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Materials science and metallurgy of the Caribbean steel drum

Part II *Heat treatment, microstructures, hardness profiles and tuning effects*

E. FERREYRA, J. G. MALDONADO, L. E. MURR, S. PAPPU, E. A. TRILLO, C. KENNEDY, M. POSADA, J. DE ALBA, R. CHITRE, D. P. RUSSELL*
*Departments of Metallurgical and Materials Engineering, and *Physics, Materials Research Institute, University of Texas at El Paso, El Paso, TX 79968, USA*

The heat treatment of the Caribbean steel drum has been found to involve strain ageing and is especially prominent in drum steels containing 0.03–0.04 wt % C. The optimum strain-ageing conditions appear to be about 350 °C for 10 min, and either water quenching or air cooling produce similar ageing effects (hardness increases) ranging from about 5 to 20%. The strain ageing combined with the strain hardening applied to the drum-head sinking and note-fabrication processes, produces a requisite elastic–plastic interaction, which allows for multiharmonic tuning and the creation of the unique chromatic tones and harmonic overtones that are a characteristic of the various instruments. These unique features of note vibrations were illustrated by comparing dynamic impact hardness profiles with corresponding, static Vickers hardness measurements for actual, tuned notes and the same, corresponding notes extracted from the drum head, respectively. Elastic–plastic and plastic-hardness profiles were compared in unique colour maps. Microstructural analyses by light metallography and transmission electron microscopy illustrate corresponding dislocation substructures and carbide precipitation. Finally, the analysis and comparison of acoustic spectra for specific steel-drum note zones illustrates their complex, non-linear behaviour, and the role that deformation-induced defects play in acoustic dispersion and multiharmonic signal production.

1. Introduction

In Part I [1], the preceding paper, we examined the principal fabrication issues of the Caribbean (Trinidad and Tobago) steel drum, especially the deformation involved in the sinking of the drum head. The cold reduction of a 316 stainless steel plate up to 40% and subsequent acoustic analysis demonstrated that deformation and deformation-related microstructures have a pronounced effect on the harmonic spectrum, and in combination with the non-linear behaviour of steel-drum notes probably account for their unique sounds.

In Part II, we continue the examination of steel-drum-fabrication issues, beginning with the heat treatment of the drum head prior to the harmonic tuning process. Heat treatment has always been a vague issue because temperatures of the drum head have never been accurately measured, and the process is invariably and incorrectly referred to as tempering, which has a very special connotation in the context of the heat treatment of carbon steels. Following a detailed examination of heat treatment and associated microstructures in drum-head samples representing maximum reductions of approximately 50% in the drum bottom, the hardness profiles associated with specific, tuned and partially tuned notes have been measured with a dynamic impact tester. These hardness profiles were then compared with the static, instrumental Vickers microhardness measurements for specific notes extracted from the drum head. Finally, the acoustic spectra for tuned and partially tuned notes are examined in contrast with the acoustic spectra for ideal circular plates in Part I [1], and in the context of a spectral analysis approach to examining the full timbre of each note in steel-drum tuning.

2. Heat treatment of the Caribbean steel drum

Originally, the fully patterned (and grooved) steel drum was placed over a variety of open fire sources, such as fire pits, the bottom half or portion of the cut barrel filled with kindling, or burning tyres, in order to burn away the residual oil or paint. However, as the instrument evolved, this firing (or heat treatment) began to be recognized to have a profound effect on the musical quality (timbre) of the tuned notes as well as the overall drum timbre. Tuners used notations like "brightness" to qualify some of these effects, and the firing of drum

TABLE I Chemical analysis[a], grain size, D[b], and average Vickers hardness number (VHN)[c]

Drum	Description	C	P	Mn	Cr	D (μm)	VHN
	Raw material						
RM(1)	Drum lid (undeformed)	<0.01	0.021	0.11	0.02	24	113
	Sunk drum						
SD-S(1)	Skirt	0.031	0.029	0.3	0.03	11	119
SD-L(1)	Lid (drum-head bottom)	<0.01	0.03	0.11	0.02	32	170
	Sunk drum upper notes						
SDUN-S(3)	Skirt	0.052	0.021	0.29	0.04	10	125
SDUN-L(3)	Lid	0.062	0.017	0.41	0.02	d	171
	Partially tuned drum						
PTD-S(2)	Skirt	0.014	0.016	0.3	0.03	12	124
PTD-L(2)	Lid (sunk)	0.036	0.014	0.31	0.02	34	182
	High quality drum						
HQD-S(4)	Skirt	<0.01	0.012	0.3	0.02	22	100
HQD-L(4)	Lid (undeformed)	0.041	0.013	0.39	0.02	16	139

[a] Arc spectrometry analysis – weight per cent.
[b] Average actual grain size determined by multiplying the grain intercept length, I, by 1.5 ($D = 1.5l$) [4].
[c] 20 indentations or 40 diagonals averaged per sample coupon. 1 VHN = 0.01 GPa.
[d] Grain distortions made meaningful measurements difficult.

heads prior to tuning has evolved as a necessary process feature to achieve superior harmonic tuning and drum sound quality. As mentioned, this process is commonly and incorrectly referred to as tempering. Temperatures often quoted for the firing of the drum head approximately 150–200 °C (approximately 300–400 °F: we emphasize temperatures in degrees Fahrenheit because this is the temperature scale commonly used by steel-drum fabricators) [2] are far below the tempering range [2]. The firing or heat treatment of the drum continues to be guided almost solely by observing colour changes or colour evolution of the heated drum head. These features, which are a consequence of oxide development (oxide thickness increases) are illustrated in the sequence of photographs shown in Fig. 1. The time to achieve the requisite colour shown in Fig. 1 depends on the heat source (or temperature) but normally involves about 1–10 min. Following the heating to a drum colour shown in Fig. 1f, the drum is removed and water cooled (or quenched). Air cooling is also often used.

To investigate the details of the heat-treatment process, we cut coupons from the base of a sunken drum with upper notes patterned on it that had not been heat treated (SDUN-L(3) in Table I) (corresponding to thickness reductions of approximately 50%; with nominal composition, in weight per cent, of 0.062% C, 0.017% P, 0.41% Mn and 0.02% Cr; balance consists of Fe). These coupons were then heat treated for varying times and temperatures (isochronal and isothermal anneals). The initial coupon hardnesses and microstructures were measured and observed, respectively, utilizing light metallography and transmission electron microscopy (TEM). Following heat treatment, each coupon hardness was remeasured, and the heat-treated microstructures observed. In addition, coupons were also cut from the bottom of the sunken drum (SD-L(1) in Table I) in Figs 1 and 2 of Part I [1] and heat treated at higher temperatures for the same ageing times.

Fig. 2 illustrates hardness variations for some representative heat treatments for both the sunken drum head (SDUN-L(3) in Table I) and the corresponding skirt (SDUN-S(3) in Table I), with nominal composition (in weight per cent) of 0.052% C, 0.021% P, 0.29% Mn and 0.04% Cr; balance consists of Fe. Note that the carbon content of the drum-head material was similar to that in the drum skirt (0.062% C versus 0.052% C in Table I). Fig. 2 shows a 5% hardness increase for the deformed (approximately 50% reduction in thickness) drum-head coupons (SDUN-L(3)) heat treated between 177 and 371 °C (350 and 700 °F). There is a very small but observable increase in the corresponding skirt hardness in this temperature range, but the skirt, it must be recalled, was not deformed while the drum lid was sunken to a thickness reduction of approximately 50%. Fig. 2a shows that above 371 °C (700 °F), the hardness drops below the starting coupon hardness, indicative of overageing of the heavily deformed drum-head (bottom) coupons.

Fig. 2a, corresponding to heating for 1 min and water quenching, shows a hardness increase peaking at around 5% at 177 °C (350 °F). It should be noted in Fig. 2a as well as Fig. 2b that the higher-temperature data shown (at 600 and 1000 °C to the right) are for coupons cut from the sunken drum bottom in Figs 1 and 2 in Part I [1] (SD-L(1) in Table I). While these coupons correspond to a 50% engineering strain or reduction, the carbon contents are <0.01% (SD-L(1) in Table I). In addition, note that in these heat treatments at lower temperatures (177 and 371 °C) using coupons from the 50% strained SDUN-L(3) drum bottom in Table I, the carbon content is about five–six times larger than for the higher-temperature aged drum samples. Consequently what may appear to be overageing at 600 °C and above, may actually be underageing as a consequence of the very low carbon content. The fact that the skirt samples exhibit the same but reduced ageing behaviour in spite of no additional straining is an indication perhaps of a requisite carbon content. However, the data clearly illustrate the effects of prior straining as well.

These characteristics are typical of strain ageing behaviour where the segregation of interstitial carbon atoms or carbon atoms migrating from carbides to the strain fields (or core region) of dislocations tends to fix the dislocations in the lattice, thereby requiring higher

