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Materials science and metallurgy of the Caribbean steel drum

Part I *Fabrication, deformation phenomena and acoustic fundamentals*

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Steel-drum fabrication, especially the sinking of the drum head (also referred to as the "pan") by hand with a hammer, has been examined in detail utilizing light metallography (LM) and transmission electron microscopy (TEM) to characterize residual microstructures corresponding to reductions in thickness of up to 50% at the bottom of the drum head. Dislocation densities in the low-carbon (0.01–0.05 wt % C), ferritic steels can exceed 10^{10} cm^{-2}. Simulations of simple, ideal, free circular notes utilizing 316 stainless-steel plates (0.05 wt % C), cold rolled to reductions up to 40%, revealed that deformation (per cent cold reduction) has an important effect on the acoustic spectrum, especially harmonic spectra. Harmonic-node splitting was observed for thin circular plates (0.076 cm thick); the frequency difference was 60 Hz at 20% cold reduction and 160 Hz at 40% cold reduction. These dispersion effects, due to deformation-induced microstructures, as well as irregularities in the note geometries and thicknesses, point to the complex and non-linear acoustic features that contribute to the unique sounds of the Caribbean steel drum.

1. Introduction

The musically tuned Caribbean steel drum (or pan) is not only the most unique musical instrument developed in the twentieth century but is probably one of the most unique musical instruments ever developed [1, 2]. Its origin involves a complex evolution of percussive rhythm instruments in carnival street bands in Trinidad and Tobago. Early rhythm steel drums were made from paint or bakery tins, in which it was discovered that three–eight bulges of different sizes in the bottom of a tin could produce sounds of various pitches. During the Second World War, leftover 55-gallon oil drums (from British and USA forces) on the island of Trinidad were often cut in two and used as dustbins. These dustbins began to replace bakery tins as musical instrument platforms, and around 1946 Elliott (Ellie) Mannette changed the design by pushing the drum head inward (concave) and placing convex (outward) notes on the domed surface. Shortly thereafter, Bertie Marshall discovered the harmonic-tuning process, which creates the modern and unique sound of the Caribbean steel drum [3, 4]. For more than 50 years, the commercial "55-gallon" steel drum has evolved as a musical instrument from a single multipitched percussion instrument to a multiharmonic, chromatic tone instrument, which currently emulates nine orchestral voices covering tonal ranges from A_1 to F_6 (essentially the middle-five octaves of a grand piano: 55–1397 Hz, respectively). Drum heads contain from three to 32 notes in patterns that, like the instrument itself, have evolved by intuition, trial and error, and often by sophisticated and unsophisticated experimentation involving variations in construction procedures, especially metal working and tuning. However, there has been little or no control of the metallurgical issues, and few systematic experiments have been carried out to examine commercial steel-drum components from a materials-science perspective. Also, the connection between the unique acoustical properties and the metallurgy and materials science of the Caribbean steel drum has thus far not received proper attention.

The acoustics of the steel drum have been studied recently by Hansen *et al.* [2], Hampton [5] and Rossing *et al.* [6]. Especially significant have been time-average holographic interferometry studies, which make it possible to visualize the mode patterns along with coupling effects of the note zones [5, 6]. The fact that all the notes exist on the same drum head or acoustic platform provides for complex, non-linear coupling. For example, when one note having a specific fundamental frequency is struck, other notes having equivalent octaves

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or harmonic frequencies are excited. These excitations increase with amplitude, and at typical percussion amplitudes nearly the full drum surface can vibrate and radiate unique sound.

Many notes on a drum head are irregular in shape as well as thickness. Consequently, the vibrational phenomena are completely non-linear. There is nothing known about the effect of deformation and especially

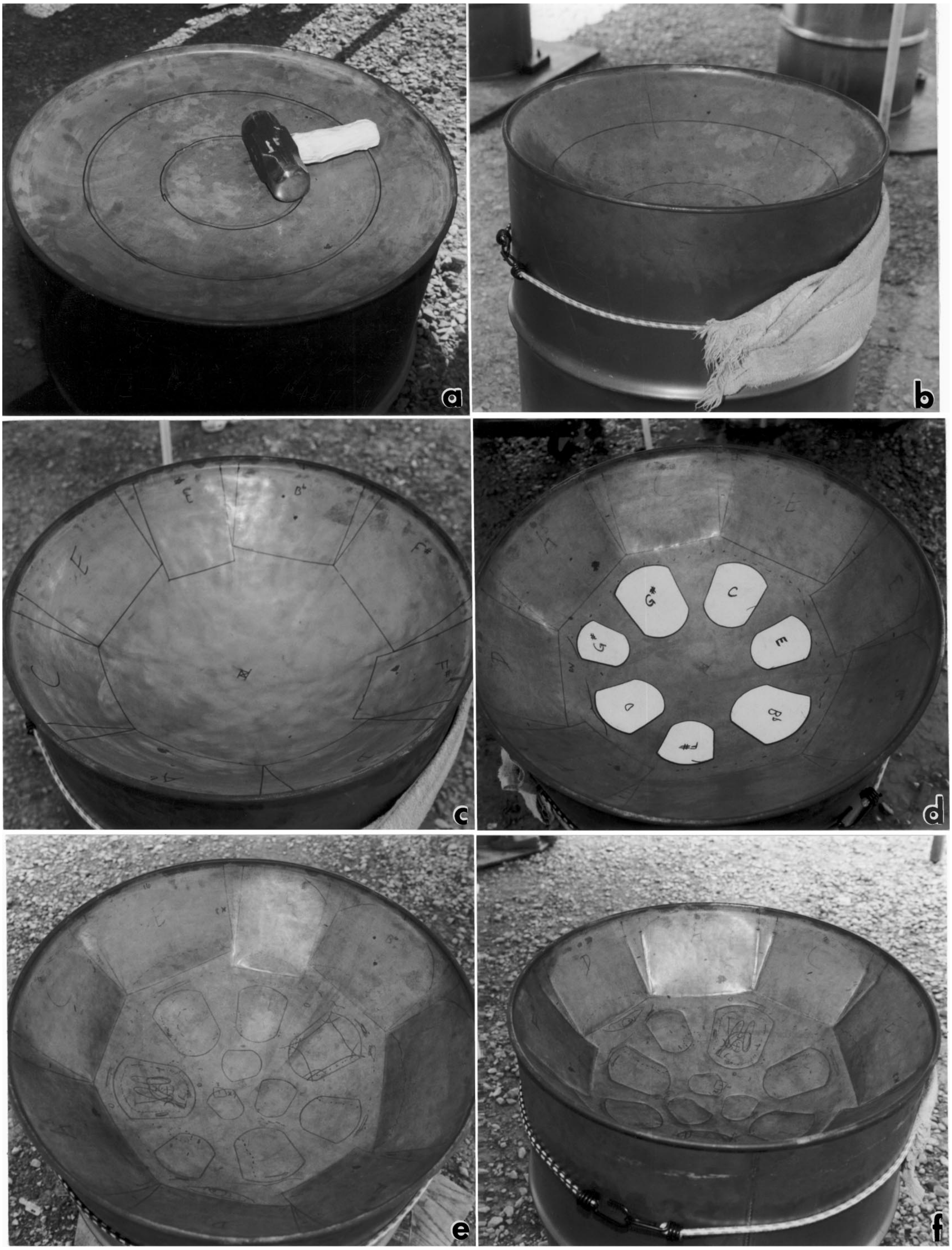

Figure 1 Caribbean steel-drum-fabrication sequence showing the specific process generally used for higher-pitch drums, such as leads, double-seconds and double tenors: (a) Concentric circles are drawn to mark out approximate note zones and aid in shaping. A 2.7-kg sledge hammer shown is used to sink the drum head. (b) Sunken drum head (to a depth of about 19 cm) showing the spiral-type motion used to keep the shape close to a uniform, concave hemisphere. (c) Sunken drum head with upper notes scribed. (d) Upper notes are formed and middle-note patterns placed for scribing. (e) All notes placed and formed for a left double-second drum. (f) Grooving around all notes to provide partial acoustic isolation using a flattened punch. Following this process, the notes are dented upward (convex), sometimes from the back of the drum head, with the height of the dent levelled to another hemispherical surface plane. The drum head is then cut from the drum sides leaving a requisite skirt length, *s*, and then heat treated and smoothed prior to tuning of individual notes.

crystal imperfections in the note zones on the vibrational spectrum or timbre. In addition, there are apparently no systematic studies of the effects of heat treatment on the development and tuning of notes.

