Precise velocity measurement of surface acoustic waves on a bearing ball

著者	山中　一司
journal or publication title	Applied Physics Letters
volume	76
number	19
page range	2797-2799
year	2000
URL	http://hdl.handle.net/10097/48086

doi: 10.1063/1.126481

APPLIED PHYSICS LETTERS VOLUME 76, NUMBER 19 8 MAY 2000

Precise velocity measurement of surface acoustic waves on a bearing ball

Kazushi Yamanaka[a] and Hideo Cho
Department of Materials Processing, Tohoku University, Aoba 02, Sendai 980-8579 Japan

Yusuke Tsukahara
Technical Research Institute, Toppan Printing Co. Ltd., 4-2-3, Takanodai-Minami, Sugito-machi, Kitakatsushika-gun, Saitama 345-8508, Japan

(Received 31 August 2000; accepted for publication 14 March 2000)

Using the photoacoustic effect of interference fringes scanned at the phase velocity of surface acoustic waves (SAW), we excited tone bursts of SAW with a center frequency of around 30 MHz on a 8 mm ϕ steel bearing ball. A surprisingly large number (around 20 turns) of round-trip propagations was observed. The time interval between the SAW at the first and the twelfth turn was as large as 93 μs, however it could be determined with a 2 ns resolution since an exact overlapping of the two wave forms was possible. Thus, we achieved a very high resolution of 0.002% in the velocity measurement, and a velocity change of 2 m/s due to the deposition of a 50-nm-thick Ag film was easily detected. Because of its noncontact nature, this method would be useful for nondestructive evaluation of bearing balls. © *2000 American Institute of Physics.* [S0003-6951(00)02719-4]

Objects with curved surfaces such as rotating axes of machines and bearing balls are important targets of nondestructive evaluation (NDE). For these objects, it is often necessary to evaluate the surface or near-surface properties using surface acoustic waves (SAW). Laser ultrasound[1] is useful for the evaluation of curved surfaces because it is a noncontact technique, whereas it is difficult to apply contact ultrasonic transducers on surfaces of large curvature. There is however only one paper, by Royer *et al.*,[2] that describes laser-generated SAW on a sphere. They generated SAW on a sphere by focusing a Q-switched yttrium–aluminum–garnet (YAG) laser beam to a spot of about 0.5 mm diameter. The SAW were detected at the pole[3] diametrically opposite to the source, where the SAW exhibited the largest amplitude of about 3 nm. Since the SAW frequency was low and the bandwidth was broad, the curvature of the surface gave rise to a significant dispersion effect[3] that changed the wave form during propagation. Although they determined the intrinsic group velocity dispersion of a sphere from signal processing of measured wave forms, the precision was not very high, and errors of around 10 m/s were encountered (Fig. 3 of Ref. 2). Similarly, Kawald *et al.*[4] described a single pulse excitation of circumferential mode of a cylinder and used the bandwidth to determine the dispersion due to a material layer on the cylinder, but the realization of a precision better than 1 m/s was not reported.

Recently we developed the phase velocity scanning (PVS) method[5] that can selectively excite SAW. In the scanning interference fringes (SIF) approach of the PVS method,[6,7] a tone burst (wave packet) of high frequency SAW (30–110 MHz) is efficiently excited when the scanning velocity ν_f of the fringes is identical to the phase velocity ν_R of the SAW. Because the SAW frequency is high and the bandwidth is narrow, the effect of dispersion is negligible, and the wave form does not change during propagation. This is advantageous for high precision velocity measurement.[8] In this letter, we describe high frequency SAW generated on a sphere by the PVS method. In particular, we show that very precise SAW velocity measurement with a relative error of around 0.1 m/s is realized on bearing balls, which is useful for sensitive evaluation of surface properties.

Experiments were performed on steel bearing balls of 8 mm diameter. One ball was used as received; we deposited Ag film on the surfaces of the two other balls by vacuum evaporation, simulating the surface property change due to surface modification or fatigue during use. Although the thickness of the film was not uniform because of the surface curvature, the maximum thickness was approximately 50 and 150 nm, for the two bearing balls.

