Screeching sound of peeling tape

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The screeching of peeling tape is a familiar albeit annoying sound. However, despite decades of study, its source has remained elusive. Herein we demonstrate that this sound is produced by a discrete train of weak shocks emanating from the fine fractures which travel supersonically with respect to the surrounding air, in the transverse direction within the detaching adhesive. Each sound pulse is generated when a fracture tip reaches the edge of the tape. We verify this using two microphones synchronized with clips from two simultaneous high-speed video cameras, one observing the fracture motions in the adhesive through the transparent substrate, while the other captures schlieren imaging of the shock fronts in the air.

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I. INTRODUCTION

The peeling of adhesive tape from a solid surface is known to progress with a stick-slip mechanism. Indeed, numerous studies investigated the chaotic trajectory of these motions and the associated pulling forces [1–7], which is important for disparate phenomena, such as fracture mechanics, triboluminescence, and earthquake dynamics. However, the early studies missed a crucial aspect of the slip mechanism, which relies on a sequence of transverse cracks which can travel supersonically, relative to the air, across the width of the adhesive under the tape as it detaches from the solid substrate. Each slip phase progresses through dozens of these transverse fractures before reaching the slow stick phase. The modeling of the physics of this stick-slip mechanism was therefore pursued in the wrong physical dimension. Thoroddsen *et al.* [8] identified this microfracture phenomenon using ultrafast video imaging, at 1×10^6 frames per second (fps), to capture the supersonic motions of the 220-µm-wide fracture bands. Subsequent studies [9–14] characterized the size of the fracture bands from the bending stress in the tape. The related phenomenon of triboluminescence is of great interest, which can even generate x-rays, when the tape is peeled under vacuum [15].

The following question remained: How is the screeching sound produced? Thoroddsen *et al.* [8], who observed elastic waves traveling up the detached part of the tape, speculated that these waves acted as the source of the sound. These waves along the tape are promoted by the tip of the fractures, as shown in Video 4 in their Supplemental Material [8]. On the other hand, Marston *et al.* [16] demonstrated a direct correspondence between the sound produced and the transverse fractures, showing identical numbers of sound pulses as the number of fractures during each slip phase. The nature of the sound is therefore more discrete than would be expected from the periodic oscillation of a ribbon of the detached tape. However, Marston *et al.* [16] did not identify the actual mechanism of the sound generation or where these sound pulses emerge from. This is the focus of the present study. One possibility is that the sound is directly generated by the rapidly moving tip of the fracture, as it moves supersonically, with respect to the air, from one side of the tape to the other. Therefore, besides forcing elastic waves in the tape, this could also directly produce the discrete sound-wave pulses. To clarify this mechanism, we have herein performed simultaneous high-speed imaging of the fractures and the sound waves in the air, using two video cameras, which are in addition synchronized with two microphones, to pinpoint the origin of the pressure pulses.

II. EXPERIMENTAL SETUP

The experimental setup is sketched in Fig. 1, with a more detailed drawing in the Supplemental Material [17]. We use 19-mm-wide Scotch tape, which is rapidly detached from a 20-mm-thick glass plate, wedged in a heavy stainless-steel support structure to minimize substrate motions during the peeling. This is accomplished by manually pulling the tape

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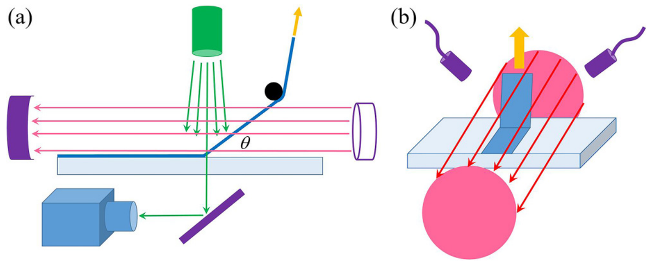

FIG. 1. Sketches of the experimental setup. (a) Side view with the bottom-view camera. (b) Front view with the collimated schlieren light shone along the glass plate and the placement of the two microphones, positioned one on each side of the tape. More detailed drawing and photographs are included in the Supplemental Material [17].