In the research to be presented in Part II of this paper, we have examined the process stages in the development of a steel drum and systematically examined numerous drum compositions and microstructures as well as various annealing schedules and their effect on microstructures. Residual drum-hardness profiles and hardness features of individual note zones have also been developed and compared along with some fundamental studies of the effects of deformation on sound spectra. This research represents the first comprehensive, technical characterization emphasizing metallurgical issues involved in the fabrication and harmonic tuning of the Caribbean steel drum (the Trinidad and Tobago steel pan).

2. Discussion

2.1. Deformation issues in Caribbean steel-drum fabrication

Steel-drum fabrication involves a complex process, which may vary depending on the orchestral voice of the drum to be built and on the builder's fabrication procedure. The fabrication procedure of the higher-frequency steel drums (lead, double-second and double tenor) is summarized in the following specific process features or components:

1. sinking or doming the drum bottom (lid) into a nearly concave hemisphere to a depth of 17.8–20.3 cm from the surface plane using a sledge hammer;
2. placing the notes on the concave drum surface;
3. forming the notes as convex ellipsoids on the drum surface within the note zones;
4. grooving an outline for each note to partially isolate its acoustics, and leveling these convex "dents" to the same secondary hemispherical line;
5. heat treating the drum surface to create a strain relief;
6. smoothing the grooved edges of the notes by hammering the zones adjacent to the grooves;
7. tuning the strain-relieved notes to characteristic fundamental frequencies, f (tonics), near the note centres and to at least one octave ($2f$) and one harmonic ($3f$) for each note.

Fig. 1 illustrates the process sequence from 1 to 4, from the sinking of the drum surface by spiral-type sledge hammering, shown in Fig. 1a and b, to the grooving of the notes using a flat punch (0.64 cm diameter) placed over each circumference and indenting the surface by roughly 10–15% (Fig. 1f). As shown in Fig. 1a, circles are drawn on the drum surface representing roughly the note zones and acting as guides in the sinking process, shown completed in Fig. 1b. The drum shown in Fig. 1 is intended to be a left double-second (there are two double-second drums: a left and a right); and the outer (lower fundamental frequency) notes are placed as shown in Fig. 1c. The mid-range frequency notes are shown in patterns on the surface in Fig. 1d,

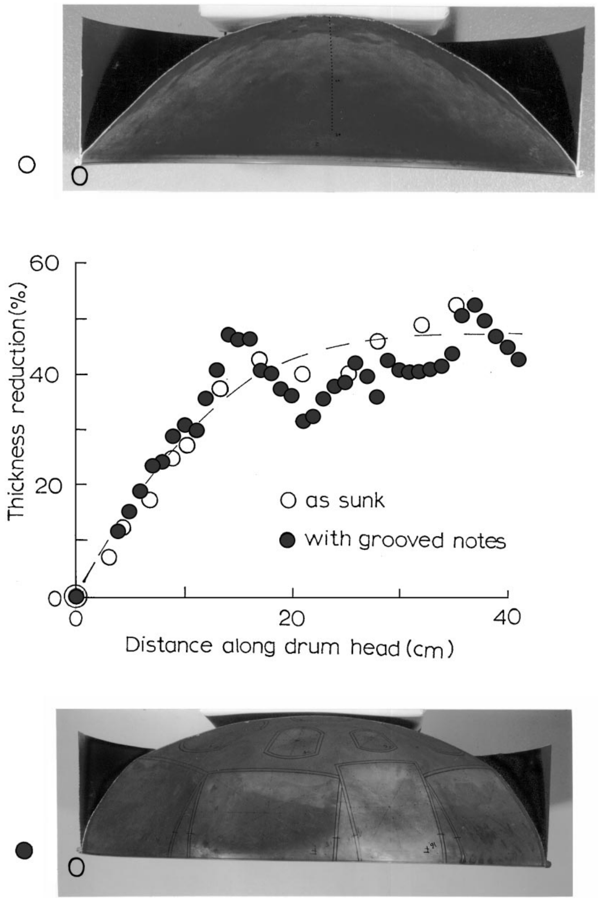

Figure 2 Per cent reduction in drum-head cross-section (thickness) for an initially sunken drum (open circles) and an identical drum head after placing notes and denting them (solid circles).

while Fig. 1e shows the fully patterned drum head (containing 18 notes). Fig. 1f shows the fully grooved and convex notes prior to heat treatment. During tuning, and following the heat treatment (to be described in detail in Part II), the notes are further shaped by glancing hammer blows near the note edges to manipulate the elastic properties of the metal membrane.

Fig. 2 shows the measurements of per cent reduction for several comparable drum thickness cross-sections (with reference to processing shown in Fig. 1b). The data recorded in Fig. 2 represent a sunken drum head, as in Fig. 1b, and a fully patterned, heat-treated and partially tuned drum; illustrating that the reductions in thickness vary non-linearly from the drum-head perimeter (at essentially no thickness reduction) to the drum bottom, where the reduction is roughly 50%. As noted above, the grooving around individual notes can reduce this cross-section by another 10–15%; consequently the maximum engineering strain in the grooved cross-section would be expected to be around 65% at the bottom of the drum, which contains the highest pitch (frequency) notes (see Fig. 1f). There is usually no processing (or deformation) of the drum sides (or skirt, as it is called). The drum head (lid or bottom) is usually 18 gauge (1.15 mm thick) low-carbon steel having a composition and gauge thickness different from the drum sides or skirt (where the 20 gauge thickness is 0.9 mm). The drum-head composition in Fig. 2 was 0.01% C, 0.03% P, 0.11% Mn, 0.02% Cr and less than 0.01%