Figure 1 shows the apparatus for generating and detecting SAW on a bearing ball. Two YAG laser beams each of 3 mm diameter, one of which was frequency shifted by 30 MHz using a Bragg cell, were directed almost perpendicu-

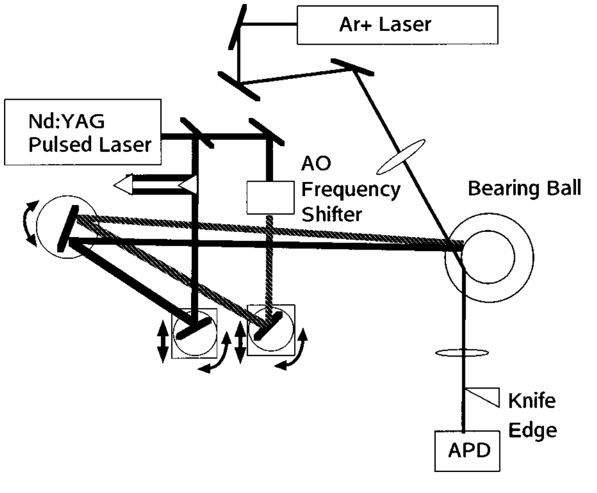

FIG. 1. Apparaus for generating and detecting SAW on a bearing ball.

---

[a] Electronic mail: yamanaka@material.tohoku.ac.jp

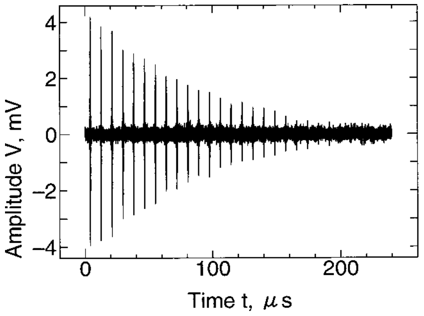

FIG. 2. Observed signal of SAW with a large number of monotonically decaying pulses.

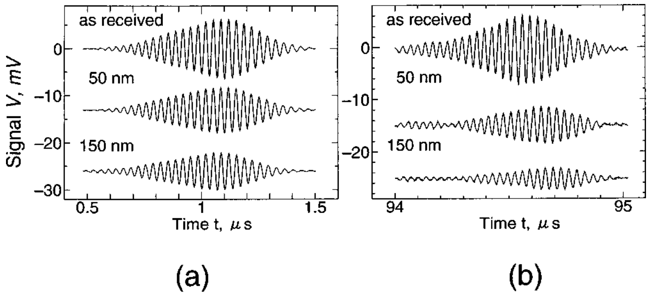

FIG. 3. Expanded wave forms of SAW at (a) the first turn and (b) the twelfth turn.

larly to the surface of a ball. Due to the interference of the two laser beams with different optical frequencies, scanning interference fringes were produced. By adjusting the mechanical stages, the average spacing of the fringes was made equal to the wavelength of the SAW, and the scanning velocity of the fringes was made equal to the phase velocity of the SAW, in order to establish an approximate phase matching. The laser has a specially designed long pulse width of around 100 ns, to allow a long interaction time between the fringes and the SAW. The long interaction time is essential for the selective generation and amplification of the SAW in the PVS method, while suppressing the bulk acoustic waves (BAW).[8]

The SAW propagated repeatedly along an equator of the ball perpendicular to the fringes. They were detected at each turn by the optical knife edge method with an argon ion laser probe focused at a position 3–4 mm away from the fringes. After detection, the frequency component lower than 20 MHz was filtered out. This filtering serves to reject BAW, which would be generated by the noninterference component of the laser beams. Since the laser pulse width is long (100 ns), the frequency of BAW is less than 10 MHz, which is completely separated from the SAW frequencies.

Figure 2 shows the observed signal. A large number of tone bursts were observed. We verified that they are SAW rather than BAW by applying a droplet of silicone oil on the top of the ball. When the droplet was small and did not reach the path between the fringes and the detection point, the signal was not changed. However, when the droplet reached the path, the signal completely disappeared. This result proves that all the signals were SAW and no BAW were generated. Furthermore, the SAW did not spread over the entire ball surface but were confined within a narrow path on which the fringes and the detection point are located. The number of round-trip propagations was as large as 20, corresponding to a total propagation length of 50 cm. The noise near the zero level is due to the 30 MHz signal driving the Bragg cell, which could be eliminated by careful shielding.

