THE UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING
Department of Mechanical Engineering

Final Report

STUDY OF ULSTRASONICS IN WIRE DRAWING

L. V. Colwell
J. H. Hemmye
L. J. Quackenbush

ORA Project 04579

under contract with:

AMERICAN STEEL AND WIRE DIVISION
U. S. STEEL CORPORATION
CLEVELAND, OHIO

administered through:

OFFICE OF RESEARCH ADMINISTRATION ANN ARBOR

October 1962

engn

UMR8710

TABLE OF CONTENTS

LIST OF FIGURES

ABSTRACT

Several approaches were taken in studying the potential use of ultrasonic vibrations in wire drawing and allied processes. Ultrasonic vibrations were applied to the wire and to the drawing die through the use of various types of transducers and horn designs. The results show that up to 50% reduction in draw force may be obtained through the proper selection and use of suitably mounted transducers.

I. PURPOSE

The purpose of the study detailed in this report was "To Investigate the Effect of Ultrasonic Vibrations in Wire and Tube Drawing Operations."

II. BACKGROUND

The application of ultrasonic vibrations to production processes has become quite extensive. There are, in fact, few areas in which this innovation has not made real contributions toward improvement of the art. Spectacular progress has been demonstrated in surface cleaning. By immersing the part to be cleaned in a solvent-like fluid and then causing cavitation to occur within the fluid ultrasonically, cleanliness unheard of ten years ago has been achieved.

Another area of development which has received considerable attention is that of drilling or machining extremely hard materials. The vibration of a specially shaped tool in conjunction with an abrasive slurry has made it possible to drill or form intricate shapes in materials such as tungsten carbide. Research and development work has made the use of ultrasonics common in such widely diversified places as the foundry and the dentist's chair.

The purpose of the work reported herein has been to study the feasibility of the application of a relatively new method (ultrasonics) to a venerable process. Within the broad scope of the purpose of this study as defined in Section I, the basic objective has been met. In the work initiated early in the study it was demonstrated that reductions of worthwhile magnitude in the wire drawing force could be achieved. The early equipment lacked sophistication; it was, in fact, a combination of unmatched components assembled especially for the task.

During the course of the experimental work, studies were made of the influence of longitudinal and radial vibration of the wire drawing die. Transducers of both magnetostrictive and piezoelectric types were used with varying degrees of success. Concurrent with the experimental work has been the interrelated problem of developing a suitable transducer and coupling horn assembly. A description of the various systems and assemblies investigated appears in the Appendix.

Shortly before the notification of contract termination, the latest in a series of transducer and horn systems was completed. A series of tests based on these new horns was completed during the last weeks of August, 1962. Because the results of these tests were of great importance in achieving the goals of the study, the body of this report is concerned with these results. In addition, there are a number of problems which have not as yet been adequately treated; some suggested approaches to them are also developed in the body of this report.

III. RESULTS

A. INTRODUCTION

The influence of ultrasonic vibrations on wire drawing was clearly demonstrated in tests run in February, 1962. It was established at that time that reductions in draw force of from 25 to 50% could be achieved when the wire drawing die was subjected to ultrasonic vibration. These tests as well as the more significant tests run in August, 1962, exhibited a regular periodic variation in the draw force. The significance of this standing wave phenomenon was not immediately recognized. Various means of eliminating the reflections producing the observed dips and peaks were proposed and investigated. It now appears that control but not necessarily elimination of the standing wave phenomenon is desirable.

1. Standing Waves

The basic principle of the standing wave phenomenon is not hard to understand. Consider for the moment the situation in which the die in a system is vibrating and the wire is not moving relative to the die. Just as a piano string will vibrate in harmonic lateral modes, so this wire will vibrate in longitudinal fashion. Figure 1 illustrates this situation. The solid curve illustrates the velocity of the point on the wire directly beneath it. In the situation as postulated, the wire exhibits the greatest strain at the points where it has the least velocity. One additional rule must be observed in establishing the standing wave: the wave must return as a mirror image. For example, at the left boundary of Fig. 1 the velocity must be zero since the wire is clamped at that point. Moreover, the wave returning toward the die from the left end must retrace its path if a standing wave is to exist; and at the left end, the wave must be reflected back along its path of approach. Similarly, the free end of the wire must vibrate freely and the velocity must be at a maximum at that point. In the same fashion, a mirror image must be reflected from the free end of the wire.

To carry the analysis one step farther, if the length of the wire were such that the free end of the wire did not fall at a peak, the wave would be reflected. The reflection would, however, be a continuation of the original wave and not a mirror image as before. This continuing wave would not in effect aid the original wave, and hence a standing wave of less amplitude would be created.