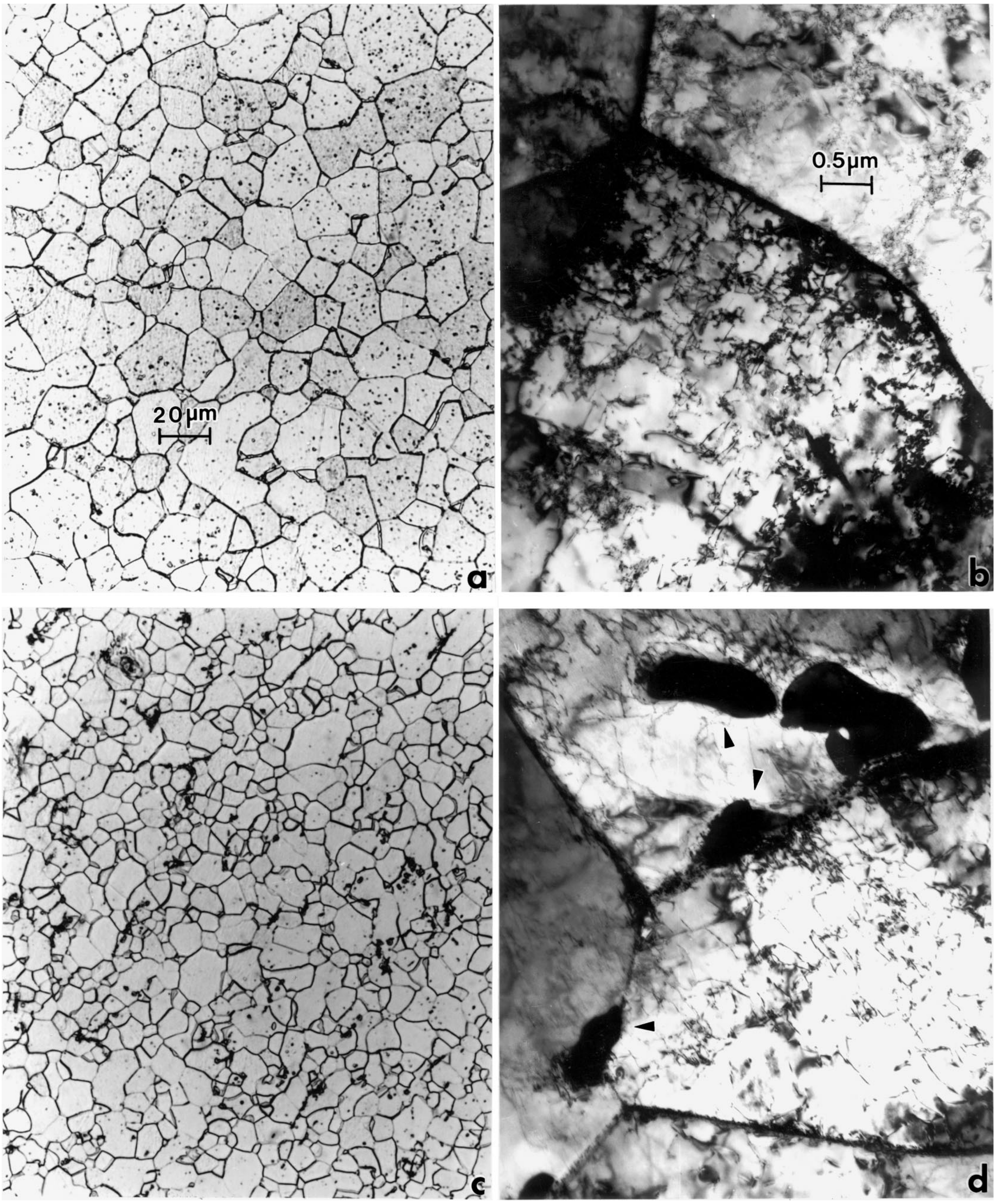

Figure 3 Microstructures of steel-drum top or head (a) and (b), and the barrel or side (commonly called the drum skirt when fabricated) (c) and (d). (a) and (c) show corresponding light microscope views of equiaxed grain structure, while (b) and (d) show corresponding TEM views of dislocation substructures. Arrows in (d) show large carbide precipitate clusters. Magnifications in (a) and (c) are the same as shown in (a). Magnifications of (b) and (d) are the same as shown in (b).

(by weight) each of Si, Mo and Zn; Fe balance. Correspondingly, the drum-skirt composition was 0.03% C, 0.03% P, 0.3% Mn, 0.03% Cr and less than 0.01% each of Si, Mo and Zn; balance consists of Fe (by weight). Fig. 3 shows the corresponding drum surface and skirt microstructures prior to any processing. The grains in both the drum surface and skirt (sides) are observed to be equiaxed and of slightly different nominal grain size using a nital etch (Fig. 3a and c). The dislocation substructures shown in Fig. 3b and d [using transmission electron microscopy (TEM) bright-field imaging after thinning 3 mm discs punched from each material and electropolishing in a solution of 800 ml methanol, 200 ml ethanol, 125 ml perchloric acid] are also similar. They are characterized by fairly dense tangles and poorly formed dislocation cells with dislocation densities ranging from 10^8 to 10^9 cm^{-2}.

Fig. 4 shows for comparison with Fig. 3a and b the grain structures in the sunken drum-bottom surface and cross-section as well as the corresponding TEM view of the bottom-surface microstructure viewed in the same context as Fig. 3b. It can be noted in the

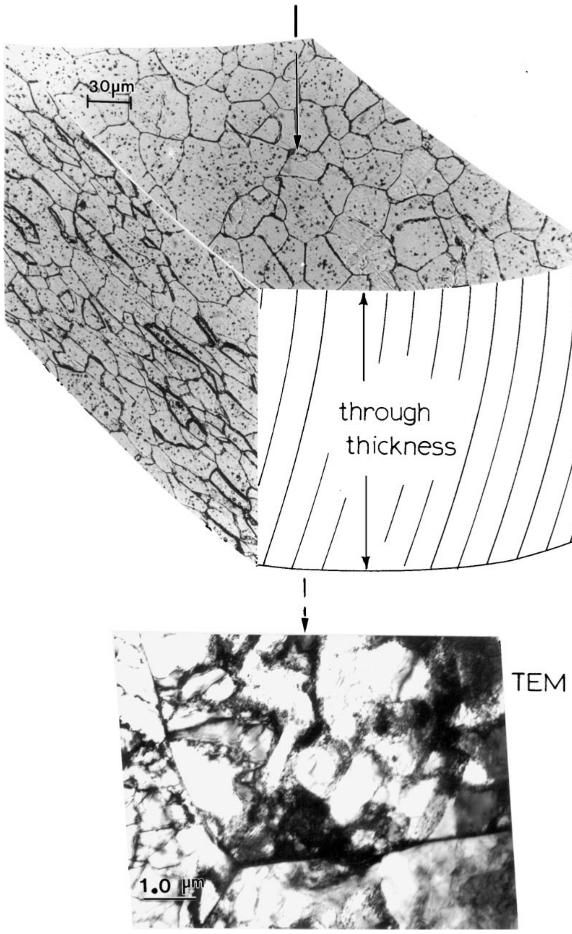

Figure 4 Light (optical) microscope views of the sunken-drum bottom surface and through-thickness cross-section. The corresponding TEM image for the in-plane (surface) view is also shown for comparison with Fig. 3b. Note well formed dislocation cell–subgrain structure.

cross-sectional view that the grains are flattened by around 50% – consistent with the measured reduction in cross-sectional thickness shown in Fig. 2. While the in-plane grain structure in the drum-head bottom is not noticeably distorted, the dislocation substructure shown is more dense than that shown in Fig. 3b, and the dislocation cells are smaller and better defined.

It should be noted in Fig. 4 that the microstructures shown represent the initially sunken drum head corresponding to Fig. 1b; prior to placing notes and grooving, etc. Consequently, as will be illustrated in Part II, this may not represent the actual microstructures associated with specific notes. However, it is not expected that the residual note reduction, hardness and associated microstructures would be significantly different.

2.2. Acoustic fundamentals characterizing the Caribbean steel drum

Fig. 5 shows a variety of note patterns placed on sunken drum heads similar to the basic concave platform illustrated in Fig. 1b. The depth of the concave platform and the fabrication or process may vary depending on the orchestral voice of the drum. Also shown are subsequent components in Fig. 1c–f and some actual examples of corresponding instruments in a steel-drum orchestra. Note that while the drum heads are essentially the same (at least the same diameter of 0.57 m), the skirt lengths are different, increasing with decreasing pitch (frequency) range: i.e. the lead or tenor drums have the highest frequencies and the shortest skirt lengths (12.7–15.2 cm), with skirt lengths increasing for higher-pitched (short) cello drums, lower-pitched (long) cello drums; and a full drum (skirt) length (0.86 m) for the bass drums, which are usually represented by a group of six drums with three notes in each drum head. The drums are played by striking the notes with special mallets, usually aluminum tubes (22–29 cm long) with neoprene tubing of various thicknesses or sponge-rubber balls over the striking end.

Fig. 6 illustrates these phenomena schematically and provides a summary of the principal acoustic features of the steel drum. The sinking depth is denoted by d in Fig. 6. The frequency characteristics of the skirt are given by

$$f' \cong v/\lambda' > (E/\rho)^{1/2}/4(s+r) \quad (1)$$

where v is the bulk sound velocity, λ' is the effective wavelength for the entire drum, E is the elastic modulus (in tension), and ρ is the drum-head density. The frequency, f', in Equation 1 represents the approximate lowest pitch (or frequency) that will be radiated by the drum. Actually, both the vibrating drum head and the skirt radiate sound, and the skirt will have an effect on the timbre of the drum – or the combined acoustic signal for any note struck (this includes the tonic and all harmonics shown in the ideal note in Fig. 6).