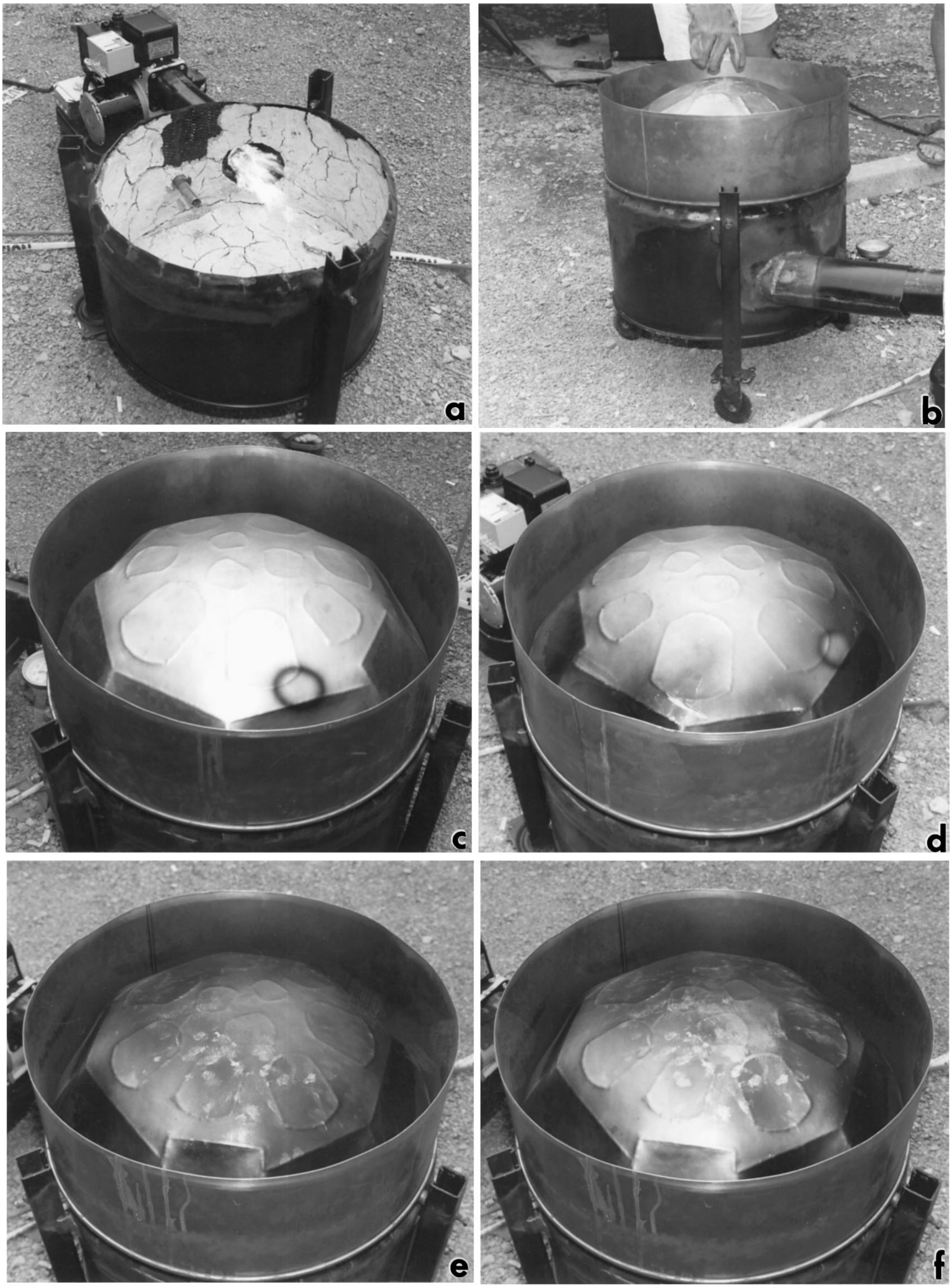


Figure 1 Typical firing (heat treatment) sequence for the double-second drum shown in Fig. 1 of Part I; based on colour changes: (a) Gas-fired heat source. Temperatures near the flame are approximately 600 °C (1000 °F). (b) Right double-second drum (Fig. 1f in Part I) placed over heat source. (c)–(f) show the oxide-layer-related colour changes, which, for the source shown, cover a time interval of approximately 5 min.

stresses to produce any subsequent plastic deformation. Strain ageing is of course dependent upon straining prior to deformation, which accounts for the fact that the skirt demonstrates only insignificant effects. Furthermore, the process is enhanced by supersaturation of carbon or, more generally, by increased carbon content [3]. A preponderance of carbides is often a manifestation of this carbon-content increase.

Figs 3 and 4 tend to illustrate these features, and Fig. 3 in particular shows very little or perceptible change in

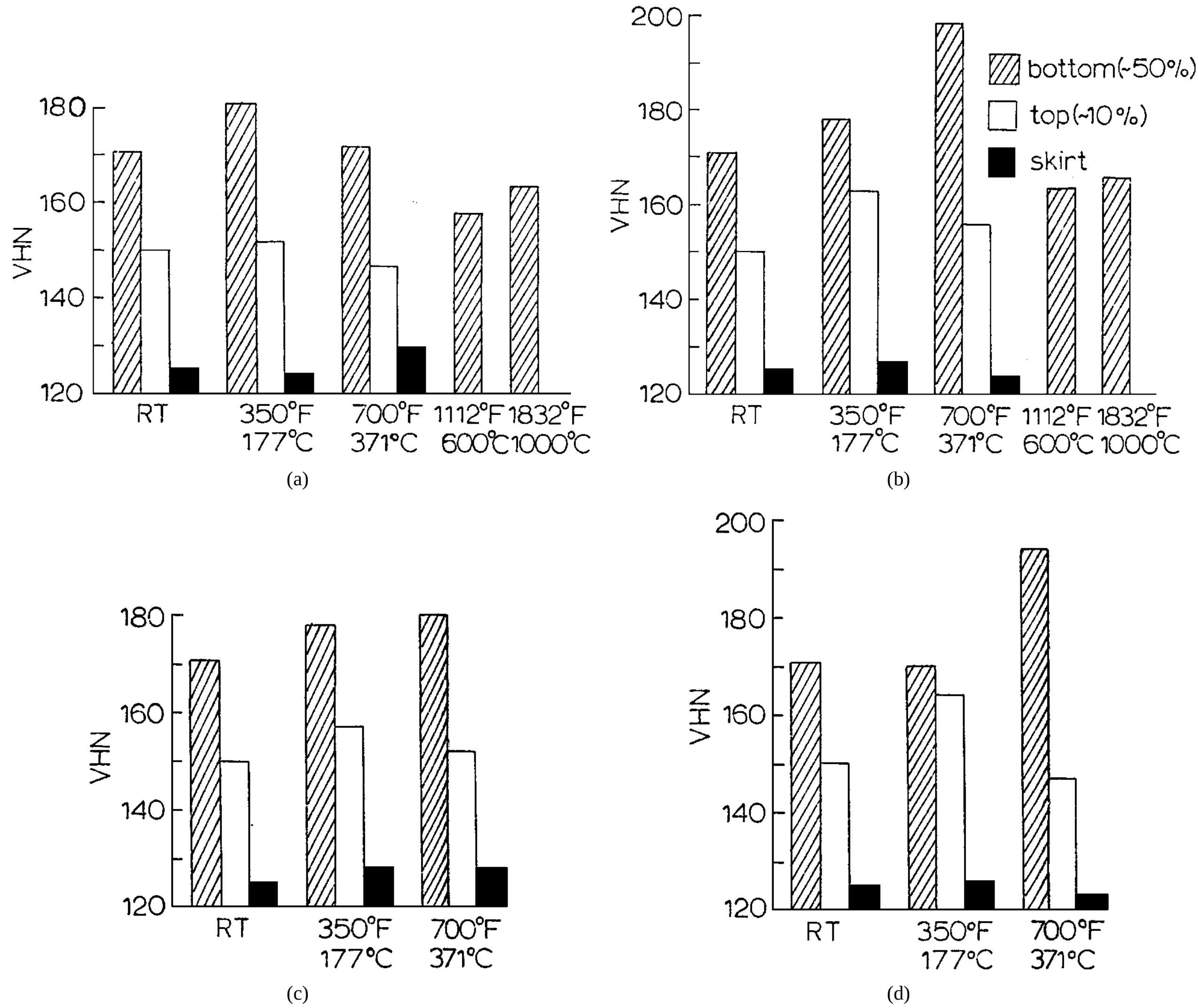


Figure 2 Heat-treatment effects at various temperatures: (a) Ageing for 1 min and water quenched. (b) Ageing for 10 min and water quenched. (c) Ageing for 1 min and air cooled. (d) Ageing for 10 min and air cooled. Note key provided in (b). Bottom coupons correspond to about 50% strain while coupons near the top or upper regions of the drum head correspond to strains of only about 10%. The skirt coupons were essentially unstrained. See Table I for data corresponding to SDUN-S and L(3). Drum-head coupons correspond to 0.062 wt % C. Higher temperature data in (a) and (b) correspond to SD-L(1) coupons where the carbon content was <0.01 wt % (Table I).

the dislocation substructure of the deformed drum head up to 371 °C (700 °F) heat treatment, but consistent with the strain ageing behaviour described above. Fig. 4, on the other hand, illustrates that dislocation substructure only begins to exhibit any observable recovery and annihilation (annealing) at 1000 °C (1832 °F); (compare Fig. 4d with Fig. 3b and d).

The heat-treatment studies summarized in Figs 2–4 suggest that the key issues involved in the development of high-quality steel drums may involve strain ageing effects, which would also be expected to depend on the carbon content and deformation strain prior to heat treatment. Consequently, as shown in Fig. 2, drum-head (or lid) materials of low carbon content would not be expected to strain age in the same way that drum steels of higher carbon content may strain age. On the other hand, if the carbon content is too high ($>0.06\%$), the drum head may fail while it is being sunken as in the case of SDUN-L(3) in Table I. In addition, the use of a torch to heat specific areas in the note zones to facilitate harmonic tuning, as illustrated typically in Fig. 5, may also involve additional strain ageing or strain relief, which needs to be adjusted to achieve appropriate note shape or tension. These effects may also vary slightly over the drum head, within different hardness zones or zones of different engineering strain.

Fig. 2 also shows that overall there may not be a significant difference in the strain-ageing behaviour of a steel-drum head if it is water cooled compared with allowing it to cool in air (compare Fig. 2a and b with Fig. 2c and d). Very short heat treatment, even for a few minutes, is shown to affect strain ageing, but longer heat treatments at slightly higher temperatures (371 °C or 700 °F) of around 10 min may, as shown in Fig. 2b and d, provide a greater hardness increase or more significant strain ageing. Interestingly enough, adequate and very uniform strain ageing is achieved below 371 °C (700 °F) for only a few minutes, and the rather sketchy heat-treatment procedures that have evolved over the years involving relatively low heat-treatment temperatures [2] have actually (and perhaps fortuitously) been somewhat optimum, as illustrated in the overview apparent in Fig. 2.