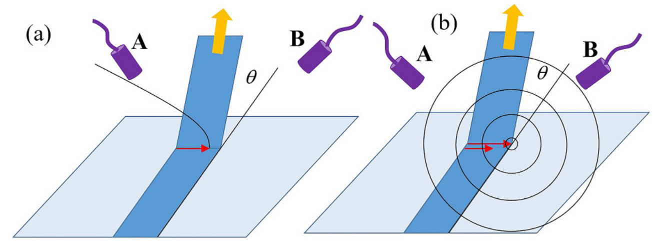

FIG. 2. Sketches of the two proposed competing sound generation mechanisms. (a) The tip of the supersonic crack produces a shock wave into the air. (b) The actual observed mechanism, where the sound shocks are generated when each crack reaches the edge of the tape.

upward while using a transverse metal rod to guide the motion of the tape and maintain nearly a constant pulling angle of $\theta \simeq 45^\circ$ with small angular variability of $\Delta\theta < 2^\circ$, as described in [8]. The discrete pressure and density fluctuation associated with the sound waves traveling in the air are captured with a schlieren setup, using two large concave mirrors and a horizontal knife-edge to image the spatial density gradients with time. The motion of the acoustic wave is recorded with an ultrahigh-speed video camera (Kirana-05M, Specialized Imaging, UK) at frame rates up to 2×10^6 fps. To minimize motion smearing, we use illumination from pulsed laser diodes (SI-LUX640, monochromatic red light $\lambda = 640$ nm) with a pulse duration of 100 ns in each frame. The light passes through a pinhole to produce a point source, which is then collimated by the concave mirror into a beam passing through the test volume next to the detaching tape. A second concave mirror focuses the light with a knife-edge at its focus. The details of the transverse fractures in the adhesive under the detaching tape are recorded by a second high-speed camera (Phantom V2512), looking up through the glass substrate, with continuous white lighting shone from the top. The short duration of the Kirana video clips (180 frames) required a dedicated image line trigger (SI-OT3), where a light beam is cut by the advancing detached section of the tape. In some recordings an image trigger in the Phantom sensor was used instead. The corresponding sound is recorded with two identical high-definition microphones (Earthworks M30, with a sensitivity of 34 mV/Pa and flat frequency response up to 30 kHz) placed on opposite sides of the Scotch tape. This allows us to compare the arrival time of the sound waves to the two microphones, to clarify their origin. The sound signals are recorded at 192 kHz using a Tektronix DPO7254 Digital Oscilloscope, at twice the frame rate of the bottom Phantom video camera.

III. EXPERIMENTAL RESULTS

The multisensor setup allows us to pin down the relationship between the supersonic cracks in the adhesive and the discrete sound pulses detected by Marston *et al.* [16]. The cracks travel transversely through the tape starting at one edge, with the sequence of cracks moving in the same direction, as sketched in Fig. 2(a). The original working hypothesis was that the supersonic tip of the crack would send out a sound front which would first reach the microphone closer to the start of the crack. The exact opposite was observed. The microphone closer to the end point of the crack saw the sound pulse first, as sketched in Fig. 2(b). Simultaneous imaging of the transverse cracks, through the bottom glass, with the synchronized sound recordings from the two microphones, is shown in Fig. 3. The tape detaches in a stick-slip fashion, with an extended stick phase, which leaves dark lines in the detached tape, separated by a rapid slip phase which consists of a sequence of approximately 220-μm-wide transverse fractures. These fractures are visible in the frame in Fig. 3(a) by the narrow dark lines near the detachment front, traveling in the direction of the red arrow. The whole sequence of stick-slip phases is also shown in Video 1 in the Supplemental Material [17]. The corresponding sound traces from the two microphones are shown in Fig. 3(b). Here the rapid slip phases show large sound spikes, while the signal in the intermediate stick phases is weak, near the background noise. The close-up in Fig. 3(c) shows that the characteristic pressure spikes only appear in one of the microphones, verifying that the source of the sound pulses occurs at the end of the cracks, where they exit the side of the tape. In this case the rms intensity of the signal on the right-side microphone is 1.9 times larger, even though the distance is only slightly shorter.

