

Manuscript Number: JECS-D-17-00850R1

Title: Evaluation of damage in front of starting notches induced by ultra-short pulsed laser ablation for the determination of fracture toughness in zirconia

Article Type: Short Communication

Keywords: ceramics; 3Y-TZP; fracture toughness; laser damage; notch

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Abstract: Machining a very sharp notch on the surface of ceramics for fracture toughness testing has been a critical issue during many years. In this work, we explore a novel method capable of inducing sharp features with negligible damage with laser pulsed ablation. We study the effect of different laser ablation parameters in the notch length and damage induced in 3 mol% yttria doped zirconia. In front of the notch it is found a very narrow microcracked zone which spreads in the notch direction, whose length only depends on the laser pulse energy; meanwhile the length of the notch is proportional to the energy deposited during the process.

Reviewer:

I'm pleased to send you my comments to the manuscript: "Evaluation of damage in front of starting notches induced by ultra-short pulsed laser ablation for the determination of fracture toughness in zirconia" (Manuscript ID: JECS-D-17-00850).

In this article, authors explored a novel method capable of inducing sharp features with negligible damage with laser pulsed ablation, and studied the effect of different laser parameters on the notch and damage lengths to produce notches suitable for fracture toughness determination. This work may be helpful for the application of laser notching method in fracture toughness measurement.

However, there still have some important points that need to be attention. The microcracks induced by laser are random. How do the crack paths look like? Is the crack initiated from the bottom of the microcracked zone? Do different laser parameters affect the determination of fracture toughness?

Furthermore, there is a mistake in page 6 and line 7-9, "(Pulse duration 120 fs...)".

I suggest this paper be minor revisions.

Editor comments (JC) :

This is indeed a paper worth publishing in JECS, even if (see below) we would have appreciated a bit more results and analysis on strength/toughness values and microstructural changes. The main interest I see in this work is the technical possibility to create small 'natural' cracks at the surface of a ceramic that would allow short crack analysis of toughness (and strength). I would personally have appreciated if you had elaborated somewhat more on :

- toughness values obtained from such cracks. You are referring to other papers, but I am sure the readers would expect to see toughness measured from such micro-cracks in the same paper.

- strength - crack size relations that you could obtain from the different cracks you have generated in your work. If they have been done on different 4-point bending bars, you have the possibility to 'break' them and see how this relation agrees with common rules.

- the potential transformation of the zirconia phase and its role on the measured toughness

- Having the potential of making FIB, a 3D characterization would have been a must (is the micro-crack network interconnected through all the crack length for example ?).

This is your choice to complement on this, but this would be appreciated and more important give a stronger and an even more impacting paper.

Reply:

We kindly thank the reviewer and editor for the comments regarding the submitted paper.

Following these comments, we have introduced two videos as supplementary material consisting on the 3D reconstruction of the microcracked zone, which we hope will help to clarify the doubts regarding the shape and interconnection of the cracks.

We have also made some changes in order to explain better the experimental procedure and the discussion. For selecting the optimal parameters of ultra-short pulsed femtolasers ablation (UPLA), first we machined all notches in the same specimen in order to study the length of the notch, its root radius, and the damage induced in front of the notch tip. The second step was a deep analysis of the damage by FIB tomography and also by nanoindentation on the microcracked area (this work on nanoindentation of the microcracked area was shown in our previous publication (M. Turon-Vinas and M. J. Anglada, "Fracture toughness of zirconia from a shallow notch produced by ultra-short pulsed laser ablation," *J. Eur. Ceram. Soc.*, vol. 34, no. 15, pp. 3865–3870, Dec. 2014). Finally, we only selected a set of laser parameters for measuring fracture toughness in several specimens. Finally we analysed the fracture surfaces of these specimens and found that the microcracked area was clearly visible and its length correlated perfectly with the length measured on the lateral surface in front of the crack tip (to see the microcracked zone in front of the notch root on the lateral specimen surface some careful polishing was needed). The selection of the laser parameters for measuring fracture toughness was based on those giving sharper notch roots radii and clearer microcracked zones in front of the notch. However, other laser parameters in the range studied could also have been used since they also produce notches and microcracked zones which fulfill the conditions for considering the microcracked area plus notch length as a straight edge crack. We believe that similar results would be found for fracture toughness since the notch lengths, root radii and microcracked extensions are not very different. As the initial main objective of the paper was only to show the influence of the different laser parameters on the damage produced, fracture toughness and strength measurements were not performed with notches induced by different laser ablation parameters. On the other hand, with respect to crack length our objective was to start with cracks clearly longer than natural cracks (in order that the specimens were broken by the artificial crack) but much shorter than the macroscopic cracks used to measure fracture toughness.