As shown in Fig. 6, the actual note as a vibrating metal membrane is often shaped within the note zone as an ellipsoidal shell, with the major axis usually oriented along the greatest note-zone dimension. This shape permits the simultaneous tuning of at least one octave ($2f$) and one or more harmonics ($3f$, $5f$, $7f$, etc.). Fig. 7 shows for reference an extensive tonic or pitch range for musical notes, and a simple harmonic series based on C_2 (f = 65.4 Hz) as the fundamental; with the approximate tonal range of a steel-drum orchestra from A_1 to F_6 marked.

As an ellipsoidal shell, a convex note on the concave drum surface is somewhat complex. If the note shape were simply a clamped circular plate as shown dotted in Fig. 6, and illustrated schematically in Fig. 8, the fundamental frequency would be given by [7]

$$f = 0.47\left(\frac{t}{R^2}\right)\left[\frac{E}{\rho(1-\nu^2)}\right]^{1/2} = A\left(\frac{t}{R^2}\right) \quad (2)$$

where t is the note thickness, R is the note radius (Fig. 8), ν is Poisson's ratio, and $A = 0.47\,[E/\rho(1-\nu^2)]^{1/2}$ (a constant). However, such a note has symmetrical (circular) harmonics, and is a simple linear note similar to a marimba bar, where, as a rough approximation, t/R^2 in Equation 2 is replaced by t/L^2, where L is the bar length.

It can be observed in Fig. 5 that the note areas and shapes differ widely, being trapezoidal, oval, nearly circular or circular, nearly rectangular, etc. Rossing *et al.*

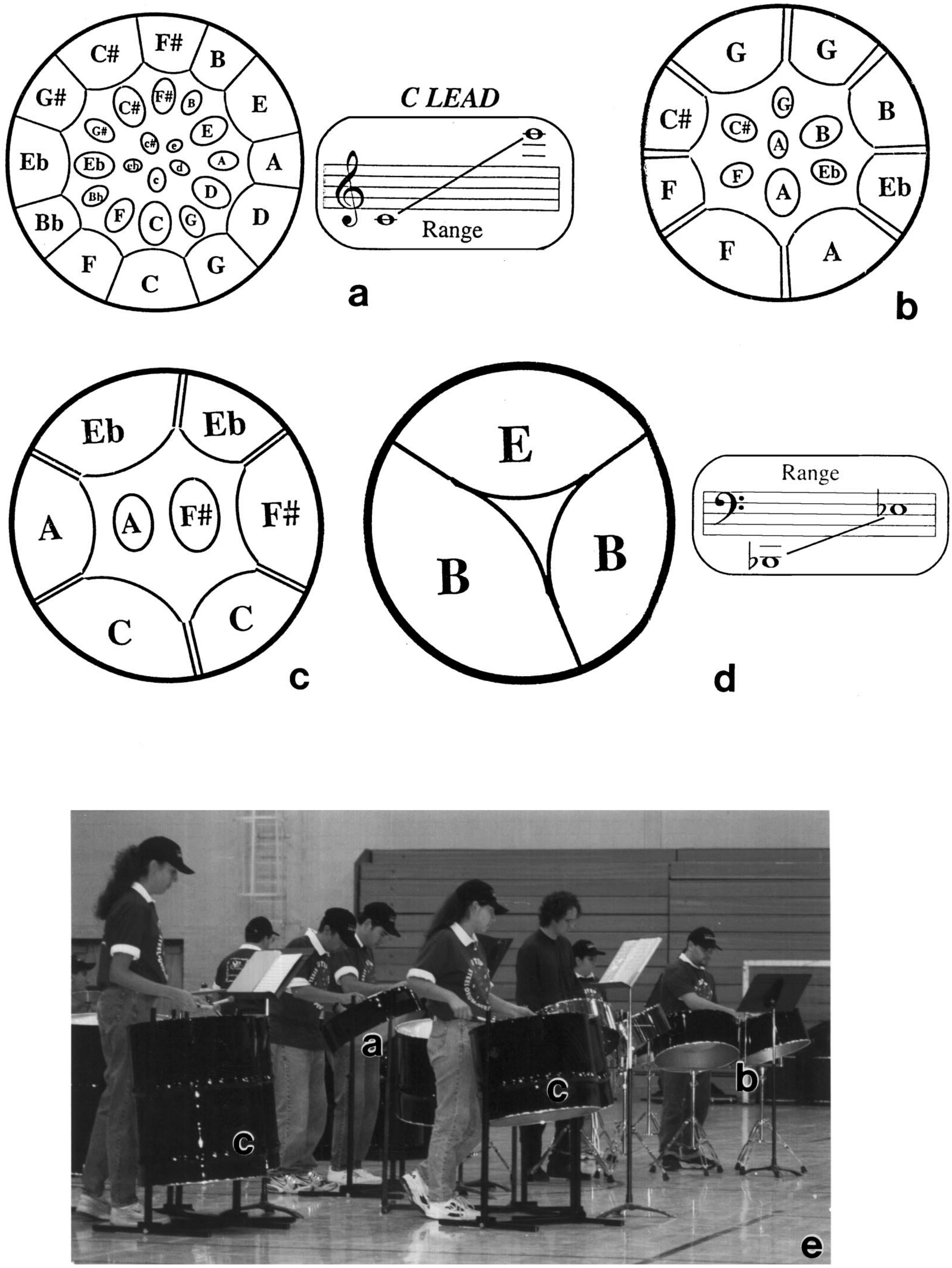

Figure 5 Examples of Caribbean steel-drum note patterns characterizing specific instrument voices and tonal ranges. (a) Lead or soprano (C-lead) pattern and tonal range. (b) Right double-second drum pattern. There are right and left drums (set of two). (c) Right cello pattern (there are short and long skirt cellos with three drums in a set: left, centre, and right). (d) One of six different bass-drum patterns. (e) UTEP "Pandemonium" steel drum orchestra with guest artist Darren Dyke, arranger, performer and tuner. The specific drums are marked according to the patterns illustrated: (a), (b), (c). Note the short and long cello skirts. (Patterns are courtesy of Panyard, Inc., Akron, OH.)

[6] have recently modelled steel-drum notes as shallow rectangular shells with length, L, width, W, and radii of curvature, R_L and R_S, as shown schematically in Fig. 9, and based on analytical models of Leissa [8]. They also observed that nodal patterns observed in many notes resembled those of rectangular plates and shells as well as elliptical plates of small eccentricity as described earlier by Waller [9].

The frequency expression for rectangular shells as shown in Fig. 9 is

$$f = \frac{\left[E/\rho(1-\nu^2)\right]^{1/2}}{2\pi R_s} \times \left[\frac{(1-\nu^2)(R\alpha^2+\beta^2)^2 + K(\alpha^2+\beta^2)^4}{(\alpha^2+\beta^2)}\right]^{1/2} \quad (3)$$