Furthermore, the schlieren high-speed video captures a sequence of weak shocks emerging from this location at the edge of the tape, as is shown in the enhanced video frame in Fig. 4 (see also Video 2 in [17]). It is telling that no density fluctuations are visible in the regions between the shocks. These isolated shocks move slightly above the speed of sound, which we measure from the video frames at $u = 355 \pm 2$ m/s, which is 4% larger than the speed of sound $c = 342$ m/s at 20 °C, or Mach 1.04. While the transverse fractures propagate at velocities between 250 and 600 m/s, in this study they still remain subsonic relative to the adhesive's Rayleigh wave speed ($c_R \approx 900$ m/s for acrylic adhesive), which did not reach the criterion $0.4c_R$ required for the microbranching instability [18]. This speed of the weak shocks is conservative, relying on the motion being perpendicular to the viewing direction, assuming a spherical sound front. No shock fronts are visible on the other side of the tape. In some isolated cases, the fractures will start near the center of the tape and travel in both directions, reaching both edges of the

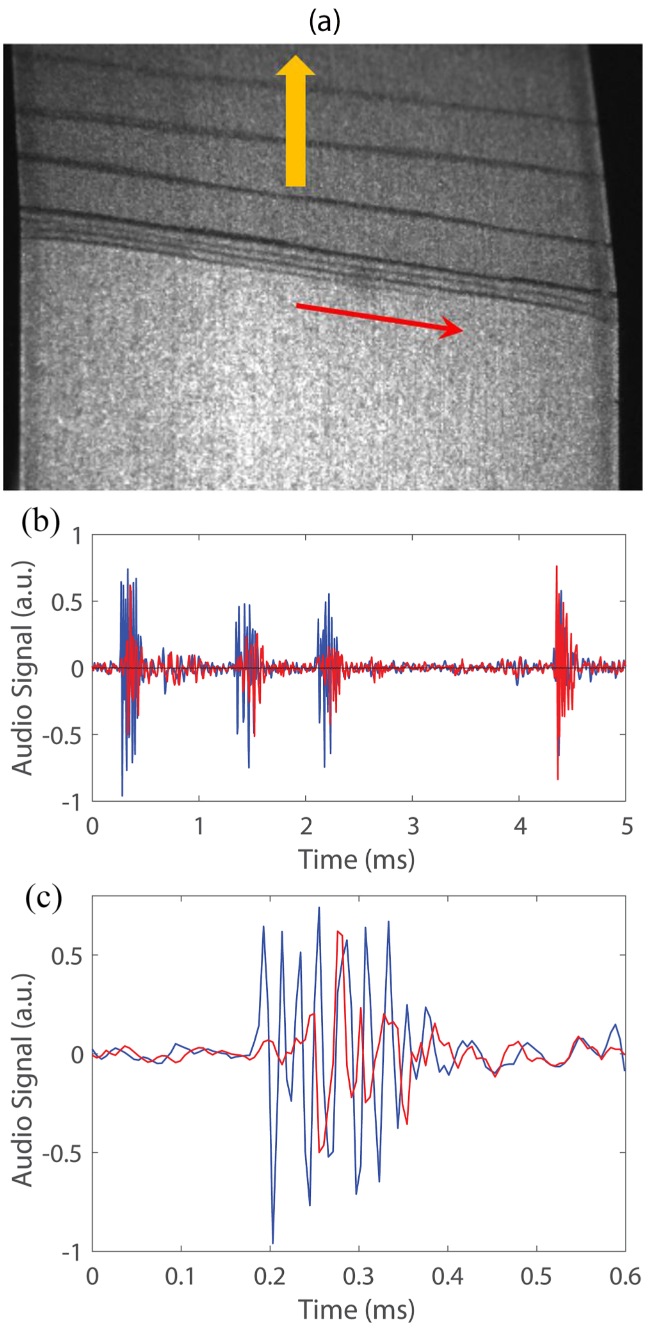

FIG. 3. Simultaneous video capture and sound recordings during a typical rapid stick-slip peeling of the tape. (a) Video frame taken through the bottom glass plate, showing typical transverse fractures traveling from left to right as indicated by the red arrow. The orange arrow shows the pulling direction of the detached section of the tape. For scale, the attached