We have also added some comments on the potential of fracture toughness

Changes:

Abstract:

Pg. 1: Machining a very sharp notch on the surface of ceramics for fracture toughness testing has been a critical issue during many years. In this work, we explore a novel method capable of inducing sharp features with negligible damage with laser pulsed ablation. We study the effect of

different laser ablation parameters in [the notch length and damage induced in 3 mol% yttria doped zirconia](#). In front of the notch it is found a very narrow microcracked zone which spreads in the notch direction, whose ~~scie~~ length only depends on the laser pulse energy; meanwhile the length of the notch is proportional to the energy deposited during the process.

Experimental procedure:

Pg. 3: Small notches were laser machined on the XZ surface of the samples by UPLA ~~using different laser parameters~~, as pictured in [Figure 1](#).

Pg 3-4: [The notches for the fracture toughness determination were produced using a pulse energy of 5 \$\mu\$ J, scanning speed of 50 \$\mu\$ m/s and four passes. In one of the samples, several notches were produced using different laser parameters in order to investigate the damage. The laser parameters investigated were the pulse energy, scanning speed and number of passes, as summarized in \[Table 1\]\(#\).](#)

Pg. 4: [Table 1. Parameters used for the ablation of the notches \(pPulse duration 120 fs, wave length 795 nm, repetition rate 1KHz, spot radius 2.8 \$\mu\$ m\).](#)

Results and discussion:

Pg. 8: [Two videos on the 3D reconstruction of the microcracked zone are incorporated as supplementary material which gives light on the shape and interconnection of the cracks.](#)

Pg. 10: The microcracking observed in front of the notch tip is not related to t-m transformation since monoclinic phase was not detected in the microcracked band by confocal Raman spectroscopy, as shown in a previous work [on 3Y-TZP \[9\]](#). It can be appreciated that the width of this microcracked band is very narrow ($\sim 2 \mu$ m for notch 7 and $\sim 4 \mu$ m for notch 13) ~~and~~, localised in the direction of the notch [and with a high density of microcracks, most of them already interconnected \(see supplementary material in the online version\)](#). The physical explanation cannot be related to photo-thermal effects and it seems likely related to thermomechanical waves induced by the laser ablation process since they are localised in the direction of the notch [16], [17] [without producing any detectable t-m transformation \[9\]](#).

Regarding the conditions for fracture toughness determination from these notches, it can be seen that they are fulfilled since not only the tip radius of the notch is very sharp (of less than 1 μ m) but also there is a non-transformed microcracked region in front of the notch so that, in principle, the total crack length can be taken as an [unshielded](#) edge straight crack with a length equal to that of the notch+microcracked band [5]. [As the microcracked density is very high and almost all microcracks interconnected \(see supplementary material\), it is then](#) expected that when the load is increased to fracture in a four point bending fracture test, the microcracked region will coalesce and form with the notch one sole crack that under higher loads will become unstable inducing failure [18]. [Values obtained in previous studies by the authors in 3Y-TZP using the laser parameters of notch 1 \(which is energetically closer to the examined notch 13; see Table 1\) \[9\] and in Si₃N₄ \[10\]](#) are in agreement with results in literature in which fracture mechanics conditions for measuring fracture toughness were fulfilled. [As all the parameters used here produce the same notch+microcracks configuration and a small tip radius, we do not expect different values in the](#)

fracture toughness values obtained from these notches.

Pg. 11: Here the notch has been machined ~~produced~~ on the surface of the specimen with the intention of producing very small cracks since fracture toughness of small cracks is the one that controls the strength of ceramics with natural cracks and R-curve behaviour.

(...)

The relative small values obtained for fracture toughness of 3Y-TZP (around 4.1 MPa \sqrt{m} , see [9]), can be explained because the condition for unstable fracture for small unshielded cracks makes very unlikely the exploitation of the toughening from the modest and sharp R-curve present in 3Y-TZP with 330 nm grain size [20]. The condition of fracture in case of the presence of R-curve behaviour is reached before the crack can grow in a stable manner.

Acknowledgements:

Pg. 12: Authors greatly acknowledge the financial support from “Ministerio de Economía y Competitividad” of Spain (grant MAT2014-60720-R and the fellowship award received by MTV)

Pg. 12: Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at [URL/DOI].

References:

Pag. 14: [20] D. Casellas, A. Feder, L. Llanes, and M. Anglada, “Fracture toughness and mechanical strength of Y-TZP/PSZ”, Scripta Materialia, vol. 45, no. 2, pp. 213-220, 2001.