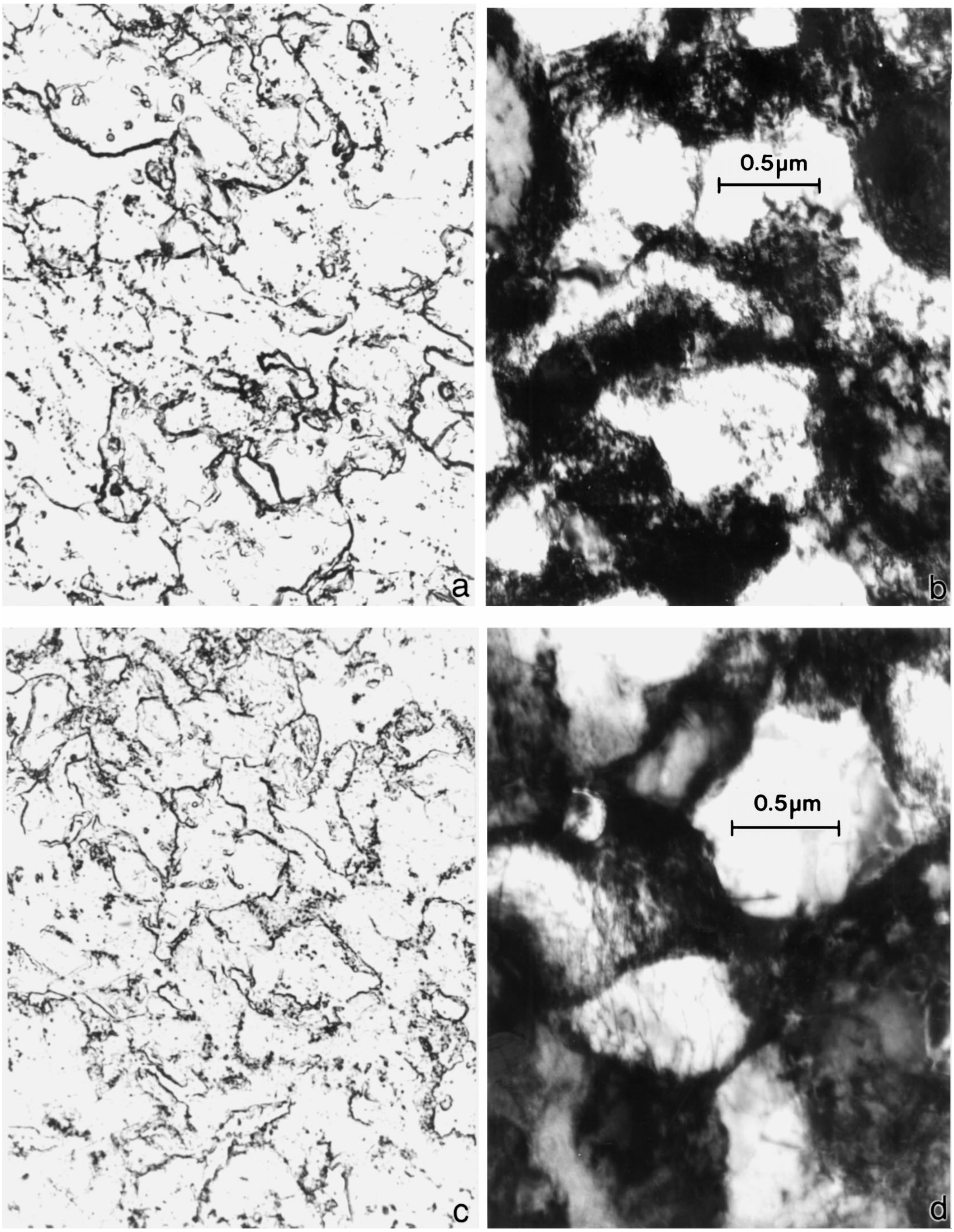


Figure 3 Steel drum (bottom) microstructures corresponding to approximately 50% cold reduction after strain ageing heat treatment for 1 min as a function of temperature: (a) light metallograph image of untreated starting coupon, (b) TEM image of (a), (c) light metallograph image at 371 °C (700 °F), (d) TEM image of (c). Note the carbon content was 0.062 wt % C.

3. Microstructural and microchemical issues

In Fig. 2 of Part I [1], two drums were represented: one a sunken (but unpatterned) drum (SD(1)) and the other a sunken drum fully patterned for a left double tenor, heat treated and partially tuned (PTD(2) in Table I). These two drums were characterized by different drum-lid (head) and skirt chemistries for each drum. In addition to these drums, we also examined two other drums. One was a sunken drum with only partial note patterning for a double tenor and a starting barrel, which has been used in musically superior drum fabrication by Ellie Mannette [4]. We designated these additional drum samples as SDUN(3) and HQD(4), respectively (Table I). These drum samples and their component lids (or drum heads) prior to and following sinking (deformation), as well as their associated skirt

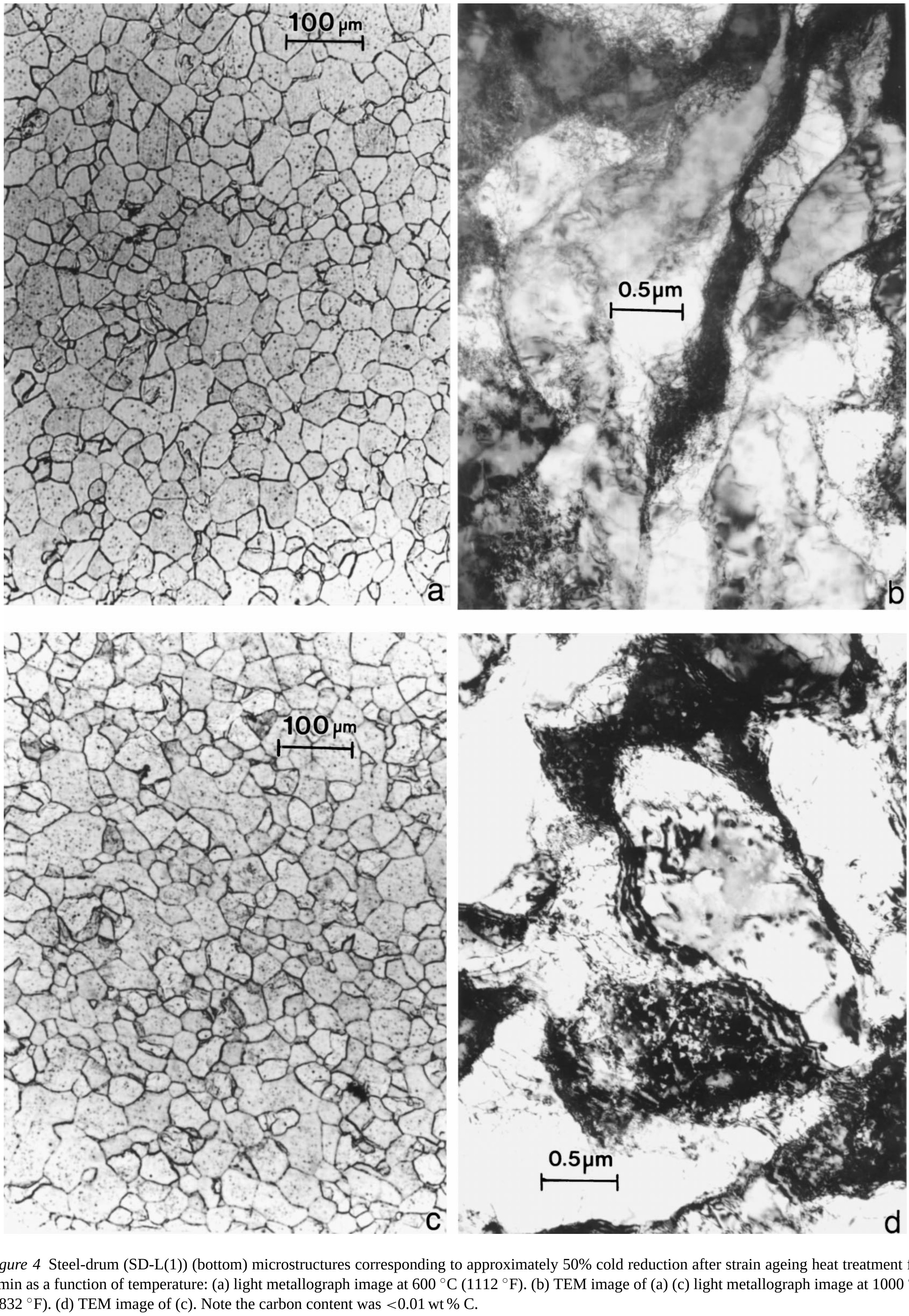


Figure 4 Steel-drum (SD-L(1)) (bottom) microstructures corresponding to approximately 50% cold reduction after strain ageing heat treatment for 1 min as a function of temperature: (a) light metallograph image at 600 °C (1112 °F). (b) TEM image of (a) (c) light metallograph image at 1000 °C (1832 °F). (d) TEM image of (c). Note the carbon content was <0.01 wt % C.

or barrel-side chemical compositions and corresponding Vickers hardnesses, are shown for comparison in Table I.

It can be noted in Table I that the incremental hardening for a sunken drum head is only about 50% (compare RM(1) and SD-L(1)) for a reduction in initial drum-lid thickness of about 50%. This can be contrasted with the incremental hardness increase of 89% for the cold rolling of 316 stainless steel plate in Part I [1] to 40% reduction. This reduction in incremental hardness is

Figure 5 Example of note adjustment by localized heat treatment using a torch.

due in large part to the fact that the initial steel-drum microstructures contain considerable dislocation densities (approximately 10^9–10^{10} cm^{-2}) (see Fig. 3b) in contrast to the annealed, 316 stainless steel (approximately 10^6 cm^{-2}) (Fig. 11a in Part I [1]).

Figs 6 and 7 show for comparison a few representative examples of microstructures (grain structure and substructures) for prefabricated steel drums (RM(1) and HQD-L(4), and SD-S(1) and HQD-S(4) in Table I), representing the undeformed drum head (lid) and skirt, respectively. Figs 6a and b, and 7a and b correspond to a lower-quality barrel, and Figs 6c and d, and 7c and d correspond to a very high-quality barrel [3]. It can be noted that in this comparison, the low-quality barrel (RM(1) and SD(1)) has a <0.01wt % C drum lid and a 0.031wt % C skirt. Correspondingly, the higher-quality barrel (HQD-L(4) and HQD-S(4)) has a 0.041wt % C drum lid and a <0.01wt % C skirt, essentially reversed carbon content. The TEM bright-field images in Figs 6b and d, and 7b and d correspond somewhat qualitatively to this microchemistry in the context of the observed carbide precipitate density. The other notable microstructural feature of the high-quality drum material is the considerably larger and different skirt grain structure shown in Fig. 7c in contrast with that for the lower-quality drum in Fig. 7a (see also Table I). In addition, the grain structures and sizes for the skirt and drum head are also reversed for these two starting barrels (compare Figs 6a and 7a with Figs 6c and 7c. The larger high-quality (HQD-S(4)) skirt grain size (with lower carbon content) is also 20% softer than the lower-quality (SD-S(1)) skirt (Table I). This feature, combined with a more favourable carbon content in the drum head in the context of the strain-ageing experiments outlined in Section 2 above, may provide some

