RESOLUTION OF CLOSELY-SPACED MACHINING-DAMAGE-INDUCED SURFACE CRACKS IN CERAMICS

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INTRODUCTION

Machining damage to structural ceramics is complex; a single machining crack consists of a series of continuous and overlapping semi-elliptical surface flaws between about 10 and 100 μm deep, as shown schematically in Fig. 1a. The mouths of these flaws are held closed by a layer of compressive residual stresses induced by the irreversible plastic deformations and material removal occurring during machining. Beneath the compressive layer is a zone of weak tension which separates the subsurface portions of the flaw faces. These residual stress fields permit stable crack growth to about 4.5 times the initial flaw depth prior to fracture, and are responsible for as much as a 40% reduction in material strength. Figure 1b shows a series of closely-spaced machining cracks, such as might be produced during multipoint grinding. In the absence of significant internal flaws prior to shaping, these surface cracks assume a strength-controlling role [1]. To successfully predict the failure strength of a ceramic part then, we need to determine the depth of the deepest machining flaw.

Fig. 1. Typical machining damage features (a) on a fracture surface, and (b) due to multipoint grinding.
Earlier, to characterize isolated or widely-spaced cracks, we have used a broadband acoustic pulse-echo measurement system to obtain the backscattered reflection coefficient as a function of frequency for a 2-3 cycle surface acoustic wave (SAW) pulse directed at normal incidence to the crack. Figure 2 gives the time and frequency responses for an isolated crack prepared by dragging a Knoop hardness indenter across the polished surface of a silicon nitride sample while subjected to a 4 N load. The easily detected null in the frequency response is due to interference between the longitudinal and shear components of the reflected SAW pulse; its location in frequency is a function of the total crack depth and is independent of the degree of closure due to the residual stresses \[2\]. As demonstrated in earlier work, as long as the reflected signal from an individual crack can be isolated from the signals of adjacent cracks, we can use theoretical scattering predictions to determine the crack depth to within about 10%, provided that a correction for the averaging effect of the transducer beam diameter is included in our calculations \[3,4\]. In cases where the reflected signals of adjacent cracks interfere and are not individually separable, as in Fig. 3, we can no longer use this simple approach. The frequency response is now a confusing tangle of interference-derived nulls, depth-derived nulls, and any additional spurious nulls due to the choice of gate window location and any digital filtering used on the data. The remainder of this paper develops a cepstral-analysis-based signal processing strategy which allows us to quantitatively characterize groups of arbitrarily spaced machining-damage-induced surface cracks, something which, until now, has not been possible.
CEPSTRAL ANALYSIS OF MACHINING CRACKS

Given a frequency response such as that of Fig. 3b, we would like to separate and extract the crack depth information from the periodic interference (crack spacing) information. If we were able to identify the lowest frequency depth-derived null in the group, we could predict the depth of the deepest, and thus potentially strength-controlling, flaw in the group. By means of the following cepstral-analysis-based signal processing scheme, we can, in fact, do just this.

As a simplified illustration, consider the case of an isolated crack with a time response $f(t)$ and frequency response $F(f)$ superimposed with itself offset by a distance $\tau$ in time (corresponding to a physical separation of $V_R \tau/2$, where $V_R$ is the Rayleigh wave velocity in the ceramic). For large $\tau$, the individual crack signals can be gated and Fourier transformed to obtain the desired depth-derived null frequency. For smaller $\tau$, the signals interfere in both time and frequency, and we are now forced to consider the combined frequency response $G(f)$ of the function $g(t) = f(t) + f(t - \tau)$:

$$G(f) = \int_{-\infty}^{\infty} [f(t) + f(t - \tau)] e^{-i2\pi tf} dt$$

$$= F(f) + e^{-i2\pi Tf} F(f)$$

$$= 2e^{-i\pi Tf} \cos \pi f \ F(f)$$

which, in terms of magnitude, can be written

$$|G(f)| = 2 |F(f)| |\cos \pi f| \tag{1}$$

For the combined time response of the two cracks then, we find that the magnitude of the FFT will contain, in addition to the null due to the crack depth, an odd harmonic series of interference-derived zeros located in frequency at $(2n + 1)/2\tau$, where $n = 0, \pm 1, \pm 2, \ldots$. To remove these periodic interference-derived nulls, we can employ cepstral analysis.

From [5-7], the amplitude cepstrum can be defined as the inverse Fourier transform of the logarithm of the magnitude of the frequency spectrum $H(f)$ of a time signal $h(t)$, and can thus be written

$$C(q) = \int_{-\infty}^{\infty} \{\log_e H(f)\} e^{i2\pi qf} df \tag{3}$$

where $q$ is the quefrency, identical to the time $t$. The words "cepstrum" and "quefrency" are obtained by rearranging the letters in "spectrum" and "frequency," respectively. Other terms of interest appearing in cepstral analysis literature, which we will define below, include
Fig. 4. (a) Time response of a 40 µm crack analytically superimposed with itself, offset by 50 ns; (b) FFT of (a); (c) amplitude cepstrum; (d) short-pass liftered amplitude cepstrum; (e) inverse Fourier transform of (d);

"rahmonics" (from "harmonics") and "short-pass lifter" (from low-pass filter).