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Evaluation of damage in front of starting notches induced by ultra-short pulsed laser ablation for the determination of fracture toughness in zirconia

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Abstract

Machining a very sharp notch on the surface of ceramics for fracture toughness testing has been a critical issue during many years. In this work, we explore a novel method capable of inducing sharp features with negligible damage with laser pulsed ablation. We study the effect of different laser ablation parameters in the notch length and damage induced in 3 mol% yttria doped zirconia. In front of the notch it is found a very narrow microcracked zone which spreads in the notch direction, whose length only depends on the laser pulse energy; meanwhile the length of the notch is proportional to the energy deposited during the process.

Keywords: Ceramics; 3Y-TZP; Fracture Toughness, Laser damage, Notch

1. Introduction

Fracture toughness of ceramics is usually determined by the single edge V-notch beam (SEVNB) method [1]. The notch is made with a saw cut and its tip is thinned by honing with a razor blade impregnated with a diamond slurry [2], [3]. By doing so, a relative sharp notch tip is finally achieved, and a number of microcracks, with a size typically 1-3 times the grain size, can be left in front of the notch tip by the machining process [4]. For the determination of K_{Ic} by this method, the stress intensity factor of this configuration of notch plus microcracks can be taken as that of a straight sharp crack as far as the length of the microcracked zone is longer than the notch tip radius [5]. This condition can be fulfilled in coarse grain size ceramics but it cannot be obeyed when the grain size is in the microscale or below, since then the radius of the notch tip should be smaller than is practically possible to achieve by honing. This makes machining sharp notches in sub-micrometer grain size ceramics for fracture toughness testing a critical issue.

One way of machining a very sharp notch on the surface of ceramics is ultrashort pulsed laser ablation (UPLA), which, in principle, is a technique capable of inducing very sharp features with negligible damage [6]–[8]. It is then an appealing technique for inducing a very sharp starting notch for measuring fracture toughness [9]–[12].

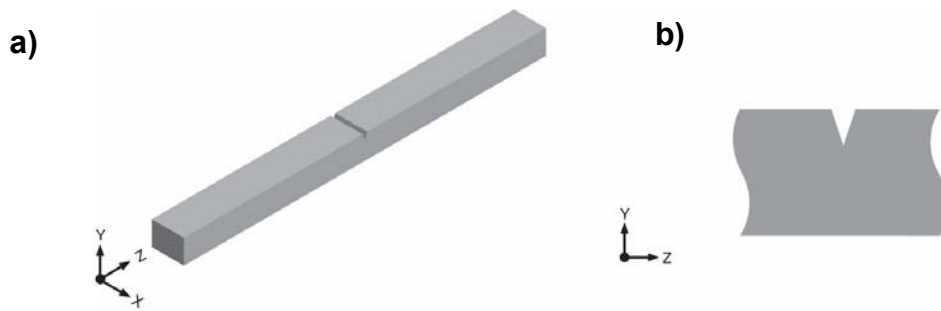
With UPLA the material is removed by direct vaporization and the heat affected zone is expected to be extremely small as compared to other techniques, provided the deposition of laser energy on the surface of the material occurs in a timescale which is much shorter than the typical time for energy transfer between electrons and lattice. Therefore, the material leaves the irradiated zone by either Coulomb or phase explosion mechanisms, depending on the density of energy of the laser on the surface [13], [14], and the rest of the material remains almost unaltered.

UPLA has been used for the production of high quality microstructures (grooves and pores) on the surface of cylindrical 3 mol% yttria (3Y-TZP) dental implants [15]. In a previous work [9], [10] we have determined the fracture toughness of this material from surface sharp notches induced by UPLA. Here the attention is focused on

1 studying the change in notch length and damage in front of notches machined under
2 different laser ablation parameters. The change in the microstructure in front of the
3 notch tip is here analysed by SEM-FIB showing that it consists mainly of a very narrow
4 short microcracked band extended in the direction of the notch. The possible influence
5 of this damage in the determination of fracture toughness is discussed.
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10 2. Experimental procedure

11 Commercial powder 3Y-TZP (grade TZ-3YSB-E, Tosoh) was cold uniaxially pressed at
12 100 MPa and sintered at 1450 °C with heating and cooling rates of 3 °C/min and 1 h of
13 maintenance, obtaining prismatic bars of 4 mm × 3 mm × 45 mm (directions X, Y and Z,
14 respectively, see Figure 1) with a density above 5.95 g/cm³ as measured by the
15 Archimedes method, and a grain size of about 330 nm. All specimens were chamfered,
16 and all surfaces were ground and polished following the standard methods up to 3 μm
17 finishing.
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Fig. 1. Schematic view of the prismatic samples and the notch configuration: a) isometric view and b) lateral view focused on the notch.