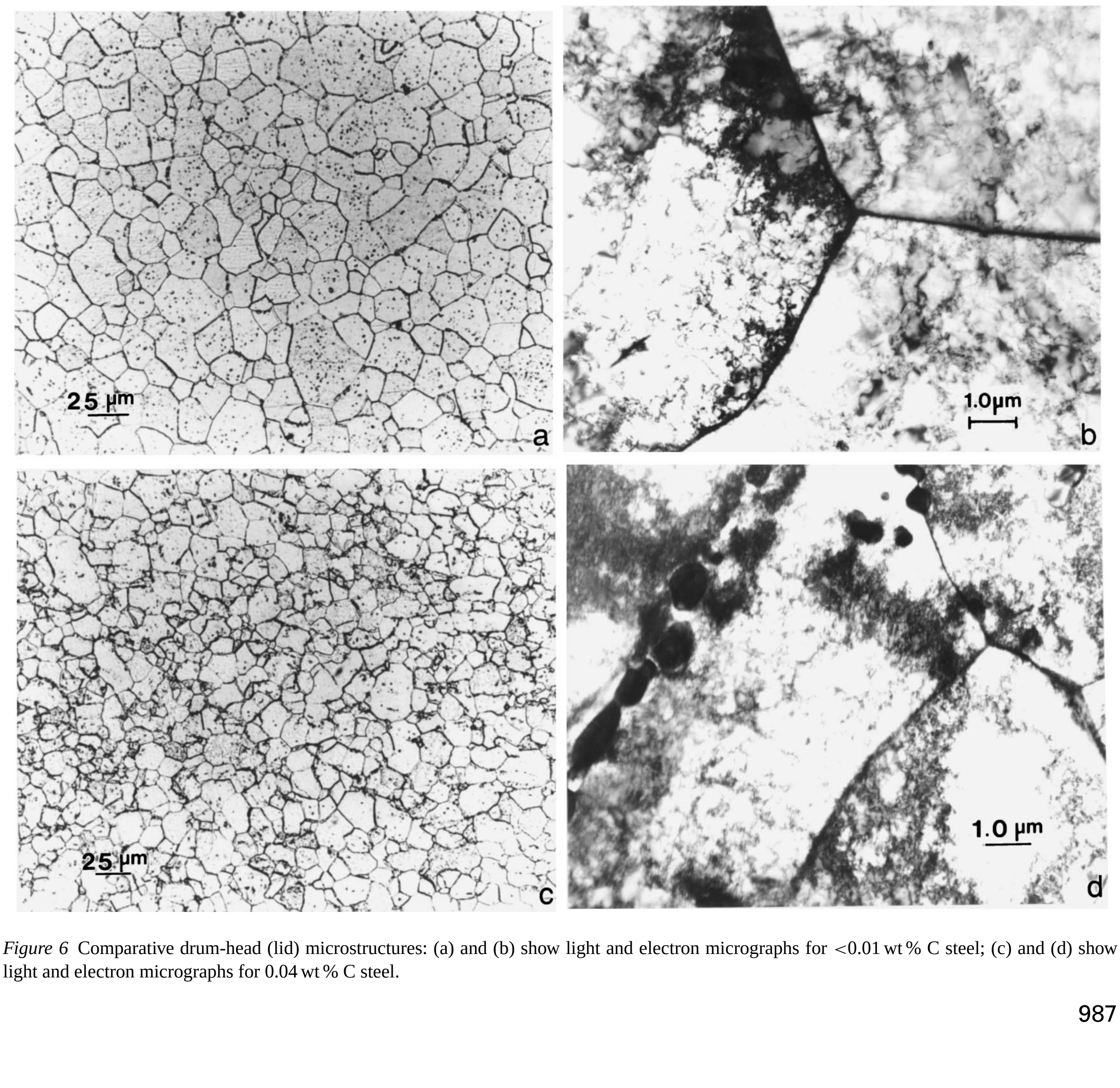


Figure 6 Comparative drum-head (lid) microstructures: (a) and (b) show light and electron micrographs for <0.01 wt % C steel; (c) and (d) show light and electron micrographs for 0.04 wt % C steel.

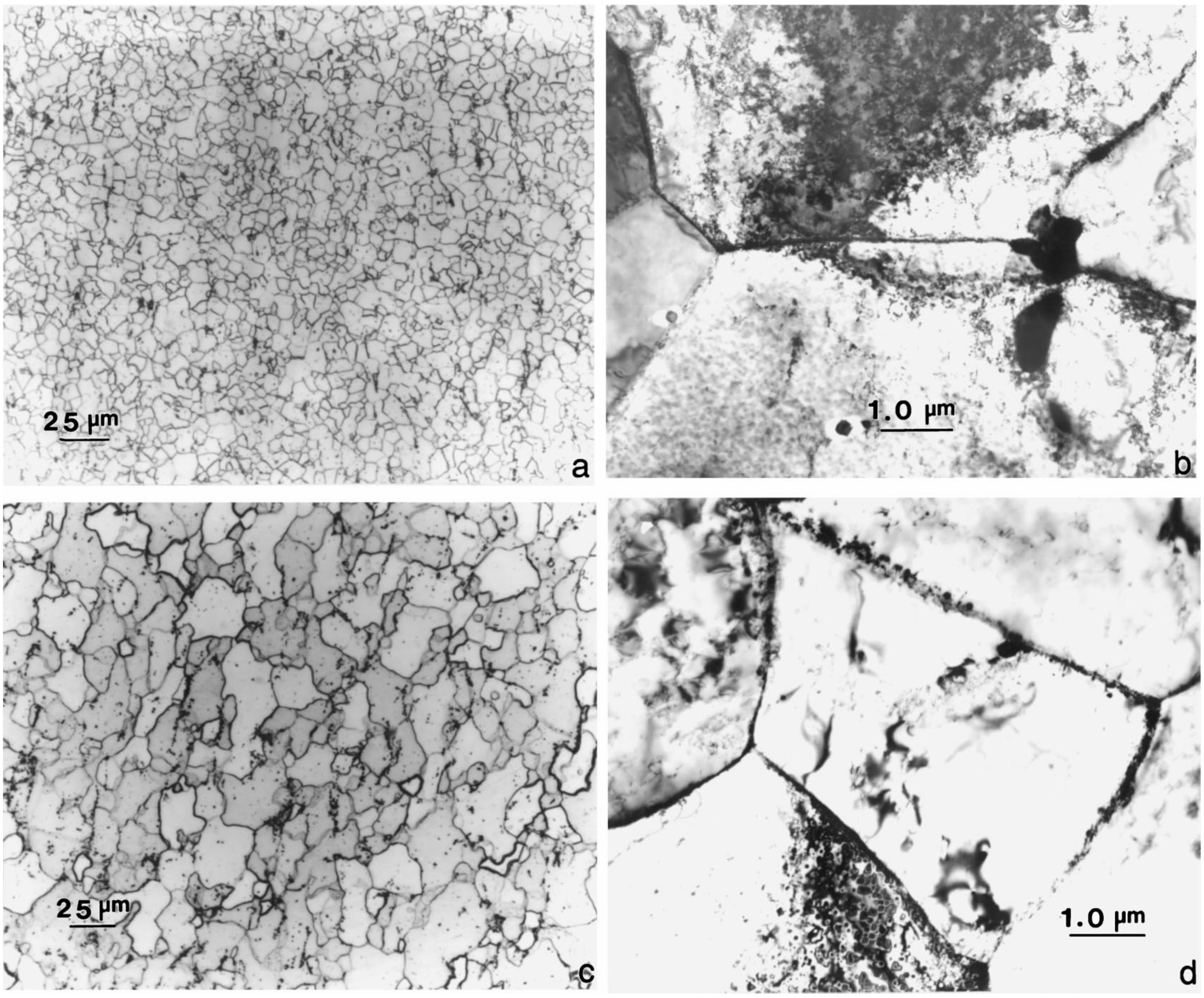


Figure 7 Comparative drum-skirt microstructures: (a) and (b) show light and electron micrographs for 0.03 wt % C steel; (c) and (d) show light and electron micrographs for <0.01 wt % C steel.

general guidelines for the selection or quality assurance for starting 55-gallon drums to be used in the fabrication and tuning of superior, orchestral steel-drum voices.

4. Hardness measurements and hardness profiles for a harmonically tuned steel drum

Fig. 8 shows the appearance of the partially tuned, double-tenor drum indicated as PTD-S(2) and PTD-L(2) (for the corresponding drum skirt and the sunken drum head, respectively) in Table I. This drum was shown in cross-section along with the per cent cold reduction (and engineering strain per cent) in Fig. 2 of Part I [1]. However, prior to cutting this drum in half, a complete acoustic analysis was performed for each note, and the so-called dynamic impact hardness for the entire drum surface along with each note area was measured. To make such measurements, a portable hardness-impact probe with a spherical test tip and a digital read-out was utilized (Equotip hardness tester). This impact device employs a spring-driven impactor, which measures the effective surface hardness. Because the test area is not a rigid plate specimen, as employed in static Vickers microhardness measurements, this dynamic impact hardness is related to both the plastic and elastic properties of the tested area. In contrast, an instrumental Vickers hardness test measures (ideally) only the plastic response of the specimen. Vickers hardness measurements were made over representative drum-surface areas between the notes and in each note by selectively cutting all the notes from the drum surface (along the groove lines) after the completion of acoustic analysis and dynamic impact hardness measurements (designated L_D hardness). A Shimadzu hardness tester, using a 3 N load to produce Vickers hardness numbers (1 VHN = 0.01 GPa), was employed in the static hardness analyses.

Hardness measurements, L_D, using the portable hardness impact probe were also obtained from the coupons cut from extracted note zones on which instrumental VHNs were obtained. The dynamic (L_D) hardness when compared to static Vickers hardness (VHN) was found to be below the actual instrumental (Shimadzu) hardness values. This could be attributed to the necessity of creating a conversion curve (H_V to L_D) for the steel used in the drums, since the conversion table used corresponds to a specific steel provided in the manual of the Equotip hardness tester (unalloyed and low alloy steel and cast steel in hot rolled and thermally treated condition). On the other hand, there was in fact a linear relationship between these two hardness tests on the same extracted coupons.

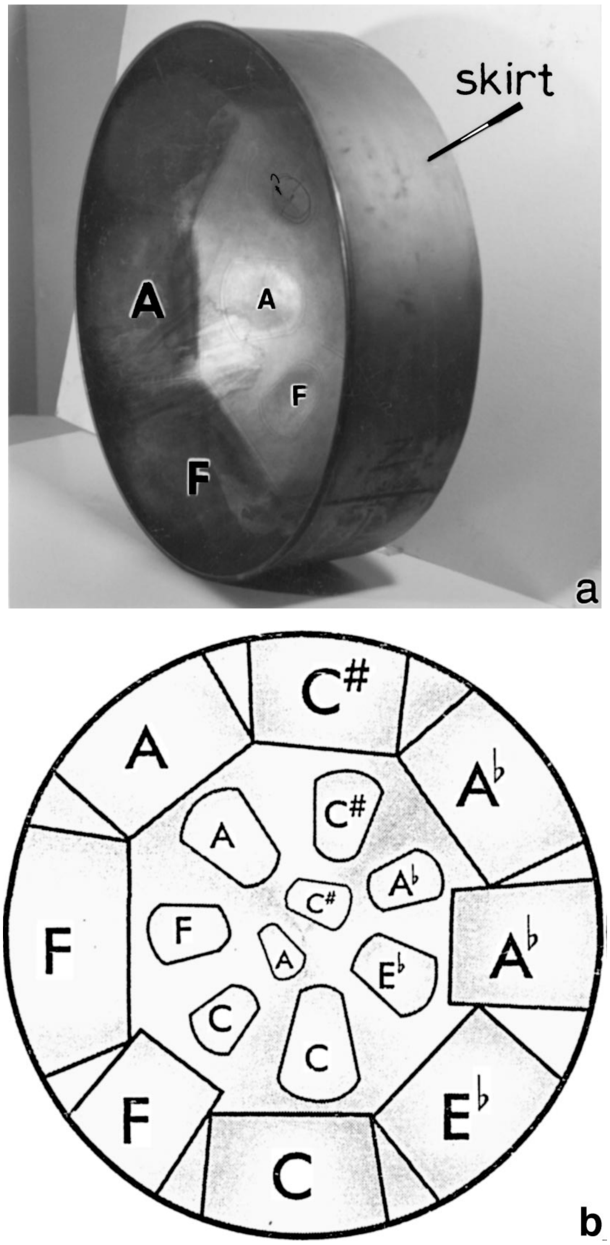


Figure 8 Double-tenor (left) drum, partially tuned (a) designated PTD-S(2) and (PTD-L)(2) to characterize the skirt and lid chemistries in Table I. (b) Shows the corresponding note pattern.