part of the tape is 19 mm wide. The frame is taken from a 96 011 fps video clip, which is included in the Supplemental Material [17]. (b) Audio signals from the two microphones, positioned one on each side of the tape. The blue curve corresponds to the microphone closer to the right edge of the tape, where the fractures end, while the red curve is for the one on the left side. (c) Close-up view of the first slip phase in (b).

tape. Weak shocks then appear on both sides. Figure 5 shows that the amplitude of the sound is a strong function of the

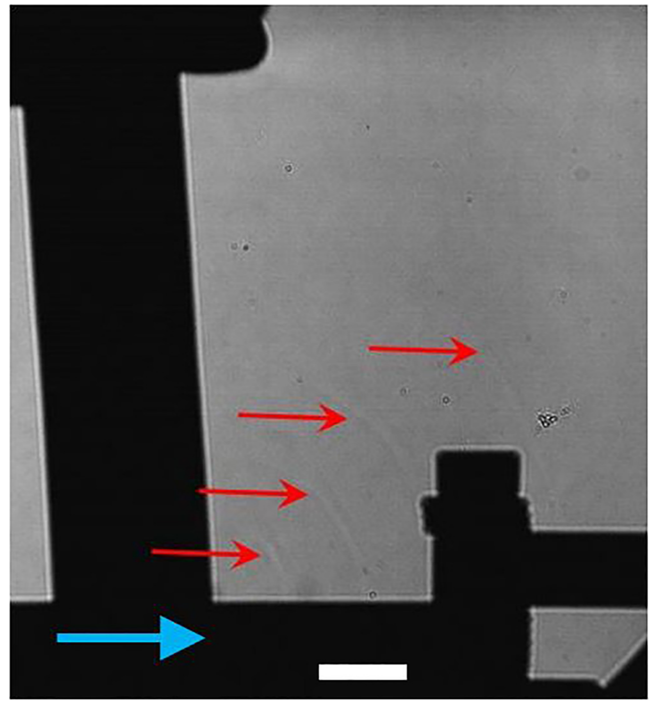

FIG. 4. Schlieren frame from a high-speed video clip, taken at 2 000 000 fps with a 100 ns exposure. It shows four weak shock fronts (marked by the red arrows) emerging from the right side of the tape. The fractures are traveling from left to right as indicated by the cyan arrow. Their frequency of appearance here is approximately 37 kHz. See also Video 2 in the Supplemental Material [17]. The white scale bar is 10 mm long.

speed of the crack tip, which is determined simultaneously from the bottom view camera.

The duration of the typical slip phase, with the transverse cracks, is about 0.5 ms, in which a sound wave can travel 0.17 m. In the large room used for the experiments, this should exclude any reverberations from the walls, interfering with these results.

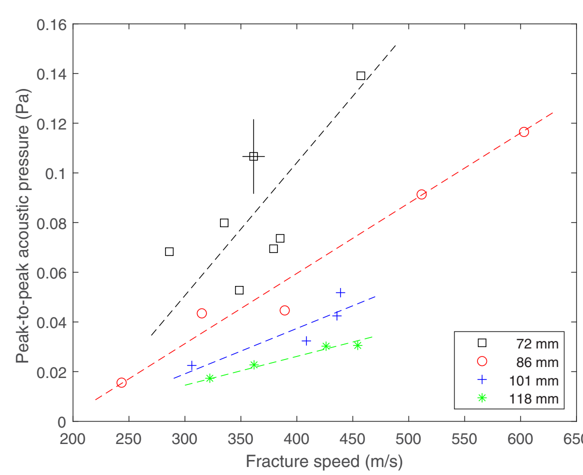

FIG. 5. Peak-to-peak sound pressure vs the observed fracture speed, measured with the microphone at different distances from the edge of the tape.