Small notches were laser machined on the XZ surface of the samples by UPLA, as pictured in Figure 1. The ablation was carried out with infrared ultra-short laser pulses (120 fs, 795 nm) along the Y-direction (Fig. 1). The system used was a commercial Ti : Sapphire oscillator (Tsunami, Spectra Physics) and a regenerative amplifier system (Spitfire, Spectra Physics) based on chirped pulsed amplification. The pulses were linearly polarized and the repetition rate was 1 kHz. The focusing system used was an achromat doublet lens with 50 mm focal length. The samples were placed on a XYZ motorized stage and moved along the X-direction. The notches for the fracture toughness determination were produced using a pulse energy of 5 μJ, scanning speed

of 50 $\mu\text{m/s}$ and four passes. In one of the samples, several notches were produced using different laser parameters in order to investigate the damage, as summarized in Table 1.

Table 1. Parameters used for the ablation of the notches (pulse duration 120 fs, wave length 795 nm, repetition rate 1KHz, spot radius 2.8 μm).

Notch Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Pulse energy (μJ)	5	5	5	5	5	5	3	3	3	3	3	3	8	8	8	8	8	8
Average power (mW)	5	5	5	5	5	5	3	3	3	3	3	3	8	8	8	8	8	8
Scanning speed ($\mu\text{m/s}$)	50	50	100	100	150	150	150	150	100	100	50	50	50	50	100	100	150	150
Number of passes	4	2	2	4	4	2	2	4	4	2	2	4	4	2	2	4	4	2
Pulses per linear micron	80	40	20	40	27	13	13	27	40	20	40	80	80	40	20	40	27	13
Energy per linear micron (mW)	400	200	100	200	133	67	40	80	120	60	120	240	640	320	160	320	213	107

Two notches, 7 and 13 of Table 1, were selected for deeper observation, since they correspond to the lowest and highest total energies delivered for producing the notch. Field Emission Scanning Electron Microscopy (FESEM, JEOL) was used for a visual examination of the notches. First, a few tens of microns were removed from the YZ lateral surface by grinding and polishing to observe the damage in the interior of the sample and to avoid any edge effect on the notch fabrication and the consequent damage.

The tomography study of the microcracked area in front of the two notches was made using a dual beam Scanning Electron Microscope / Focused Ion Beam (FIB/SEM, Neon40, Zeiss), using a Ga^+ ion column. A platinum layer was deposited on the surface prior milling to reduce the curtaining effect. Slices on the XZ plane with a thickness of 12 nm were milled using a current of 500 pA in the Y direction (Fig. 1). The volumes

involved in the study were $5.7 \times 9.3 \times 8.1 \mu\text{m}^3$ for notch 7 and $5.7 \times 25.7 \times 8.1 \mu\text{m}^3$ in the case of notch 13.

FEI Avizo software was used to stack the slices and to create a segmented surface of the microcracks. Few prior gaussian and edge-preserving filters were required in order to improve image quality and erase artifacts.

3. Results and discussion

Figure 2 shows a general view of the notches. In front of each one there is always a small microcracked band. It can be seen in Table 2 that the lengths of the notches are between $\sim 10 \mu\text{m}$ and $29 \mu\text{m}$ and that the microcracked bands are between ~ 7.3 and $24 \mu\text{m}$ in the direction of the notch. There is also a correspondence between the laser energy deposited and the dimensions of the notches and microcracked bands so that the two notches produced with the lowest and highest laser pulse energies (number 7 and 13) are also the ones with shorter and longer total damage (notch + length of microcracked band).