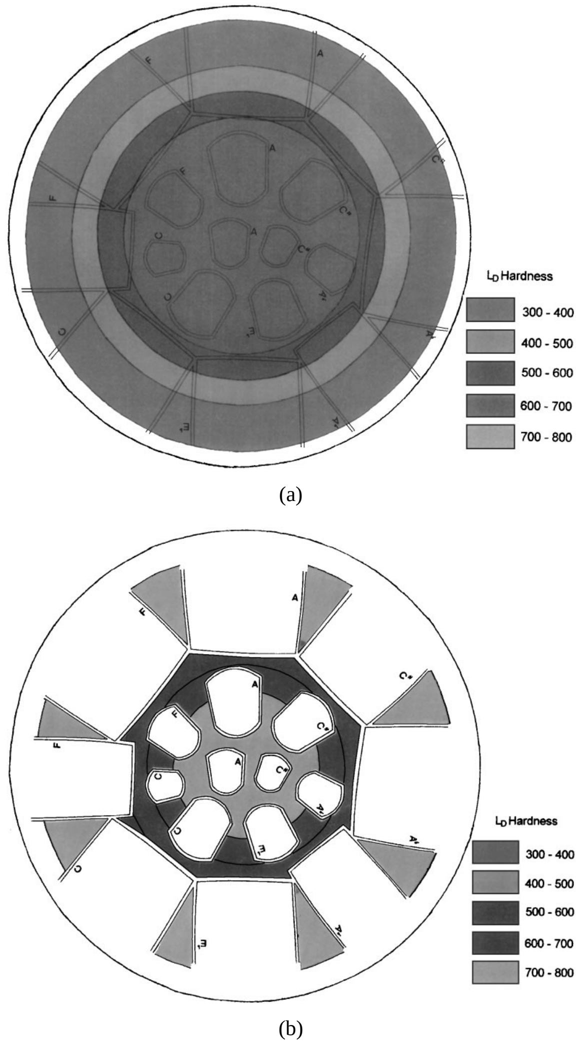


Figure 9 Dynamic impact, L_D, hardness maps for a double-tenor drum: (a) sunken drum–note patterns are shown positioned on the mapped surface, (b) completely fabricated and partially tuned drum showing hardness profiles outside of the note zones–the colour keys shown in (a) and (b) indicate intervals of 100 L_D hardness.

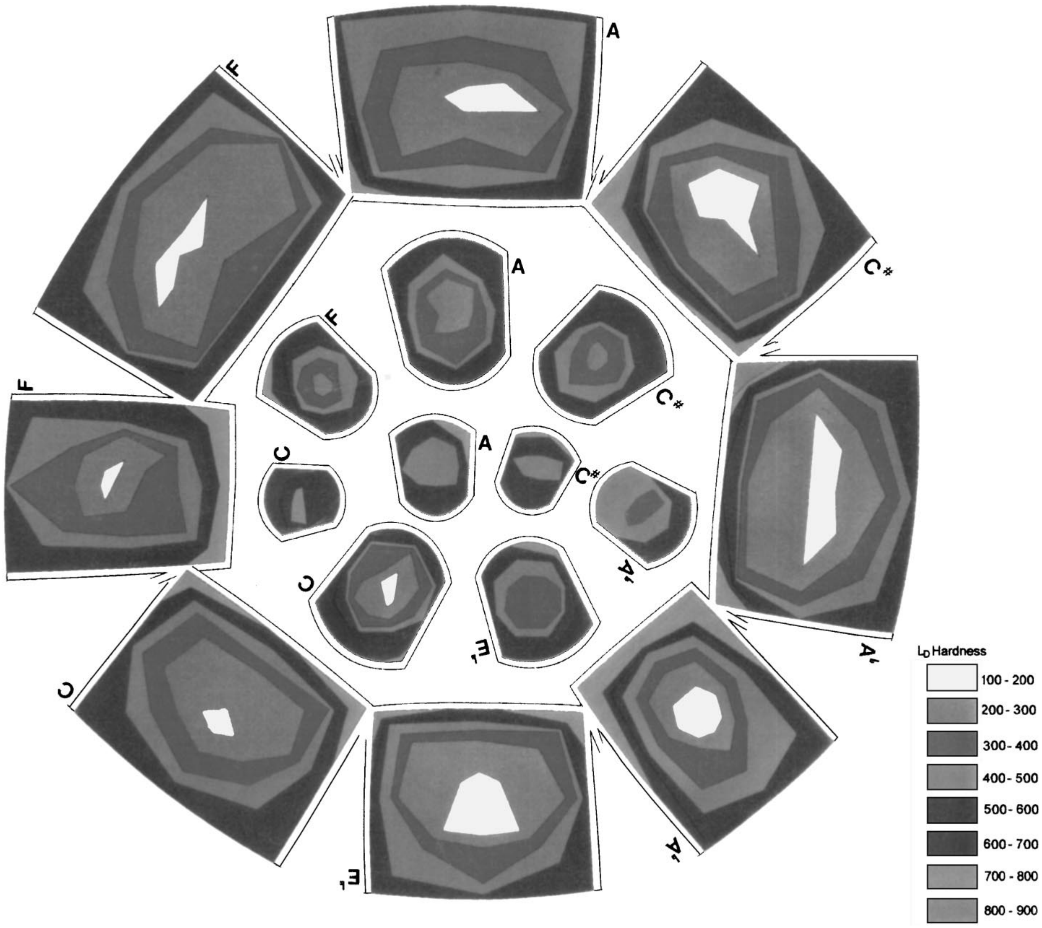
Dynamic impact, L_D, hardness measurements were also made over the drum surface for the as-sunk drum head (shown in Fig. 2 of Part I [1]), which contained no notes (and indicated by SD-S(1) and SD-L(1) in Table I). These hardness measurements were made prior to cutting the drum in half and measuring the corresponding thickness reductions plotted in Fig. 2 of Part I [1].

Fig. 9 shows for comparison the dynamic impact hardness, L_D, profiles for the as-sunk drum head (Fig. 2 of Part I [1] and Table I of Part II) and the fully patterned double-tenor drum. The as-sunk drum L_D profile in Fig. 9a was obtained by measuring one-fourth of the drum surface and creating a symmetrical composite by colourizing intervals of 100 L_D. In Fig. 9b, a similar technique was employed to map the hardness profiles of the drum platform outside of the note areas. In Fig. 9a the four hardness zones are somewhat coincidental with the original markings established to guide the sinking process as shown in Fig. 1a of Part I [1]. Fig. 9b shows that considerably more hardening is induced into the drum surface during the note placement, grooving and shaping operations.

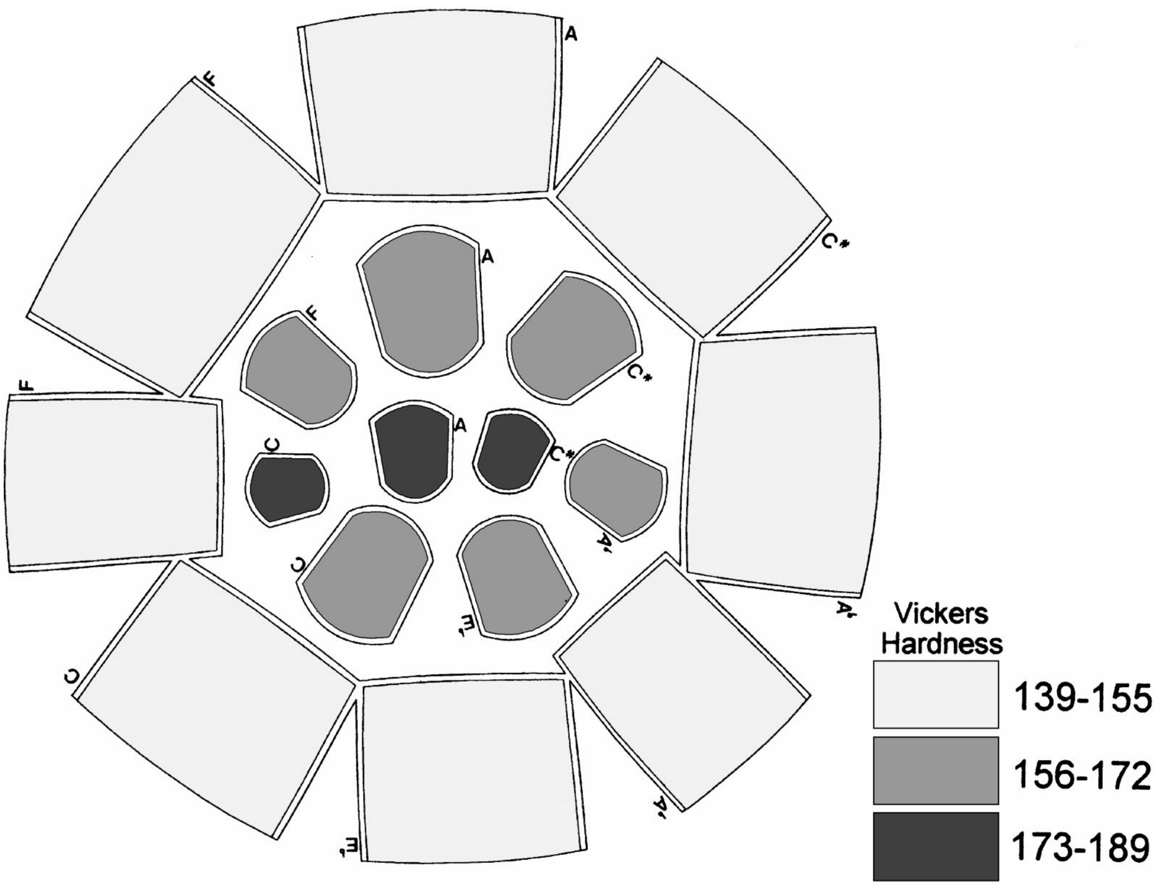
Fig. 10 shows for comparison the dynamic impact hardness mappings for each note of the double-tenor drum, and the corresponding static instrumental Vickers hardness measurements. The mappings in Fig. 10a show rather dramatically the elastic–plastic coupling, which characterizes the notes as vibrating membranes producing multiharmonic spectra. Fig. 10b shows essentially three hardness regimes to characterize the plastic strength of the note as a rigid platform, which actually shapes the note, with hardness variations of 17% in the outer, larger notes shown yellow, and roughly 10% in the intermediate (green) and inner (blue) notes.