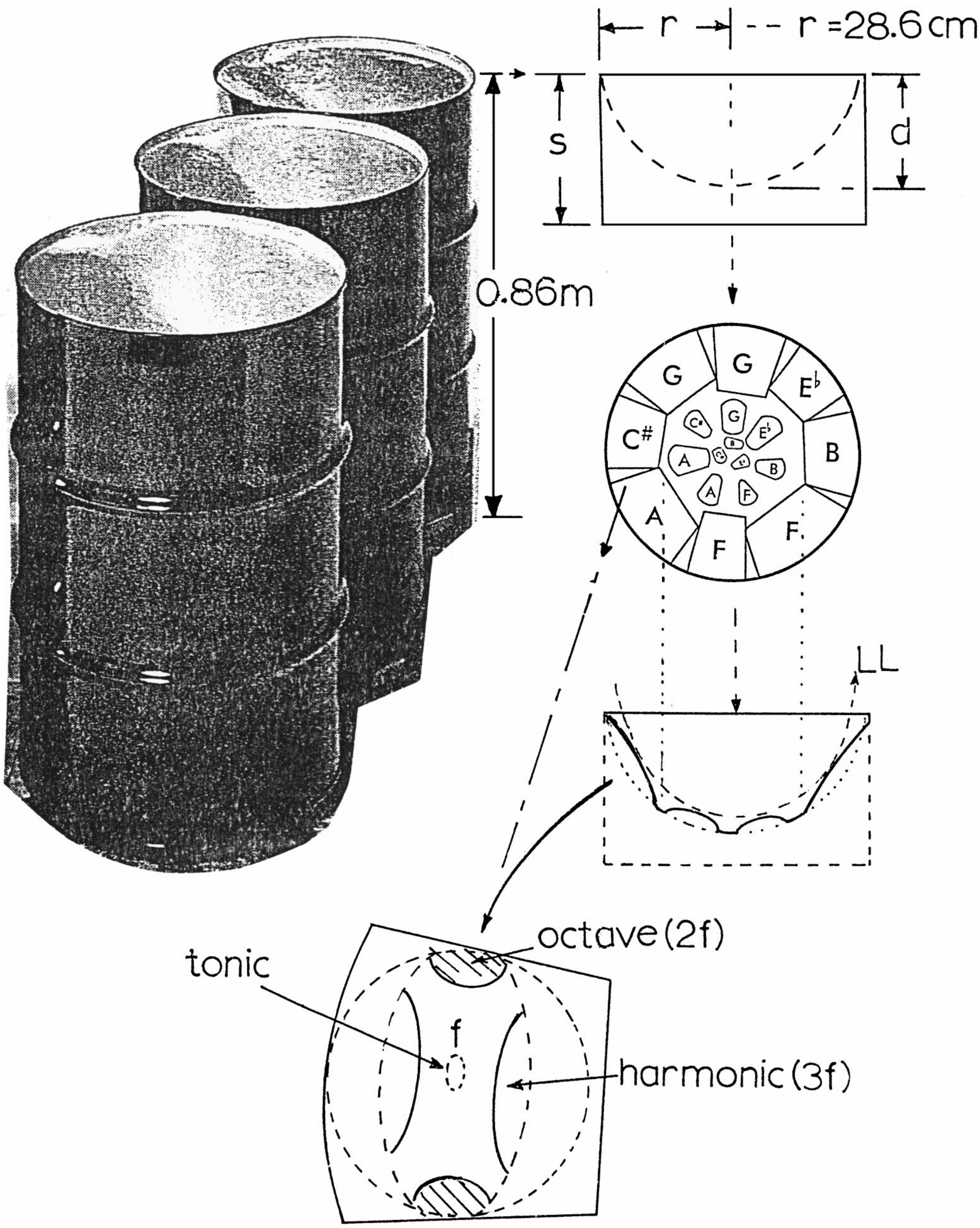

Figure 6 Schematic-diagram sequence illustrating fabrication parameters and features as well as the harmonic issues in note tuning. From the top, the drum-head sinking depth is denoted by d. The skirt length is denoted s. Patterning (for a right double-second drum using Ellie Mannette's note style) is shown for note dents (convex) in cross-section. The dented (convex) notes are levelled to the levelling line denoted LL. Notes are hammered to conform to an ellipsoid, which can be tuned to a fundamental frequency, f, and at least one octave, $2f$, and a harmonic, $3f$, as shown. The dotted circle represents an ideally circular note.

where $R = R_S/R_L$, $K = 0.08(t/R_S)^2$, $\alpha = [\pi R_S(2_{m-1})]/W$ and $\beta = (\pi R_S(2_{n-1}))/L$. The indices m and n allow only for modes of vibration that are symmetric about the shell centre. Of course in contrast to Equation 2, Equation 3 is a very complex, non-linear expression for only the tonic of a note. But as shown in Fig. 9, the note is commonly shaped as an ellipsoidal plate where the radii are both non-linear and variable. Furthermore, by considering the thickness variation in the drum head as shown in Fig. 2, the larger notes especially will have a varying thickness, which produces a non-linearity in thickness as well. Consequently, R and K as well as α and β in Equation 3 are non-linear.

A computer interrogation of Equation 3 by Hampton [5] and Rossing *et al.* [6] has shown that the frequency of notes modelled as rectangular shells is most sensitive to changes in curvature. But changes measured in the modal frequencies of the larger notes in a double-second drum after heat treatment were attributed to substantial changes in the elastic modulus, E [6].

It would seem unlikely that the elastic modulus would be altered during a simple strain-relief anneal because it is invariant during heavy deformation of the drum head,

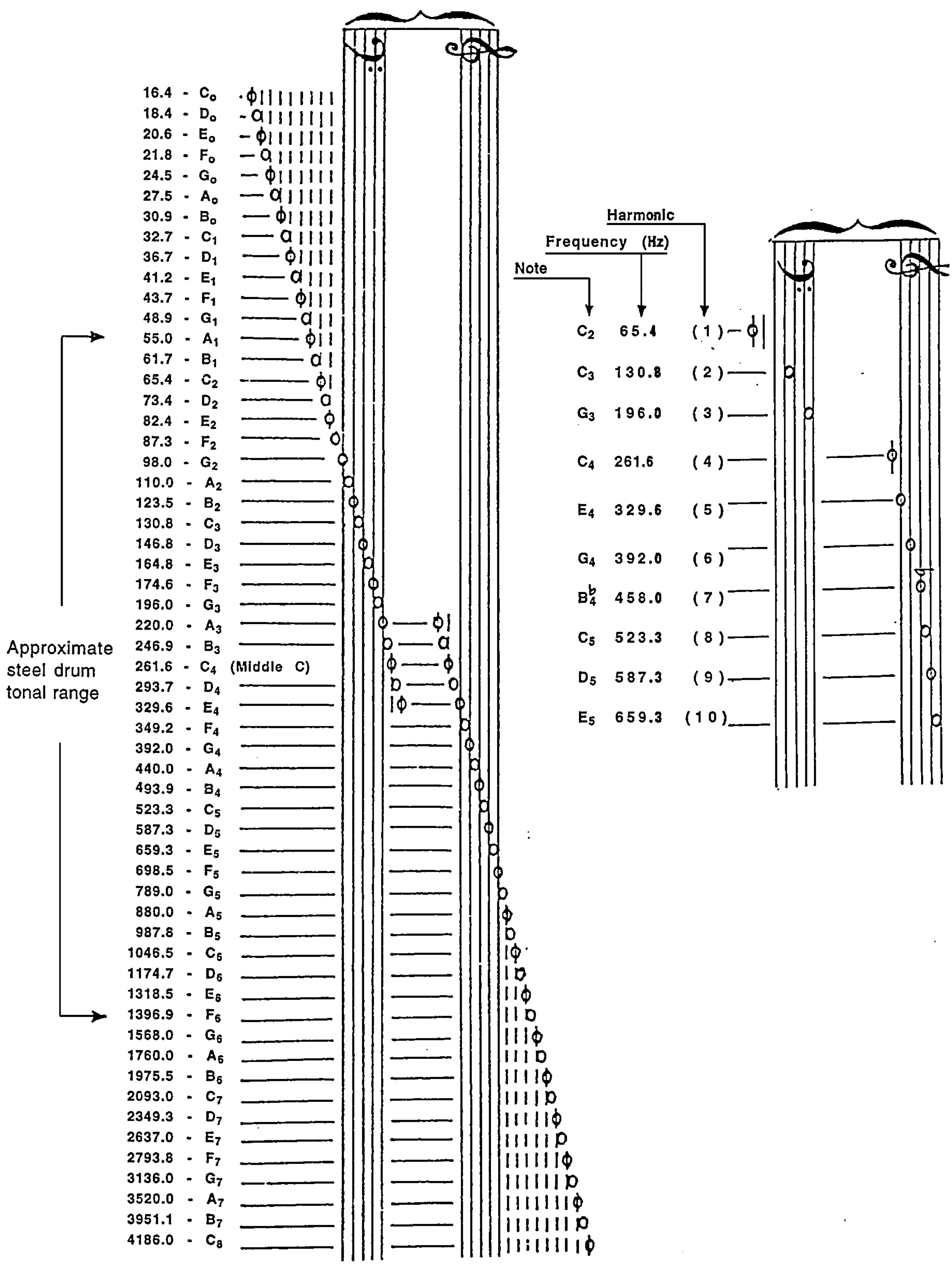

Figure 7 Frequencies of the notes in the scale of equal temperament (in the scale of C) showing the approximate tonal range for steel-drum orchestras and the harmonic series based on C_2 as the fundamental (right). G and F clef staffs provide whole note references. Octaves are defined as $2f$, $4f$, $6f$, etc., where f is the fundamental frequency in hertz.

as illustrated ideally in Fig. 10. Fig. 10 in fact illustrates (with reference to Fig. 2) that the yield stress and corresponding plastic hardness will vary with reduction in drum-head cross-section (engineering strain), and that if any deformed zone in the drum head were tested in simple tension, the effective yield stress of the original material would correspondingly increase. The elastic regime (area under the linear part of the stress–strain diagram) would also increase, but the modulus of elasticity would remain constant. Consequently, frequency variations during heat treatment result from shape changes in the notes caused by elastic–plastic interactions – to be described in more detail in Part II.