To remove the interference nulls from Eq. (2), or from the frequency response of a group of cracks, as in Fig. 3, we compute the cepstrum. Since we have taken a logarithm, signals multiplied in the spectrum are
Fig. 5. (a) Digitally low-pass filtered time response of three cracks: 400 g, 0 ns offset from time zero; 55 μm 35 ns offset; 40 μm, 50 ns offset; (b) FFT of (a); (c) amplitude cepstrum; (d) inverted short-pass liftered cepstrum; note that the null for the 40 μm crack is suppressed.

now additive in the cepstrum, where they can be easily identified and subtracted. Performing an inverse Fourier transform on an appropriately edited cepstrum will thus give us back the frequency spectrum without any interference-derived nulls, which is exactly what we are looking for. This approach is illustrated in Fig. 4 where, paralleling the discussion leading to Eq. (2), the time response of an isolated 40 μm crack has been analytically superimposed with itself, offset by 50 ns. Since the interference-derived nulls in the frequency spectrum form an odd harmonic series, the corresponding "rahmonics" in the amplitude cepstrum of Fig. 4c alternate in sign (for an even harmonic series they would all be positive); the separation of 50 ns corresponds to the time offset between the cracks. By subtracting the rahmonics from the cepstrum and performing an inverse FFT then, we can, in fact, obtain the crack frequency response without any of the interference-derived nulls. This is done rather crudely in Figs. 4d and 4e by applying a "short-pass lifter" consisting of a sine-squared window to bring the cepstrum smoothly down.
Fig. 6. Inverted short-pass liftered cepstrum of the group of grinding cracks in Fig. 3.

to zero over the interval from about 28-48 ns in quefrency. We could also have used a more elegant "comb" lifter and removed only the rahmonic spikes from the amplitude cepstrum [6]. Fortunately, as it turns out, nearly all of the crack depth information is found in the first 40-60 ns of the cepstrum, so that simply discarding all of the higher quefrencies has only a small effect upon our ability to recover the depth-derived null.

To understand how cepstral analysis may be applied to the much more complex case of actual grinding damage, consider the example of Fig. 5, in which we have analytically superimposed the time response of a 55 μm crack between that of two 40 μm cracks. A digital low-pass filter has been used to remove the high frequency electronic noise from the data. In the frequency response, we do not know a priori which nulls are due to crack depths or to interference. Since the 55 μm and 40 μm cracks are not carbon copies of each other, the interference between them is less pronounced; consequently, the rahmonics in the cepstrum are less well defined. Interference between the various rahmonics and, in the case of real machining damage, the effects of attenuation losses (attenuation causes the rahmonic series to decay exponentially with increasing quefrency), all contribute to a loss of crack spacing information. In addition, the rahmonics at 15 and 35 ns (corresponding to the distances between the 55 μm crack and each of the two 40 μm cracks) occur within the region of the cepstrum containing the crack depth information. Thus, in the inverted cepstrum, while we can guarantee that any nulls below about 45 MHz are entirely due to crack depth information, we cannot entirely remove the effects of interference. In Fig. 5d then, we see clearly the null due to the deepest crack, and to the right, the suppressed remains of two residual interference-derived nulls. As in the frequency spectrum, the nulls from the 40 μm cracks are dominated by the response in the deepest (potentially strength-controlling) 55 μm crack.

As a final illustration, Fig. 6 shows the result of applying the technique to the actual grinding damage signal of Fig. 3. The null corresponding to the deepest flaw is easily found. In this case, as with most other grinding damage examined, very little position information can be extracted from the cepstrum. However, by shifting the initial time domain window to include data from different overlapping portions of the sample and then observing the appearance and disappearance of this null as a function of position, we can, with some effort,
still determine the flaw location. For very closely-spaced cracks (separation of less than 25 μm), all of the interference-derived nulls will be above 45-50 MHz (see Eq. 2). In this case, cepstral analysis is not required, since any lower-frequency nulls will be depth-derived.

CONCLUSIONS

By means of a cepstral-analysis-based signal processing scheme, it is now possible, for the first time, to evaluate groups of closely-spaced machining-damage-induced surface cracks. Although it may not always be possible to identify the locations of specific cracks, the depth of the deepest (potentially strength-controlling) crack can always be found. Since the depth-derived nulls in the inverted edited cepstrum are less distinct than in the FFT, the nulls for the deeper cracks tend to dominate and obscure those of shallower cracks. This loss in frequency resolution contributes to an increase in depth prediction error to about 20%, as opposed to about 10% for isolated or widely-spaced cracks. Application of this technique is limited by the long time required to process the data, currently about ten to twenty minutes per point on the sample surface.

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REFERENCES