Fig. 11 illustrates in more detail the methodology in constructing each dynamic impact hardness profile in Fig. 10a and shows the actual hardness measurement profiles used in creating the colourized note maps.

Fig. 12 illustrates the dynamic impact hardness variations by zones within the drum head and the corresponding fundamental (tonic) frequency associated with these hardness zones and notes within the zones.

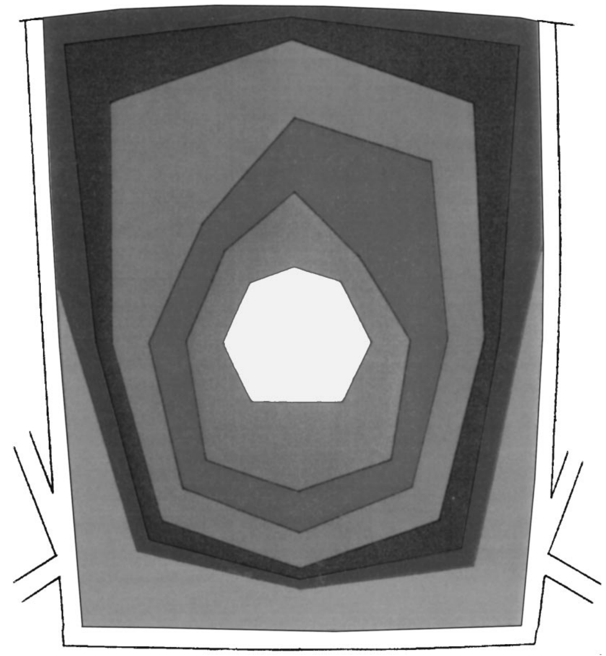


(a)

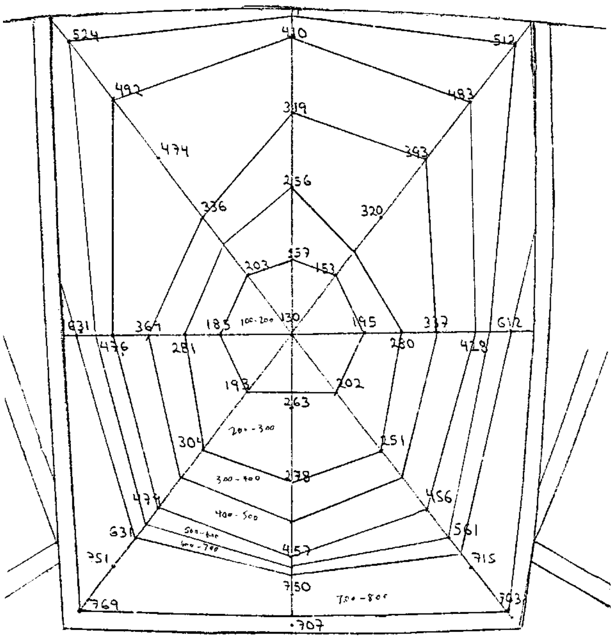


(b)

Figure 10 Comparison of note zone dynamic impact, L_D, hardness maps (a) with the static Vickers hardness profiles for the same notes for the double-tenor drum in Fig. 9b (b). Hardness zones are shown in the corresponding colour keys.



(a)

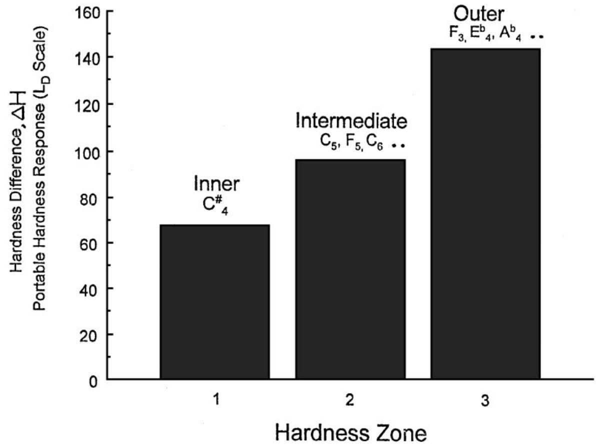


(b)

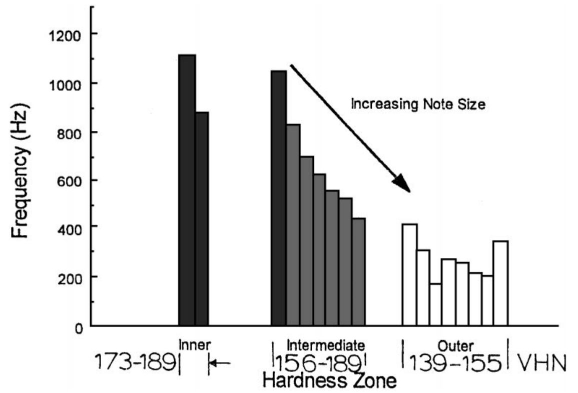
Figure 11 Enlarged A^b note zone in Fig. 10a showing the colour-map details (a) and the original hardness-profile measurements from which the colour map was constructed (b).

Fig. 13 shows both linear and logarithmic (base ten) plots of the long note length, L, within the grooved areas as a function of the fundamental frequency for each note in the double-tenor drum of Figs 9–12. Fig. 13b shows the double-tenor notes (in Fig. 13a) plotted along with a wide range of steel-drum voices (including double tenors, seconds, cellos, tenor bass and bass). The data for these voices (shown shaded in Fig. 13b) were obtained from the previous work of Rossing et al. [6]. These results confirm that the fundamental frequencies for steel drum notes are given by

$$f = C/L^{3/2} \tag{1}$$



(a)

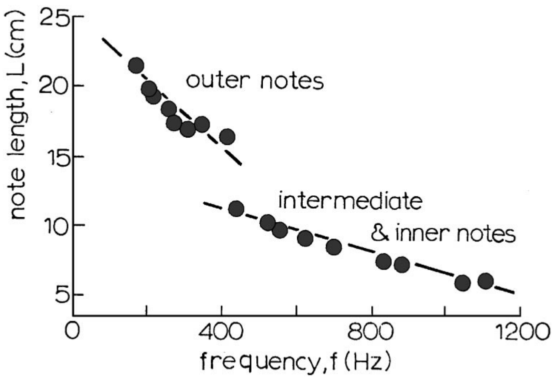


(b)

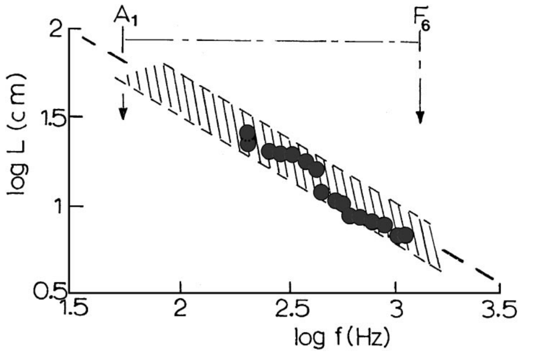
Figure 12 Dynamic impact hardness variations for the inner, intermediate and outer note zones for the double-tenor drum (a) and note frequency variations for these same zones using a Vickers hardness notation (b) (1 VHN = 0.01 GPa).

where C is a constant (which includes $[E/\rho(1-\nu^2)]^{1/2}$, where E, ρ and ν are the elastic modulus in tension, the density and Poisson's ratio, respectively), and L is the longest dimension or note length. Equation 1 is independent of the note thickness and, like more complex relationships for shells, etc., presumably does not contain any microstructural parameters. However, this is not at all descriptive of the actual note voice or timbre. In effect, the relatively simple shaping of ellipsoidal notes is essentially all that is required to produce a frequency very near the tonic. However, the harmonic tuning will be a much more complex feature of the note thickness and microstructure (or hardness), and these features will be discussed in more detail later in connection with acoustic analysis of the notes.

Fig. 14 illustrates the extraction of notes from the double-tenor drum head for the measurement of instrumental (digital) Vickers hardness as shown in Fig. 10b, and the metallurgical examination of the associated microstructures. Fig. 14b and c shows the residual, central note (C#) microstructure following hardness measurements. The grain structures shown in Fig. 14b are somewhat more exaggerated than those observed for the sunken drum head and are a result of additional hammering to shape the note. The dislocation substructure through the note centre shown in the TEM image of Fig. 14c is also not significantly altered from that observed in the sunken drum head (Fig. 3 in Part I [1]), but



(a)



(b)

Figure 13 Simple note length versus frequency for a double-tenor drum: (a) linear plot, (b) log–log plot superimposed on previous data for a full range of drum voices (shown shaded) measured previously by Rossing *et al.* [6].