It is interesting to note in Equations 2 and 3 that the only materials parameters involved in the determination of the fundamental frequency (and harmonic

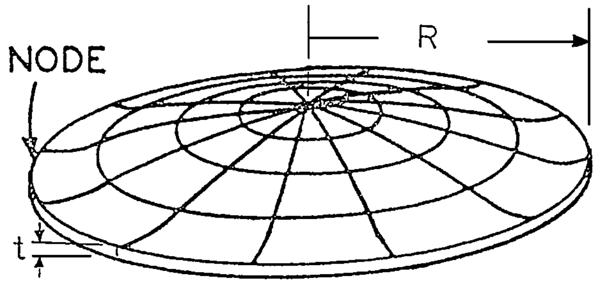

Figure 8 Schematic for circular note (plate) of radius, R, and thickness, t. "Node" indicates the clamped boundary and fundamental frequency in the centre for first mode of vibration.

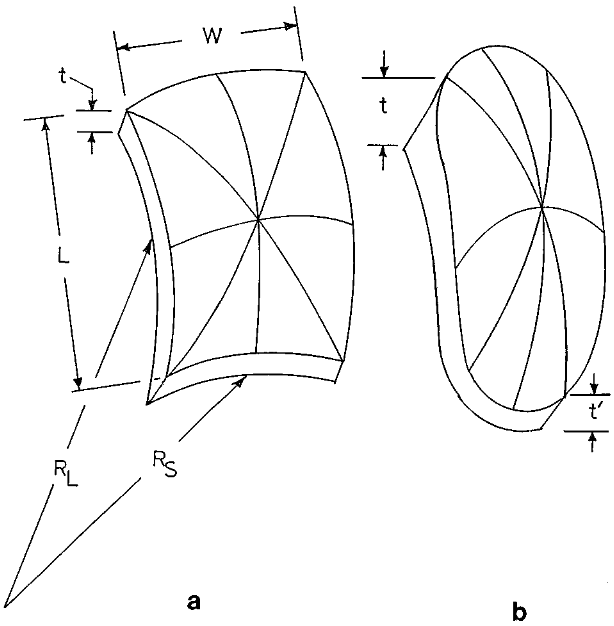

Figure 9 Schematic representations for rectangular shell note representation (a) and an ellipsoidal note with varying thickness and complex curvatures (b). The radii of curvature corresponding to the shell length and width are indicated by R_L and R_S, respectively, in (a). In (b) t and t' illustrate different thicknesses ($t' < t$).

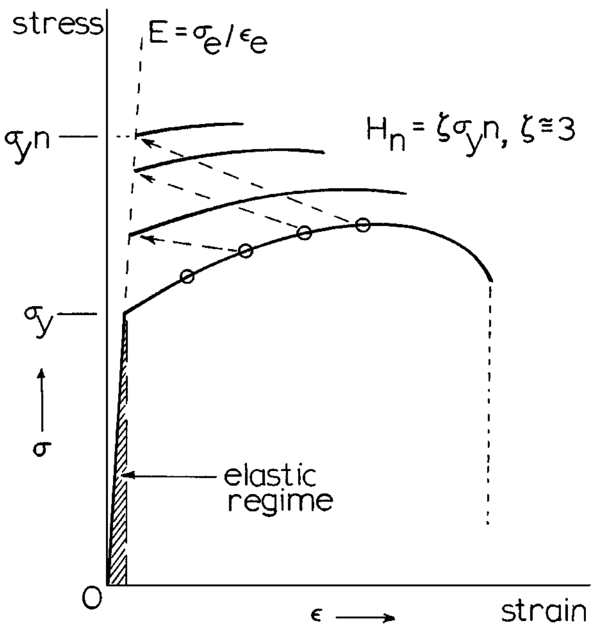

Figure 10 Idealized stress–strain, σ–ε, diagram showing yield-stress values, σ_y, and yield-stress increments, $\sigma_y n$, for re-testing at strain values noted along non-linear (plastic) curve. The elastic modulus, E, is invariant.

generation) are E, ρ and ν; all are invariant constants for any particular drum. The fact that notes around the upper portion of the drum head are deformed differently than notes in the bottom of the drum head would seem to beg the question of how or whether deformation influences the pitch or overall timbre of steel-drum notes. Indeed, it is not known what effect the deformation microstructure (as shown in Figs 3 and 4) has, not only on note timbre (pitch and harmonic generation), but also on the overall drum (including the skirt) timbre. We have not found any literature citations where these specific features have been investigated, even for simple notes such as variously hardened marimba bars.

2.3. Effect of deformation on the acoustic response for a free circular plate: the extracted ideal note

A simple series of experiments were conducted to examine the effect of deformation (in terms of per cent reduction in thickness) on the acoustic response of free circular plates. Referring to Fig. 8, there is no constraint around the perimeter of this circular note, and the fundamental frequency is given by a slight modification of Equation 2 [7]

$$f = A'(t/R^2) \tag{4}$$

where $A' = 0.41[(E/\rho(1-\nu^2)]^{1/2}$.

A 0.635-cm-thick plate of annealed 316 stainless steel (17% Cr, 10.3% Ni, 2.1% Mo, 0.6% Si, 1.4% Mn, 0.045% C; balance Fe, by weight) with an elastic modulus of 193 GPa, $\nu = 0.28$ and $\rho = 7.86$ g cm^{-3} was cold rolled by reverse, multiple-pass rolling to reductions of 10, 20, 30 and 40%. These rolled plate samples and an annealed, unrolled plate were all uniformly milled to a uniform thickness of 0.34 cm, and circular discs 3.65 cm in radius were then cut from each per cent reduction sample. A 1-mm hole was drilled in each circular plate (1 mm from the edge), which was hung with a 28-gauge steel wire looped through the hole and struck with a 0.78-cm diameter tungsten-alloy mallet to record the acoustic spectrum, using Macintosh-compatible software. Samples of each of the plates, from which circular discs were cut, were also ground to thin sections 0.2-mm thick, dimpled, and 3-mm discs, punched from these thinned specimens for electropolishing in a Struers Tenupol-3 dual-jet electropolisher. The solution consisted of 6% perchloric acid, 94% ethanol and was used at −20 °C. Electron transparent discs were then observed in a Hitachi H-8000 analytical TEM operated at 200 kV accelerating potential in the conventional transmission electron microscope (CTEM) mode, utilizing a goniometer tilt stage [10]. Fig. 11 shows for comparison the subgrain microstructures for the annealed, starting plate (0% reduction) and the 40%-reduction sample. The 40%-reduction sample in Fig. 11b has a very high dislocation density (approximately 10^{10} cm^{-2}) in contrast to the annealed plate (Fig. 11a), where the average dislocation density was 10^6–10^7 cm^{-2} [10].

