results. Pre-cracking procedures must be specified independently for ductile and brittle polymers to facilitate the selection of proper pre-cracking technique. New promising pre-cracking technique is developed via femto-laser. Femto-laser produces very small crack tip radii with minimum damage independent on the tested specimen dimensions leading to accurate fracture toughness values.

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