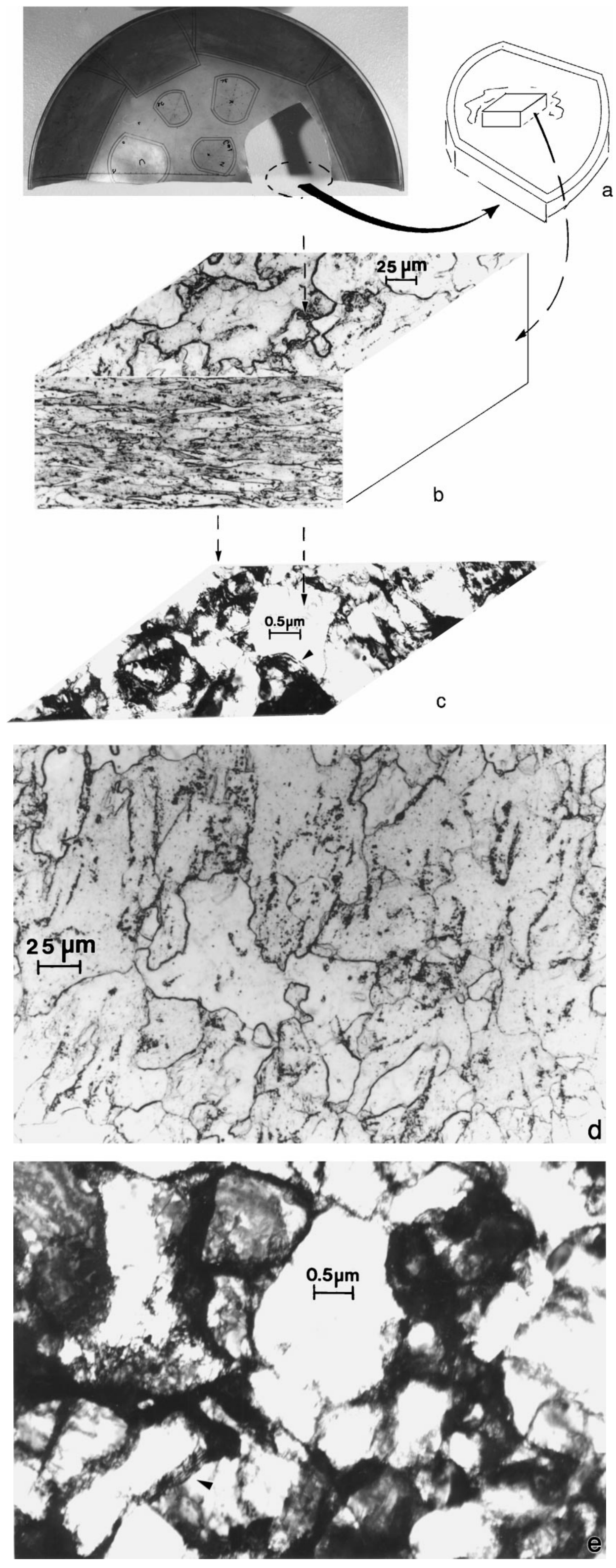


Figure 14 Microstructures typical of notes extracted from the double-tenor, partially tuned drum (PTD(2)). (a) Note (C#) cut from the drum-head half-section. (b) Light metallograph images of the grain structure in the plane of the note and through the note thickness (near the note centre). (c) TEM image of dislocation substructures in the plane of the note (corresponding to (b)). (d) Light metallograph image of grain structure in the regions adjacent to the note (refer to Fig. 9b). (e) TEM image corresponding to plane section in (d).

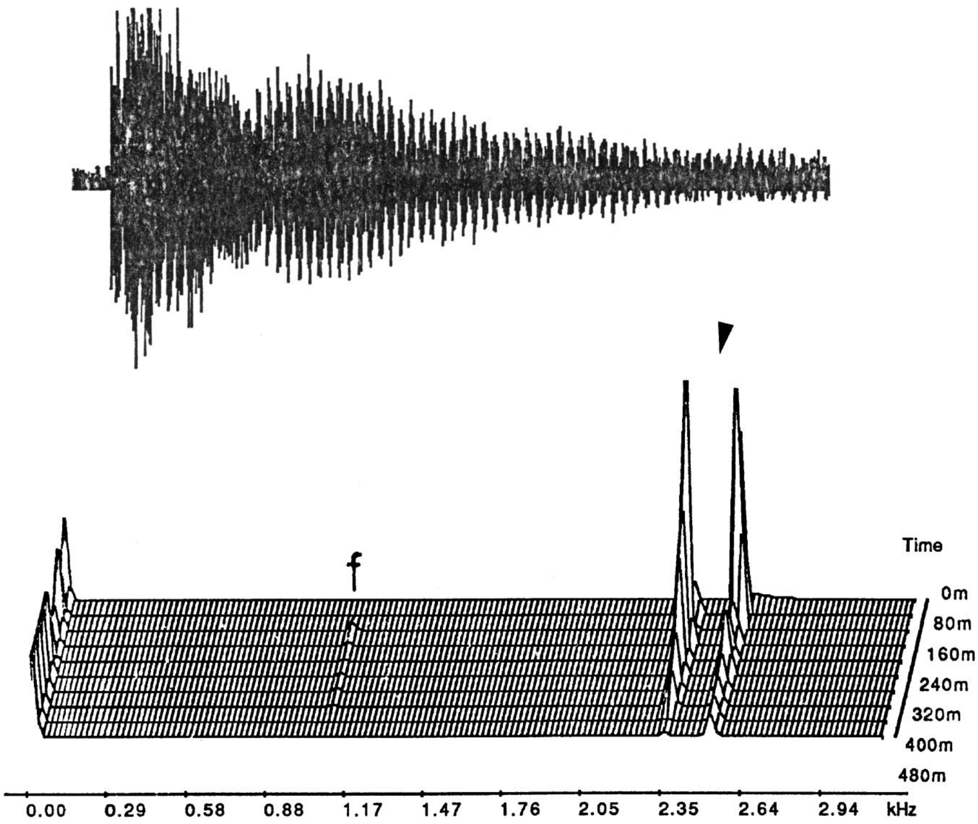
there is evidence of recovery and subgrain formation at interfaces marked by arrows in Fig. 14c and e.

It should be recognized that the dislocation substructures illustrated in Fig. 14c for the note centre, and the corresponding and essentially identical substructure that characterizes the steel drum head or acoustic platform shown in Fig. 14e, are reflected in the Vickers hardness profiles shown in Fig. 10b. Although we have not illustrated the acoustic spectra for these steel-drum notes, it should be apparent from Fig. 10, especially comparing Fig. 10a and b, that the harmonic tuning involves a complex interaction between the plastic-note properties, which manifest themselves in the dislocation substructure, and the elastic-note properties. These interactions are also the embodiment of the strain-ageing phenomena induced by the heat treatment of the drum head, a treatment that fundamentally manipulates the "rigidity" of the dislocation structure by the diffusion of carbon atoms along the elastic strain fields of individual dislocations. Tuning of the notes also involves elastic adjustments to the notes, adjustments that provide permanent vibrational modes producing audible octaves and harmonics, as well as the note pitch. Of course, note distortions, which can occur by repeated playing, require retuning.

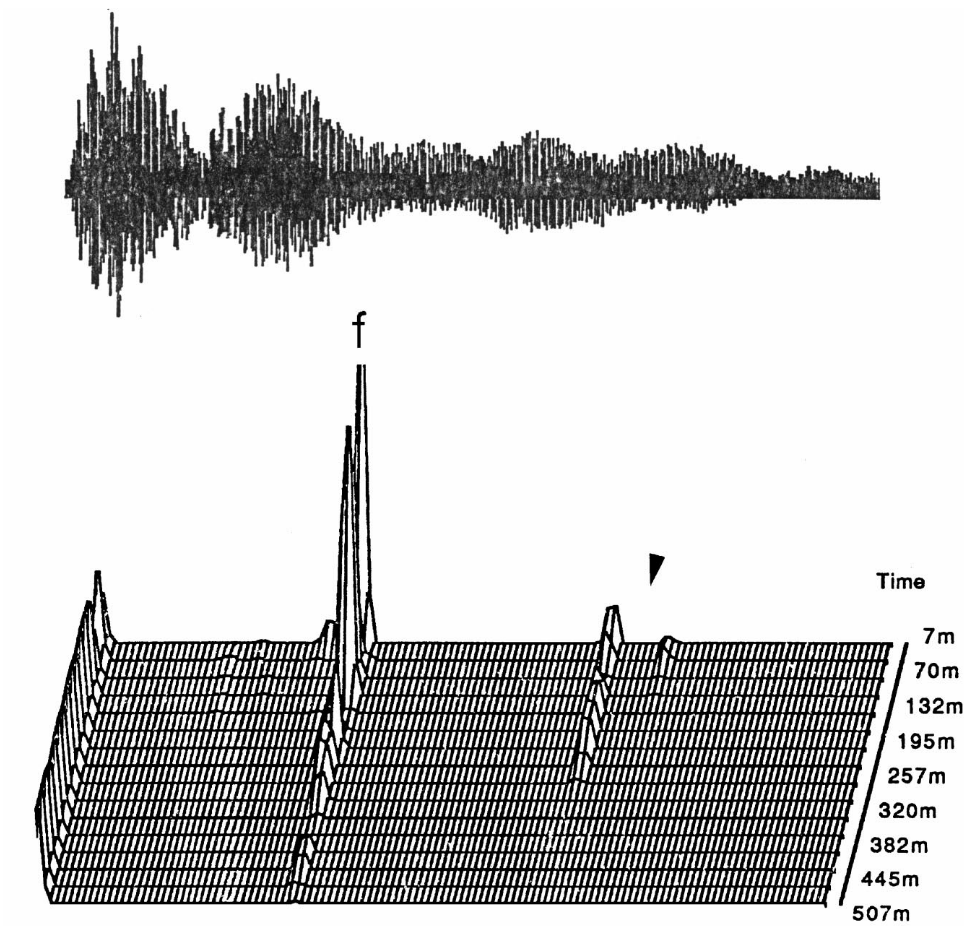
5. Acoustic analysis and tuning issues

Utilizing the acoustic-analysis software illustrated in Part I [1] for the analysis of ideal, free circular plates, we performed a complete analysis for each note voice pattern in the partially tuned (left) double-tenor drum (PTD-2(2) in Table I and Fig. 10); and we examined these patterns for evidence of harmonic features noted for the ideal, circular notes [1].

Fig. 15 shows for comparison the thinnest and most deformed 316 stainless steel, free circular plate spectra



(a)



(b)

Figure 15 Comparison of acoustic spectra for 316 stainless steel free circular (7.3 cm diameter) plate (a) with A^b steel drum, 7.3 cm long note (Fig. 10a) (b). Note that in the corresponding linear plots of amplitude, frequency and time, the harmonics for each are split as indicated by the corresponding arrows. The fundamental is marked *f*.

with those for the most comparable steel-drum note (double tenor A^b–near A_5) in the partially tuned drum shown in Fig. 10. This note (A^b) was in fact a partially tuned note. It has a maximum dimension or note length of around 7.3 cm, which essentially matches the free, circular plate diameter of 7.3 cm. The note thickness varies from about 0.7 to 0.8 mm in contrast to the 40% cold-rolled, 0.76-mm-thick free circular plate. The fundamental frequencies, however, differ by about 280 Hz. The corresponding engineering strains are also similar (approximately 40%). The comparison of these note spectra are rather striking as might be expected; the steel-drum note contains a split harmonic with $\Delta f \cong 170$ Hz in contrast to $\Delta f = 160$ for the circular disc. However, the fundamental in the circular disc has no acoustic energy, while in the steel drum A^b note, the split harmonic has low but audible energy in contrast to the fundamental. When tuned, however, its energy is increased. As a consequence, the effect of deformation and deformation microstructures, illustrated in Part I [1], is also observed to be a notable feature of some steel-drum-note spectra (timbre), contributing significantly to the multiharmonic sound of steel-drum notes. These multiharmonic features (strong fundamental and harmonic) are actually demonstrated for many of the steel-drum notes, and Fig. 16 shows some of these phenomena for a range of tuned note pitches. Unlike the shifting of audible amplitudes to harmonics, steel-drum notes usually contain audible tonics and harmonics.