The 316 stainless steel was chosen for this analysis because the initial grain structure (size) of

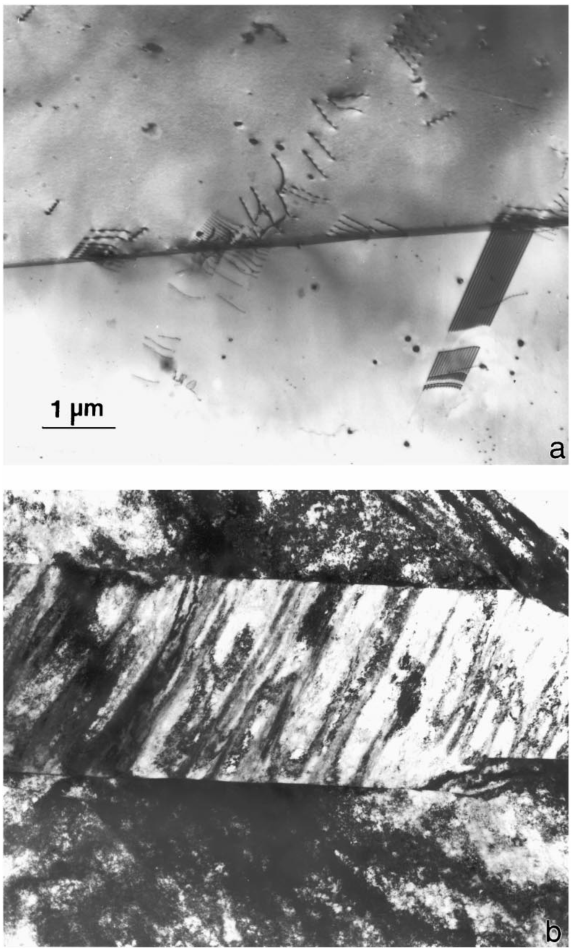

Figure 11 TEM bright-field images showing the annealed (0% reduction) microstructure for 316 stainless steel plate (a) and a 40% cold-rolled microstructure for the same 316 stainless steel plate (b). Dislocations and stacking faults are shown emanating from a boundary in (a), while (b) shows dense dislocations and planar defects associated with an annealing twin. Magnification is the same and shown in (a).

approximately 35 μm roughly matched the equiaxed structure for a low-carbon drum steel (Fig. 3a), but the dislocation microstructures were significantly reduced (Fig. 11a). In addition, there was no significant transformation from austenite to martensite as a consequence of deformation by rolling reduction, and the carbon content was in the range of that for drum steels. The annealed, starting plate hardness was also measured to be similar to drum-steel hardnesses. An average Vickers hardness number (VHN) of 202 (VHN $=$ 0.01 GPa) was recorded using a Shimadzu digital microhardness tester with a 3 N load.

Fig. 12 shows for comparison the corresponding sound spectra (amplitude–time) for the annealed circular disc (0% reduction), as well as discs deformed to 20 and 40% reduction, for the initial plate thickness of 0.34 cm (Fig. 12a) and for approximately half this thickness (0.16 cm in Fig. 12b), and finally roughly half this thickness again (0.076 cm in Fig. 12c). Corresponding hardness values for each of the reductions are also shown for comparison in Fig. 12a. The original (0.34-cm thick) discs in Fig. 12a were milled to roughly half the thickness and retested acoustically in Fig. 12b, and then milled roughly in half again and retested (Fig. 12c). Although there are subtle differences between these dif-

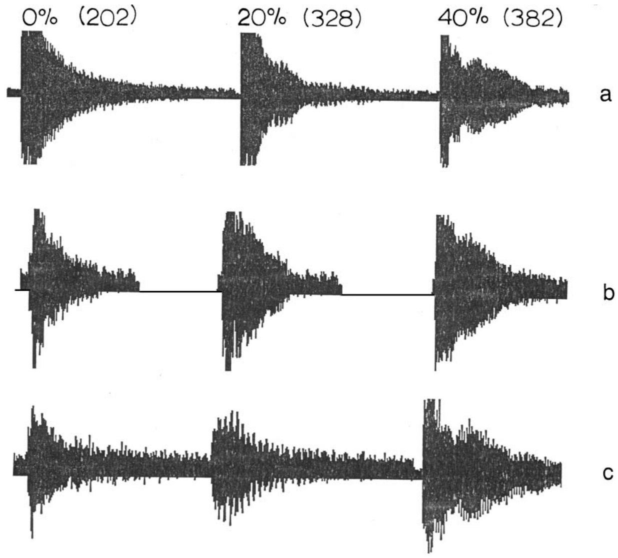

Figure 12 Acoustic spectra (amplitude versus time) for free circular plates cold-rolled to per cent reductions noted; with corresponding Vickers hardness numbers (VHN) (1 VHN $=$ 0.01 GPa). (a) $t = 0.34$ cm, (b) $t = 0.16$ cm, (c) $t = 0.076$ cm. Plate thicknesses are nominal values.

ferent thicknesses, there are notable differences for the most deformed (40% reduction) discs in contrast with the annealed discs. Note that hardness at 0% reduction of 202 VHN (2.02 GPa) increases to 382 VHN (3.82 GPa) at 40% reduction: an 89% increase in hardness. These features are more readily apparent in the

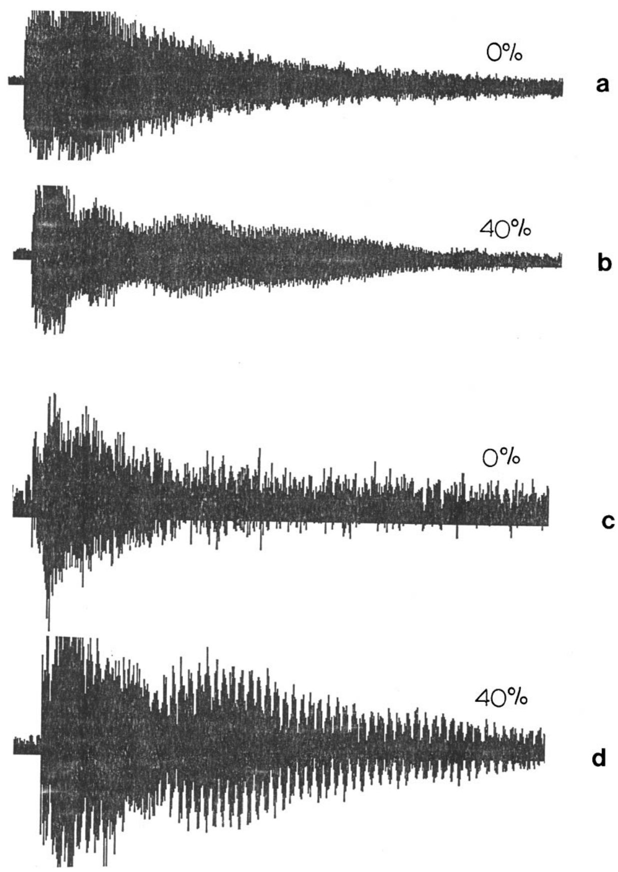

Figure 13 Selected, expanded acoustic spectra in Fig. 12. (a) Annealed plate (0% cold-reduction); $t = 0.34$ cm. (b) 40% cold-rolled plate; $t = 0.34$ cm. (c) Annealed plate (0% cold-reduction); $t = 0.076$ cm. (d) 40% cold-rolled plate; $t = 0.076$ cm.

expanded spectra for the original disc thicknesses in contrast with the thinnest discs as shown in Fig. 13 for the annealed (0% reduction) and 40%-reduced samples. The deformed (40%-reduced) discs in Fig. 13 are observed to contain prominent harmonics, which contain additional features for the thinnest free circular disc (Fig. 13b–d).