Why are the shocks generated when the cracks reach the end of the tape? Here the fact that the tip moves supersonically plays a key role. This implies that a partial vacuum is produced between the tape and the solid when the crack opens. The crack moves too fast for this void to be filled immediately, even though air is sucked in from the direction perpendicular to the crack. The void therefore moves with the crack until it reaches the end of the tape and collapses onto the stationary air outside. The speed of the fractures in this work is in the range 250–600 m/s, i.e., Mach numbers Ma in the air are in the range 0.7–1.8. We are thereby clearly in a regime where compressibility will be significant, as such compressibility effects are often assumed to start at Ma $\simeq 0.3$. With reference to the above point, we are indeed discussing a partial vacuum, which becomes progressively stronger with larger Ma-number values. The void fills at the speed of sound generating a dynamic pressure of $\rho c \Delta v = 9600$ Pa, where Δv stands for the velocity of the air rushing into the void, here taken as the mean speed of the front in the slip phase. The void is originally only $h \sim 200$ µm in size, but closes up in $t_c = h/c \simeq 0.6$ µs, which causes a very sudden pressure pulse, thereby producing the discrete sound, which we perceive as the annoying screech. Extrapolating the measured pressures to the source, assuming $p \sim 1/r$, we get an impulsive pressure at an original impulse dimension of 1 µm as high as 5000 Pa, of the same order as observed. Keep in mind that while the area of the spherical wave grows proportionally to $1/r^2$, the flux of energy is proportional to $p^2 \sim 1/r^2$.

One can form an alternative explanation based on the motion of the tape when the fracture reaches the edge. The gradual arc of the fracture band near its tip is shown to be about five times its width δ [8]. The sudden detachment of the tape from the solid at an angle of 45° therefore takes a time of $T \simeq 5 \times \delta/v_{\text{fract}}$. The tape therefore moves from the solid to an average distance of $\delta/2$ at a velocity of $\xi' = 0.1 \times v_{\text{fract}}$. The sound wave generated by this boundary motion $\xi' = B/r^2$ has an intensity $B = \xi' \times (\delta/2)^2 = 5.4 \times 10^{-7}$ m^3/s. The corresponding pressure at a distance of 72 mm (Fig. 5) is predicted as $p = \rho_{\text{air}}(B 2\pi f)/r^2 = 37$ Pa, which is much larger than observed, supporting the former mechanism of the void cavity collapse. The finer details of the sound generation mechanism, at the edge of the tape, will thereby require further study.

In our experiments we rapidly pull the tape manually. The pulling angle is constrained by a horizontal rod, making it close to constant at $45^\circ \pm 2^\circ$, during the short distance used in the close-up imaging, which takes less than 100 µs. We believe the small variation in angle and pulling velocity has no effect on the nature of the sound-generation mechanism. Future work using mechanical pulling, like the ingenious machine developed by Dalbe *et al.* [11,12], where the angle and pulling velocity are maintained constant, could be used to investigate this over longer pulling distances.

IV. CONCLUSION

Herein we have shown that the screeching sound of peeling tape consists of a train of weak shocks that are generated when the transverse fracture bands, in the slip phase [8], reach the edge of the tape. We used two microphones and two synchronized high-speed video cameras to simultaneously track each fracture band, in a bottom view, revealing that when they reach the edge of the tape they produce a shock front in the air, which we visualized with a separate schlieren system. The elastic waves traveling in the detached tape could also produce some sound, but our imaging results showed clearly that the train of weak shocks overpowers any such contributions.

Note added. During the early phase of this study, one of the authors, Ravi Samtaney, passed away.

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DATA AVAILABILITY

The data are available from the authors upon reasonable request.

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[17] See Supplemental Material at https://link.aps.org/supplemental/10.1103/p19h-9ysx for details, which includes a sketch and a photograph of the experimental setup, as well as two video clips. The first showing the stick-slip motions from the bottom and the second the weak shocks in the air, using schlieren imaging.

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