The note timbres recorded in the acoustic spectra shown in Fig. 16 may become useful tuning patterns along with strobe analysis for tonic and harmonic adjustment during tuning. A careful comparison of tuning sequence changes in these spectra and corresponding frequency–time renderings, as shown in Fig. 15(b), may in fact simplify the tuning process. In addition, more critical acoustic signal analysis of steel-drum notes along with heat-treatment (strain ageing) variations might eventually lead to an understanding of very subtle harmonic qualities contributing to superior or even special sounds for a variety of steel-drum voices.

While the tuning is independent of the steel-drum skirt, the overall timbre can be altered by varying the skirt length. But beyond this, there is no manipulation of the skirt during fabrication, i.e. it is not worked (deformed), and it is not strain aged in the same way the drum head is because during heat treatment the drum-skirt temperatures never reach those in the drum head. It is likely that just as deformation influences note timbre, variations in skirt deformation or even strain-ageing effects may also have some influence on the overall drum timbre (voice quality).

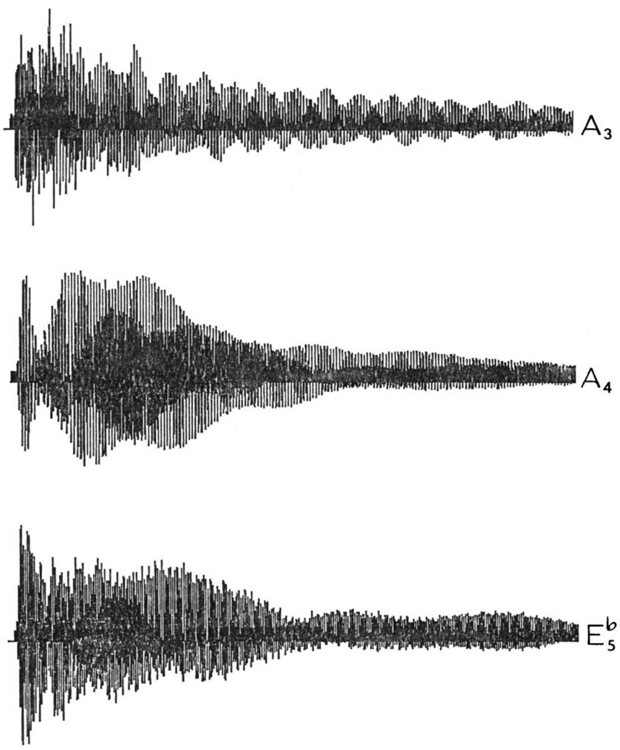


Figure 16 Comparison of acoustic spectra for numerous tuned notes from a double-tenor steel drum.

6. Strain-hardening issues and steel-drum innovations

In the stress–strain diagram shown somewhat ideally in Fig. 10 of Part I [1], the linear portion (shown dotted) produces an elastic regime (shown shaded). Often this linear slope is almost coincident with the stress axis, and the equation for the plastic portion of the curve (especially for steels) is often approximated by the so-called Ludwik–Holloman power-law equation [7]

$$\sigma = K\varepsilon^n \tag{2}$$

where K is often called a material-strength coefficient and n is the work-hardening coefficient. Of course, increasing values of K imply increasing material plastic strength, while n is a measure of how much harder a metal or alloy must be strained in tension to make it stretch a certain amount more at a given strain rate. For good formability of a sheet metal, n should be high; ideally n varies between zero and one as illustrated in Fig. 17a. The larger the value of n, the greater the resistance to necking because the rate of work hardening will be greater in the necked region. Of course, when a sheet metal is stretched biaxially as in the sinking of a lid or bottom of a 55-gallon drum to form a Caribbean steel-drum head, the process is more complex because the maximum strain at instability varies with the strain ratio in a forming operation. A forming-limit diagram (FLD)

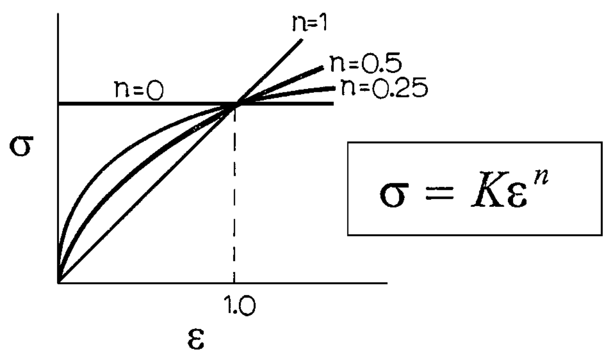


Figure 17 Strain-hardening/work-hardening characteristics.

TABLE II A comparative matrix for several materials

Metal/alloy	Crystal structure[b]	n	K (Psi/MPa)[c]	
0.6 wt % C steel	bcc	0.10	228 000	1572
4340 steel	bcc	0.15	93 000	641
0.05 wt % C steel[a]	bcc	0.26	77 000	531
70/30 brass	fcc	0.50	130 000	897
Austenitic stainless steel	fcc	0.52	220 000	1517

[a]Good quality drum steel (lid or bottom).
[b]bcc, body centred cubic; fcc, face centred cubic
[c]Room temperature (approximately 20 °C); $K = G/x$, where G is the shear modulus and x varies from 10^2 to 10^3.

[7, 8] can serve as a guide in analysing sheet-metal deformation processes, and could in fact be constructed for a sunken steel-drum head by placing a circular grid pattern on the underside of the undeformed drum head, and then measuring the major and minor dimensions of the ellipses formed after sinking the drum head. The FLD varies with gauge number (or thickness) of the drum sheet and also with the degree of prior work hardening. In fact, Equation 2 is often written in the more general form

$$\sigma = K(\epsilon_o + \epsilon)^n \tag{3}$$

where ϵ_o is the prior strain hardening.

Table II and Fig. 17 show strain-hardening characteristics, etc., for a few materials, including low-carbon steels typical of conventional steel-drum materials. This table also indicates the crystal structure, which is important in the context of slip multiplicity–or the behaviour of dislocations during the deformation (sinking) process. Table II clearly shows that austenitic stainless steels may provide a superior drum head in terms of strength and strain hardening. Brass (70 wt % Cu–30 wt % Zn) also looks promising. However, brass would not strain age and would probably not require firing of the sunken and patterned drum head. A more promising approach in producing experimental steel drums might involve constructing standard 55-gallon barrels with appropriate gauge austenitic stainless steel (type 316), which would not be susceptible to martensite formation with per cent cold reduction. Stainless steel would also strain age differently than the conventional drum steel shown in Table I, and any attempts to produce a multiharmonic steel drum from new material would require considerable testing and careful control and recording of process variables.

7. Discussion

More than a century ago, Hermann Helmholtz wrote: "These secondary tones, including the higher ones, usually continue to sound longest in elastic metal of fine, uniform consistency, because its greater mass gives it a greater tendency to continue in any state of motion which it has once assumed, and among the metals the most perfect elasticity is found in steel, and better alloys of copper and zinc, or copper and tin" [9]. So, while it may have been circumstantial, if not accidental, that the Trinidad and Tobago steel drum (or pan) came about, it is indeed serendipitous that the development of the instrument as one of the most complex, non-linear music sources has followed a rather rigorous metallurgical-process regime over the past half century, including strain hardening during actual fabrication, and strain ageing in preparation for harmonic tuning of patterned notes. The tuning process itself poses some of the most complex issues because the maintenance of superior musical quality for a steel drum requires continuous tuning in many cases. Although the fundamental frequency or note pitch does not deviate significantly as a consequence of shape-related functionality, the development of octaves and especially multiple harmonics requires subtle adjustments in the elastic–plastic note properties by special hammering to pull the note surface in specific ways. Fig. 16 in particular attempts to demonstrate that by recording individual note spectra, these spectra may serve as effective "voice prints" to guide the tuning process and the necessary and specific hammer strokes.

Strain ageing has been shown to be the important consequence of heat treatment of the drum head. Effective strain ageing undoubtedly contributes to the ability to adequately tune notes, and possibly to the ability of notes to sustain a tuned configuration. To provide an adequate level of hardening by strain ageing, it is probably necessary to assure the drum head is heated to at least 177 °C (350 °F). However, 350 °C is probably an optimum temperature and should be sustained for at least 10 min. It does not seem to matter whether the drum head is water quenched or air cooled, although water quenching allows the drum to be worked or tuned without waiting for the drum head to cool. Of course if the drum head is heated to temperatures significantly less than 350 °C, the ageing time would have to be increased (perhaps considerably) to produce the same ageing conditions [3]. Ageing times of 30 min for temperatures between about 250 and 350 °C would not seem unreasonable, but it would be useful to have a more comprehensive matrix relating strain, temperature and ageing time in relation to some characteristic hardening increment, ΔH.

Although we have not specifically altered and monitored the microstructures or associated properties of steel-drum skirts, the implications of actual strain hardening (work hardening) of the sunken drum head seem to indicate that a purer drum timbre results for an annealed (undeformed) skirt. This occurs because of an overall reduction in acoustic dispersion. Since strain ageing is of no real consequence in the skirt, the carbon content may be considerably lower than the drum head. The drum-head carbon content is important for appropriate strain-ageing effects, and an optimum seems to be about 0.04–0.05 wt % C. Correspondingly, the skirt can be <0.01 wt % C. In addition, the drum-head grain size should be smaller than the skirt (see Table I). However, it may be possible to alter the overall drum timbre by cold working the skirt, and this is a simple aspect of steel-drum development that should be pursued. Variations of the skirt or even the drum-head material as implied in Fig. 17 may also prove interesting in providing different sound or timbre alternatives as well as variations in the pitch and harmonic range. Certainly the steel drum does not have to be confined to a 55-gallon drum configuration, and changes in the drum-head size could also have a significant effect on the drum sounds. In fact, from Equation 1 of Part I [1], it is apparent that in addition to altering the overall drum timbre by changing the skirt length, the drum-head radius can make a corresponding change.

8. Conclusions

We have shown that cold reduction (per cent) creates defects (dislocations) that increase the acoustic dispersion. To the extent that this dispersion (or harmonic peak splitting) may contribute to the unique multiharmonic steel-drum sound, it may be possible to increase the drum-bottom reduction (or deformation) and alter the timbre of the higher-frequency notes patterned there. Since deformation microstructures contribute to the unique harmonic features of the steel drum, it may not be possible to create these special sounds by machine forming of the drum head. Consequently, the historic, hand forming of steel drums not only personalizes the tens of thousands of instruments created worldwide, but may in fact be a requisite fabrication methodology to create their unique sounds. Nonetheless, more research aimed at investigating the machine forming of steel-drum heads may prove enlightening.

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