The implications of the different acoustic spectra shown in Figs 12 and 13 are perhaps better illustrated in Fig. 14 for frequency–time–amplitude plots for the 0.34-cm- (Fig. 14a) and 0.076-cm-thick discs (Fig. 14b) along with a further expansion of the harmonic responses observed in the 0.076-cm-thick discs (Fig. 14c). The expanded harmonic-signal view shown in Fig. 14c shows a systematic splitting of these peaks for the 20 and 40% reductions, indicating increased acoustic dispersion as a consequence of the deformation: $\Delta f = 0$ at 0% reduction; $\Delta f = 60$ Hz at 20% reduction; $\Delta f = 160$ Hz at 40% reduction. Note also in Fig. 14c that the 0% reduction peak is shifted

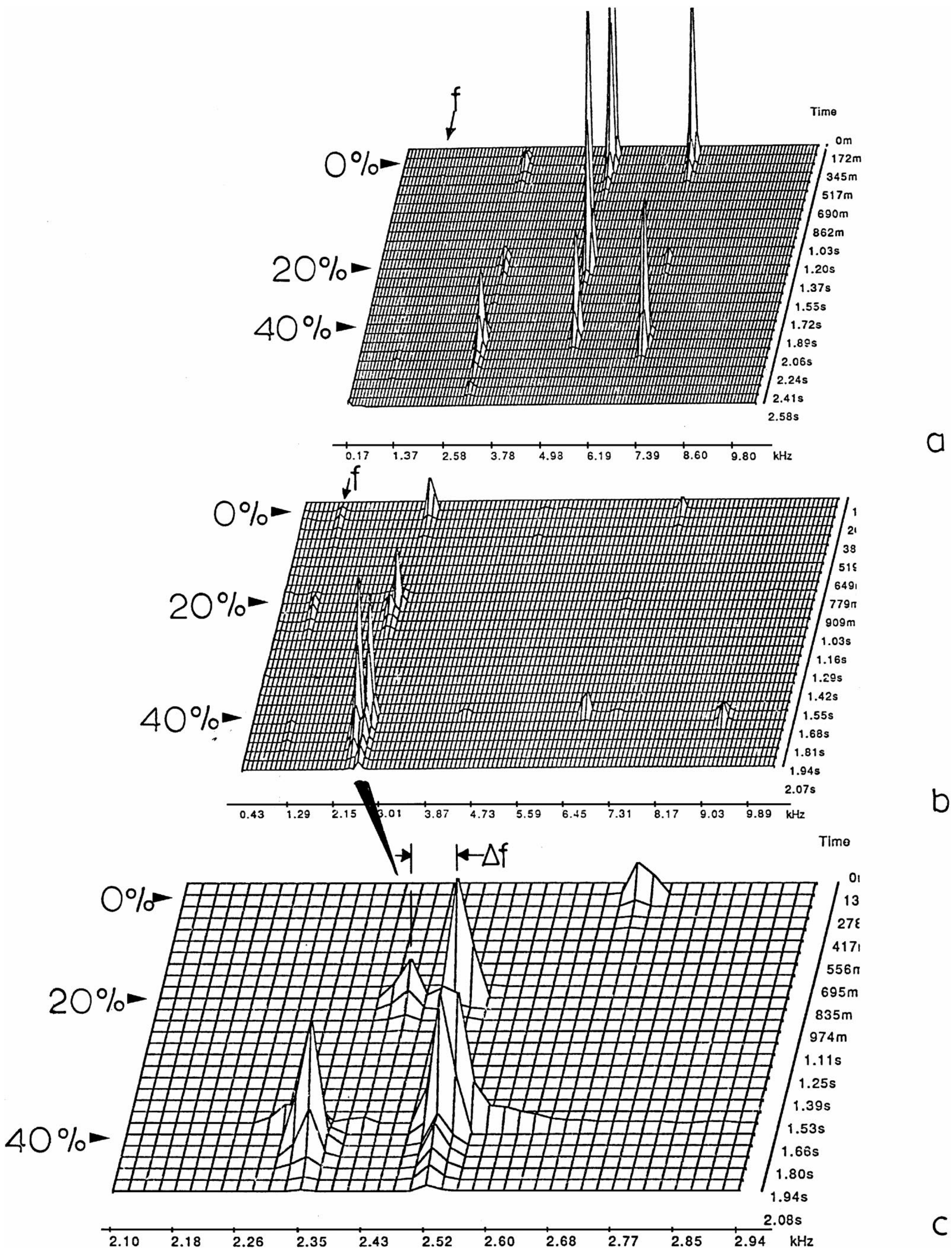

Figure 14 Comparative amplitude–frequency (harmonic) spectra for selected free circular plates in Fig. 12. (a) $t = 0.34$ cm. The fundamental frequency is denoted f. The spectra correspond to cold reductions of 0, 20 and 40% as noted. (b) $t = 0.076$ cm. The fundamental frequency is denoted f. (c) Expanded frequency spectra for first harmonic series in (b). Note shift of peak at 0% reduction due to slightly thicker plate.

approximately 24 Hz from the centroid of the split peaks at 40%-reduction. This shift is due to a slightly different thickness for the annealed (0% reduction) discs in contrast to the 20%-reduction and 40%-reduction discs, and illustrates the sensitivity of the acoustic spectrum (and timbre) to the thickness of the note (Equations 2 and 4).

Another interesting feature in Fig. 14a and b is the observation that the harmonics dominate the acoustic signal; i.e. the amplitude of the fundamental frequency or ideal pitch of the note is relatively inaudible compared with the first and second harmonics in the 0.34-cm thick discs, and the first harmonic in the 0.076-cm discs. Furthermore, the amplitude of the split harmonic is greatest for the 40% reduction disc as shown in Fig. 14b. Fig. 14 illustrates the very dramatic, if not complex, effects deformation (and related substructure as shown in Fig. 11b) has on the overall timbre of a steel-drum note, and especially of very thin notes whose thicknesses are comparable with the average note thickness in a Caribbean steel drum (Fig. 14b and c). The 0.076-cm-disc thickness in fact corresponds to the drum-head thickness near 34% reduction or in the intermediate hardness zone of the drum head. These effects are not indicated in the representations of note pitch shown in Equations 1–3, for example, and contribute in a complex and non-linear way to the note timbre. These observations for relatively ideal, free circular discs also suggest that the variations in deformation from the top to the bottom of a steel-drum head (Fig. 2) as well as the deformation or deformation-related substructure in the skirt may also influence the overall sound spectra.

3. Conclusions

In Part I of this two part paper, we have demonstrated the fundamentals of Caribbean steel-drum fabrication and measured the corresponding reductions in cross-section thickness associated with the initial sinking of the drum head. These reductions (or engineering strains) approach 50% in the base of the drum head. Microstructures corresponding to these heavily deformed regions of the drum base were also compared with the original drum top (or lid) microstructures. Dislocation cell structures were observed to be reduced in size from those originally observed in the undeformed drum top, and the overall dislocation density increased. Equiaxed grains in the plane of the drum head were essentially unchanged, but grains in the thickness cross-section were elongated and reduced by about 50%, corresponding to the measured engineering strain. The microstructures in the drum sides or skirt were similar to those in the undeformed drum lid and were not altered during fabrication. Only the skirt length is varied, depending upon the tonal range of the drum; it decreases with higher-frequency timbres.

We have shown as a consequence of the variations in the thickness of the drum head, corresponding to the per cent reductions produced by the deformation associated with manual sinking, that the note zone thicknesses (especially larger notes in the upper drum-head regions) will vary as much as 30%, and because of the ellipsoidal note shapes, the radii of curvative will also vary non-linearly. Consequently, the fundamental frequency or pitch as well as associated harmonics will be a complex, non-linear function of note-shape parameters, and variations in frequency will occur for subtle changes in note shape. These shape changes can be altered significantly by heat treatment.

We have conducted a series of simple experiments to examine the effect of deformation (per cent reduction in thickness) and deformation-related microstructures on the acoustic spectrum for simple circular discs of 316 stainless steel, representing reductions up to 40%, and with nominal thicknesses of 0.34, 0.16 and 0.076 cm, the last representing the thickness range for mid-range steel-drum notes. The results illustrate rather dramatic effects, especially for harmonic spectra, and harmonic frequencies are shown to split into nodes whose frequency difference increases with per cent cold reduction. Deformation microstructures in ideal (free) circular plates commensurate with the thicknesses of steel-drum notes, therefore, appear to have a substantial effect on note timbre as a consequence of acoustic (phonon) dispersion. Harmonic-frequency shifts were also observed to be sensitive to the ideal-note thickness, and these effects are also probably a feature of the non-linear steel-drum notes. In addition, these dispersion effects due to deformation-induced microstructures also shift the tonic and harmonic amplitudes and thereby have a significant effect on note timbre. Consequently, the considerable deformation, which characterizes the fabrication of steel drums, apparently contributes significantly to the unique harmonic overtones they produce.

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