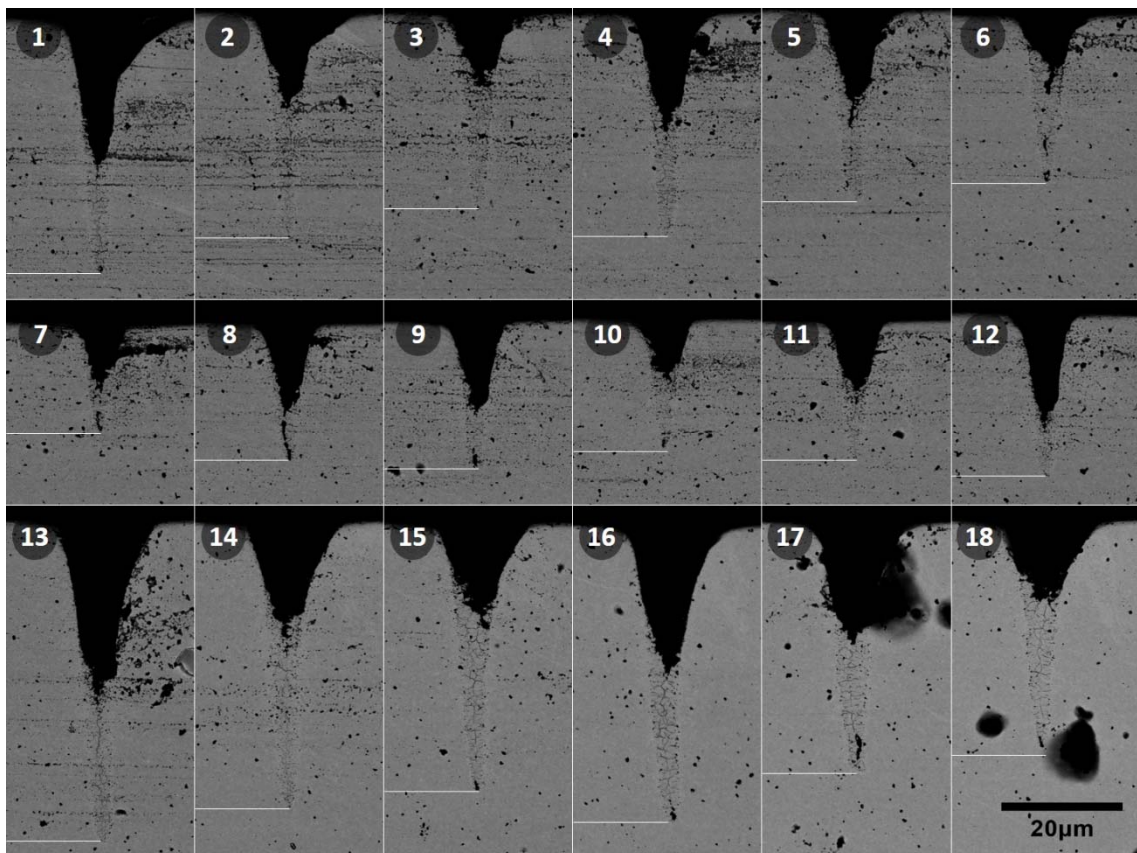


Figure 2. YZ cross section of notches, with length of microcracked band marked with a white line. The laser ablation conditions for each notch are given in Table 1.

Table 2. Summary of notch and microcracked band lengths.

Notch Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Notch length (μm)	24.1	15.5	12.1	19.4	15.3	9.0	10.8	14.3	15.0	10.4	11.6	17.9	28.7	19.2	15.5	24.4	20.2	13.2
Length of microcracked zone (μm)	17.6	21.2	20.0	17.2	15.8	18.6	7.3	8.4	9.3	11.2	11.4	9.1	24.0	27.9	28.4	24.1	20.7	24.0
Total length (μm)	41.7	36.7	32.1	36.6	31.1	27.6	18.1	22.7	24.3	21.6	23.0	27.0	52.7	47.1	43.9	48.5	40.9	37.2

Taking into account laser pulse energy, scanning speed, number of passes, pulse duration, and an estimated energy loss of 8% after the laser light passes through the focalization system (see Table 1), the total radiation energy per unit of length can be obtained and plotted as a function of notch depth (Figure 3a). As expected, the notch depth increases with the radiation energy per unit of length.