Figure 3(a) shows the expanded signals at the first turn on the as-received ball (top), the Ag-coated ball with a maximum thickness of 50 nm (middle), and with a maximum thickness of 150 nm (bottom). Figure 3(b) shows expanded signals at the twelfth turn. The signals were averaged over 10 measurements and digitized with a sampling interval of 2 ns. The signal-to-noise ratio was very high. Although the temporal separation of signals in (a) and (b) was large (93 μs), their shape was hardly changed.

The similarity of the two signals is important for precise time interval measurements when we apply the pulse echo overlap method or the cross correlation method. To test the similarity, we tried to overlap the signals by shifting the twelfth signal to the first signal. When the shift was 93.470 μs, the phase of the twelfth signal lagged slightly behind that of the first signal, as shown in Fig. 4(c). When the shift was increased by 8 ns, the phase of twelfth signal was slightly ahead of that of the first signal, as shown in Fig. 4(a). However, when the shift was 93.474 μs, a value calculated from the peak in the cross-correlation function of the two signals, the signals almost completely overlapped, as shown in Fig. 4(b). Because the similarity of the signals was very high, a variation of 4 ns led to an easily detectable phase mismatch. Consequently, the uncertainty in determining the phase delay of the two signals was less than 4 ns at around 2 ns. Since the total time interval was as long as 93 μs, the relative magnitude of this uncertainty is estimated to be 0.002%.

Taking advantage of this excellent temporal resolution, we tried to detect a small velocity change due to the deposition of a 50- or 150-nm-thick Ag film. In Fig. 3, the differ-

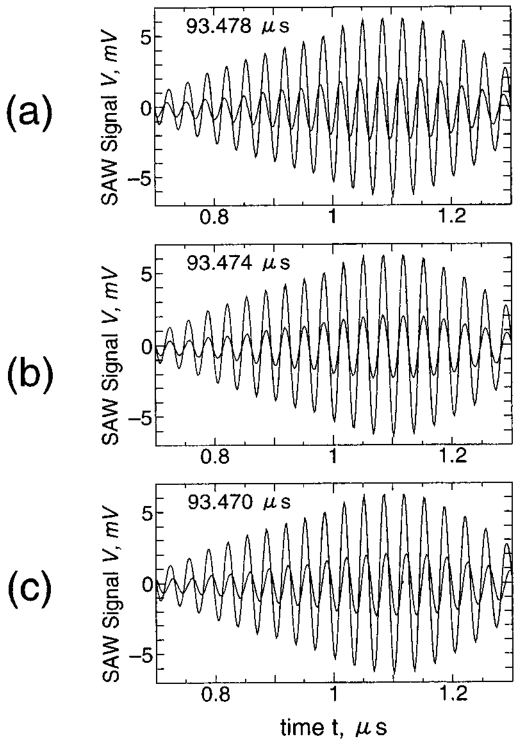

FIG. 4. Overlap of SAW wave form at the first and twelfth turn.

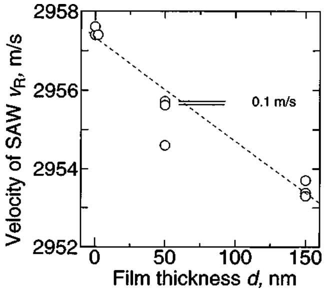

FIG. 5. SAW velocity as a function of the Ag film thickness.

ence of the time interval between the first (a) and twelfth (b) signals due to the deposition of the Ag film is clearly noticeable. This shows the dispersion effect due to the presence of the thin film. However, even in this case, the dispersion effect within the narrow bandwidth of the wave form was negligible, and no distortion of the wave form was observed.

For quantitative measurement, the cross correlation function of the signals in Figs. 3(a) and 3(b) was calculated. The time interval was determined to be 93.474 and 93.556 μs for the as-received ball and Ag-coated ball with a maximum thickness of 50 nm, respectively. Since the diameter of each ball was 8.0 mm, the SAW velocity was estimated to be 2957.6 and 2955.0 m/s, respectively, indicating a difference of 2.6 m/s. The SAW velocities obtained in three different measurements were plotted as a function of the film thickness in Fig. 5. A clear trend is observed for the decrease of SAW velocity with an increase of the Ag film thickness. The typical scattering of the measured velocities was around 0.1 m/s (considering that the absolute value was 2958 m/s, the relative scattering was as small as 0.0034%).