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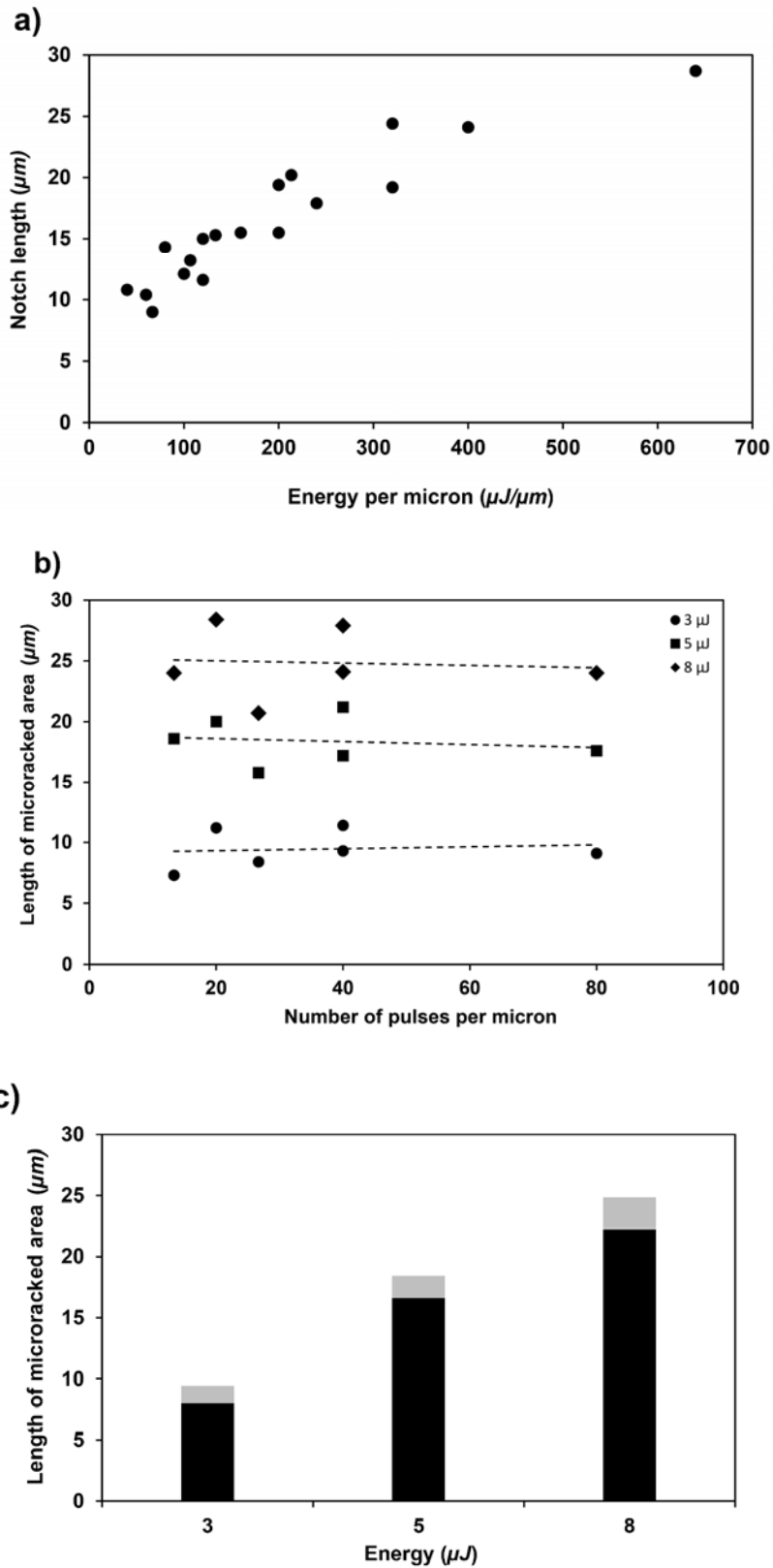


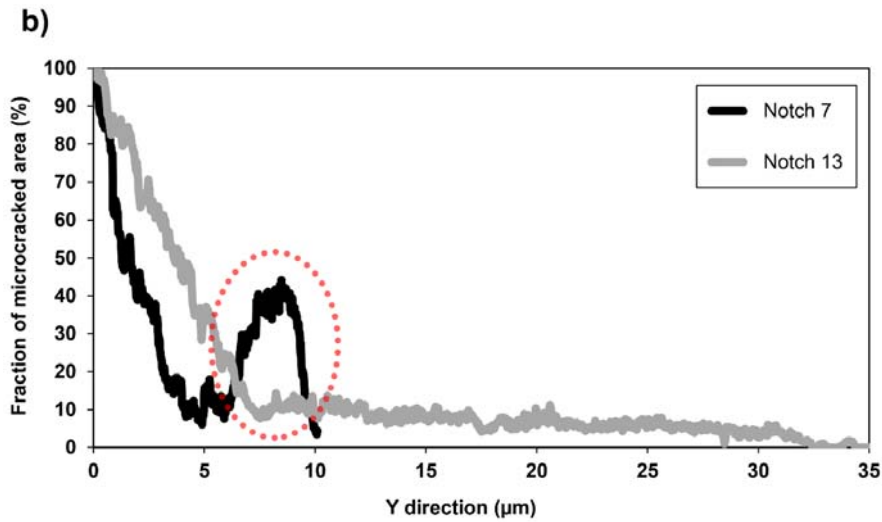
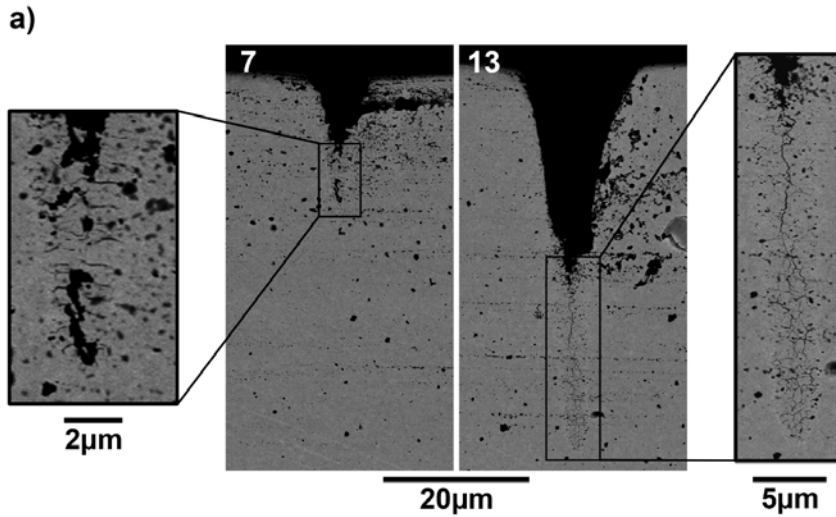
Fig. 3. a) The notch length in terms of energy per unit of length. b) The length of microcracked band in front of the notch versus the number of pulses per unit of

1 length. c) Average of length of the length of the band versus pulse energy with
2 standard deviation (in grey).
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4 However, the size of the damage in front of the notch does not depend on the total
5 energy, since it does not change with the number of pulses per unit of length. It varies
6 only with the energy of the pulse, as it can be observed in Figure 3b where the
7 microcracked band length in front of the notch is plotted in terms of the number of
8 pulses per unit length. Therefore, scanning speed and number of passes has no effect
9 on the extent of damage observed. The average extension of the microcracked band
10 length is plotted in Figure 3c in terms of the pulse energy.
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19 In Figure 4a notches 7 and 13 with their microcracked bands are shown in more
20 detail. The tomographic analysis was carried out in the slab indicated by the rectangle
21 drawn in front of the notch with dimensions of $5.7 \mu\text{m} \times 9.3 \mu\text{m}$ in the YZ plane and
22 with a depth along the X-direction of $\sim 8.1 \mu\text{m}$ in the case of notch 7. In the case of
23 notch 13 (right) the same dimensions as for notch 7 with the exception of the length in
24 the Z direction was now $\sim 25.7 \mu\text{m}$ since micro-cracking was detected up to $\sim 24 \mu\text{m}$
25 from the notch root. Two videos on the 3D reconstruction of the microcracked zone
26 are incorporated as supplementary material which gives light on the shape and
27 interconnection of the cracks.
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37 In order to compare both notches, a region of interest was defined as that which
38 encloses all the cracked region in front of the notch. The beginning is arbitrarily
39 defined as the location where the surfaces of the notch are opened by a gap of $2 \mu\text{m}$,
40 and it extends below the notch tip until no damage is detected. This was done to avoid
41 some ambiguity in the detection of the true notch tip in some notches.
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38 Fig. 4.a) Details of notch and microcracked band in specimens 7 and 13. b) Ratio of
39 cracked area along the direction of the notch.
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45 The slabs in front of the notch were sectioned along planes perpendicular to the
46 notch (plane XZ, see Fig. 1) and the cracked area in each slice was measured. The
47 fraction of cracked area detected in this way is plotted in Fig. 4b, normalised by the
48 area of the slice. At the beginning, during the first cuts, the slices contained the full
49 notch width so that practically a 100% of cracked area was found along Y direction.
50 This cracked area diminished along the Z direction very fast in the two specimens
51 studied until the notch roots were reached at ~ 5 and $7 \mu\text{m}$ from the starting slice for
52 notches 7 and 13, respectively. Below the notch root, the fraction of cracked area is
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1 very similar in both notches (~ 8%) and it decreases much more slowly in both
2 specimens. The increase observed in specimen 7, marked with a circle in Fig. 4b, is
3 related to the small hole present in front of the notch and shown in Figure 4a. The
4 cracked area disappeared at a distance from the notch root of 10 and 24 μm , for
5 specimen 7 and 13, respectively.
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10 The microcracking observed in front of the notch tip is not related to t - m
11 transformation since monoclinic phase was not detected in the microcracked band by
12 confocal Raman spectroscopy, as shown in a previous work on 3Y-TZP [9]. It can be
13 appreciated that the width of this microcracked band is very narrow (~ 2 μm for notch
14 7 and ~ 4 μm for notch 13), localised in the direction of the notch and with a high
15 density of microcracks, most of them already interconnected (see supplementary
16 material in the online version). The physical explanation cannot be related to photo-
17 thermal effects and it seems likely related to thermomechanical waves induced by the
18 laser ablation process since they are localised in the direction of the notch [16], [17]
19 without producing any detectable t - m transformation [9].
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31 Regarding the conditions for fracture toughness determination from these notches, it
32 can be seen that they are fulfilled since not only the tip radius of the notch is very
33 sharp (of less than 1 μm) but also there is a non-transformed microcracked region in
34 front of the notch so that, in principle, the total crack length can be taken as an
35 unshielded edge straight crack with a length equal to that of the notch+microcracked
36 band [5]. As the microcracked density is very high and almost all microcracks
37 interconnected (see supplementary material), it is then expected that when the load is
38 increased to fracture in a four point bending fracture test, the microcracked region will
39 coalesce and form with the notch one sole crack that under higher loads will become
40 unstable inducing failure [18]. Values obtained in previous studies by the authors in 3Y-
41 TZP using the laser parameters of notch 1 (which is energetically closer to the
42 examined notch 13; see Table 1) [9] and in Si_3N_4 [10] are in agreement with results in
43 literature in which fracture mechanics conditions for measuring fracture toughness
44 were fulfilled. As all the parameters used here produce the same notch+microcracks
45 configuration and a small tip radius, we do not expect different values in the fracture
46 toughness values obtained from these notches.
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3 Here the notch has been machined on the surface of the specimen with the intention
4 of producing very small cracks since fracture toughness of small cracks is the one that
5 controls the strength of ceramics with natural cracks and R-curve behaviour. The UPLA
6 technique can be also applied to a macroscopic starting blunt notch to make a very
7 thin sharp notch at the root of the blunt notch [19]. Similarly a microcracked region
8 would then be formed from which fracture toughness of long cracks could be
9 determined. In this case the microcracked band in front of the ablation notch would be
10 less than 1% of the the macronotch + micronotch length so that it even may be a good
11 first approximation not to take this microcracked band into consideration in the
12 calculation of the fracture toughness. In any case, it is clearly revealed on the fracture
13 surfaces after testing without the need to polish the lateral surface for its detection
14 [9], [10]. The relative small values obtained for fracture toughness of 3Y-TZP (around
15 4.1 MPaVm, see [9]), can be explained because the condition for unstable fracture for
16 small unshielded cracks makes very unlikely the exploitation of the toughening from
17 the modest and sharp R-curve present in 3Y-TZP with 330 nm grain size [20]. The
18 condition of fracture in case of the presence of R-curve behaviour is reached before
19 the crack can grow in an stable manner.
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40 **4. Conclusions**