Since the velocity difference due to the 50-nm-thick Ag film was 2.6 m/s, the minimum detectable variation of film thickness is calculated as $50\times 0.1/2.6=1.9$ nm. This sensitivity would be enhanced to 0.19 nm at 300 MHz, since the sensitivity is proportional to the acoustic frequency when the film thickness is much less than the wavelength.[9] This sensitivity is comparable to the sensitivity reported for the transient grating photoacoustic measurements at 270 MHz.[10,11]

The long propagation distance of SAW due to the multiple round trip propagations is a unique feature realized for the first time in the present work. The reasons for this are summarized as follows.

(1) As in all laser ultrasonic methods, the excitation and detection was completely contact-free. Therefore the SAW were free from any attenuation or scattering due to the ultrasonic coupler or the transducer.

(2) In the PVS method, the amplitude of SAW is proportional to the laser pulse width T. The amplitude is larger than in the conventional laser ultrasound.[7]

(3) As another feature of the PVS method, BAW are suppressed when the phase matching condition is satisfied by the SAW.[8] Thus the SAW are not disturbed by BAW.

(4) Since the frequency is 30 MHz and the velocity is around 3000 m/s, the product ka of wave number and ball radius (4 mm) is as large as 80π. In this range of ka, the dispersion effect is negligible,[2,3] and the wave form does not change with the propagation of SAW, as confirmed in Fig. 4.

In conclusion, we reported a surface characterization method based on multiple round-trip propagations of high-frequency surface acoustic waves on a bearing ball. We generated tone bursts of SAW with a center frequency of 30 MHz, and observed a surprisingly large number of round-trip propagations. This method is useful for sensitive measurement of small changes in SAW velocity, as well as attenuation and nonlinear effects caused by surface modification, defects, and residual stresses, since it is free from the diffraction effect. A highly sensitive NDE system of steel or ceramics bearing balls may be constructed based on this method.

This work was supported by the Proposal-Based New Industry Creative Type Technology R&D Promotion Program from the New Energy and Industrial Technology Development Organization (NEDO) Japan. Yoshimasa Ohashi is acknowledged for his assistance with the experiments.

[1] C. B. Scruby and L. E. Drain, *Laser Ultrasonics Techniques and Applications* (Adam Hilger, Bristol, 1990).
[2] D. Royer, E. Dieulesaint, X. Jia, and Y. Shui, Appl. Phys. Lett. **52**, 706 (1988).
[3] I. A. Viktorov, *Rayleigh and Lamb Waves* (Plenum, New York, 1967), p. 33.
[4] U. Kawald, C. Desmet, W. Lauriks, C. Glorieux, and J. Thoen, J. Acoust. Soc. Am. **99**, 926 (1996).
[5] K. Yamanaka, Y. Nagata, and T. Koda, Appl. Phys. Lett. **58**, 1591 (1991).
[6] H. Nishino, Y. Tsukahara, Y. Nagata, T. Koda, and K. Yamanaka, Appl. Phys. Lett. **62**, 2036 (1993).
[7] K. Yamanaka, O. Kolosov, H. Nishino, Y. Tsukahara, Y. Nagata, and T. Koda, J. Appl. Phys. **74**, 6511 (1993).
[8] K. Yamanaka, Jpn. J. Appl. Phys., Part 1 **36**, 2939 (1997).
[9] B. A. Auld, *Acoustic Fields and Waves in Solids* (Krieger, Malabar, FL, 1990), p. 278.
[10] M. J. Banet, M. Fuchs, J. A. Rogers, J. H. Reinold, Jr., J. M. Knecht, M. Rothschild, R. Logan, A. A. Maznev, and K. A. Nelson, Appl. Phys. Lett. **73**, 169 (1998).
[11] J. A. Rogers, J. Appl. Phys. **86**, 2959 (1999).