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42 a) Ultra-short pulsed laser ablation can produce shallow surface notches on the
43 surface of 3Y-TZP with a very directional narrow microcracked band in front of the
44 notch tip and in the direction of the notch; b) the length of this band of microcracks
45 depends on the laser pulse energy but not on the total energy absorbed during
46 ablation of the notch; c) the set of parameters of ultrashort pulsed laser ablation
47 which produces a sharper notch with a very well defined band of microcracks has been
48 determined; d) the sharpness of the notch together with the length of microcracked
49 fulfill the requirements of fracture mechanics for considering the crack length for
50 fracture toughness determination as the notch length plus the length of the
51 microcracked region.
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Acknowledgements

Authors greatly acknowledge the financial support from “Ministerio de Economía y Competividad” of Spain (grant MAT2014-60720-R and the fellowship award received by MTV) and the “Secretaria d’Universitats i Recerca de la Generalitat de Catalunya (grant 2014-SGR-130), the European Commission (CREATE-Network, RISE Project N^o 644013) and to Dr. T. Trifonov for its assistance in the FIB/SEM equipment. PM also acknowledges support from Junta de Castilla y León (Project SA116U13, SA046U16) and MINECO (FIS2013-44174-P, FIS2015-71933-REDT).

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at
[URL/DOI]

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1 Fig. 1. Schematic view of the prismatic samples and the notch configuration: a)
2 isometric view and b) lateral view focused on the notch.
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4 Figure 2. YZ cross section of notches, with length of microcracked band marked with
5 a white line. The laser ablation conditions for each notch are given in Table 1.
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9 Fig. 3. a) The notch length in terms of energy per unit of length. b) The length of
10 microcracked band in front of the notch versus the number of pulses per unit of
11 length. c) Average of length of the length of the band versus pulse energy with
12 standard deviation (in grey).
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18 Fig. 4.a) Details of notch and microcracked band in specimens 7 and 13. b) Ratio of
19 cracked area along the direction of the notch.
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28 Table 1. Parameters used for the ablation of the notches (Pulse duration 120 fs, wave
29 length 795 nm, repetition rate 1KHz, spot radius 2.8 μm .
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33 Table 2. Summary of notch and microcracked band lengths.
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44 Supplementary material:
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47 Video 1. 3D reconstruction of notch 7 from images obtained by FIB tomography. The
48 microcracks connected to the main crack are marked in red, meanwhile the separated
49 cracks are shown in green.
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53 Video 2. 3D reconstruction of notch 13 from images obtained by FIB tomography.
54 The microcracks connected to the main crack are marked in red, meanwhile the
55 separated cracks are shown in green.
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Video 1

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Video 2

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