2. Energy Transfer

In a sense, the purpose of vibrating the wire drawing die was to perform work on the wire. From the field of mechanics we find that the work involved in a system like the one described is proportional to the product of point strain and point velocity. It follows, then, that the greatest amount of work will be performed when the velocity is greatest, or in other words, when standing waves are present.

3. Radial Vibration

In an effort to make the study as well rounded as possible, certain exploratory work was done to investigate the influence of radial vibration of the die on wire drawing. It was clear from the vibrational analysis that the radial mode would be difficult to excite, and this was demonstrated in the experimental work. As shown by the tests described in the Appendix, very little success was achieved in the direct attempt to achieve this mode.

B. TESTS

Results from a test series covering impedance matching appear to demonstrate the presence of radial vibration of the die rather well. The magnetostrictive transducer and horn assembly illustrated in Fig. 3 was used in a series of tests wherein the location of the die was varied. Initially the die was pressed into the extreme end of the horn (at the top of the drawing) and after each run the die was moved 1/2 in. toward the other end. Die locations and tabulated data are presented in Fig. 2.

It was anticipated that there would be some point within the horn where the impedance match between the system and the wire would permit the greatest amount of work to be done on the wire. When work with minimum area is equated under the draw-force curve, Run No. 54 appears to define the die location for the best impedance match. At the location described, the longitudinal motion of the horn is theoretically zero, as illustrated by the dashed line in Fig. 3. However, there is maximal strain at the velocity node, and because of Poisson's ratio the motion becomes radial rather than longitudinal. In comparing the runs made in this series, the minimum or dip appears to be broadest for Run No. 54, with some evidence of a small secondary effect causing a slight rise at the bottom of the peak. It is of great significance that on each run in which appreciable effect was noted, the distance between comparable points on the traces was found to correspond with a half-wavelength distance on the wire itself. Ripples occurring at a much higher rate were also present on traces from Runs No. 48, 50, and 53. Although no rigorous proof is at hand, excitation tests of the draw-force dynamometer system produced comparable frequencies.

Two important points were established by the test series from Run No. 48 through Run No. 61. First, there is a location within the horn at which the most pronounced effects can be produced while drawing wire. Second, it is possible to exercise radial vibrations at the die and, as a result, to achieve reductions in the draw force.

In regard to impedance matching and radial mode vibrations, a number of vital questions remain unanswered. The impedance matching tests were very abbreviated in nature and not complete enough to permit the development of equations defining the actual impedance of the wire, either radially or longitudinally. Only partially answered were some basic questions concerning standing waves. In Fig. 3 note that the last dip in the trace, where a dip actually occurs, falls about 7 mm from the end of the wire. This 7-mm distance corresponds with a quarter wavelength, and fits the standing wave requirements specified in Section III-B. The location of the dips relative to the left edge of the trace (that is, the start) is not as clearly defined as might be expected. A reasonable amount of variation might be expected in view of the way in which the wire was fastened to the cross head, but the almost total unpredictability encountered led to another abbreviated test.

Figure 4 illustrates two short tests made in an attempt to clarify the relative influence of reflections from either end of the wire on the standing waves. Run No. 10 was made with bright annealed C-1010 wire curled before passing to the die. It has been generally accepted that a bend in wire will tend to disrupt longitudinal vibrations at that point; and by comparison of the trace for Run No. 10 with those of other runs in which the wire was not curled, it is apparent that the bend had some influence on the behavior of the system. It should be recognized that the bend did not destroy the vibrations, it merely relocated the point at which reflections occurred and attenuated the amplitude of the reflection. Conversely, Run No. 47 was made with four rubber stoppers hung on the wire so that vibrations would be not only prevented from reflecting back to the die, but almost completely absorbed. From a comparison of traces it is clear that the draw force required for this run was almost as great as that required for Run No. 49, in which no vibration was present. (The abrupt dip in the trace for Run No. 47 was caused by slippage of the wire in the jaws.) Runs No. 10 and 47 demonstrate rather well that there is a need for reflections or standing waves in the system if the greatest effect is to be exploited.

IV. AREAS FOR ADDITIONAL STUDY

The present report must necessarily leave many questions unanswered. The desirability of standing waves has been demonstrated intuititively but not rigorously. The use of gang dies separated by multiples of a quarter wavelength would seem to be a most appropriate means of investigating this phenomenon more thoroughly. In this same vein, the use of a continuous length of wire would permit the parameters involved in the standing wave development to be varied and the results to be observed immediately.

Of considerable interest and importance is the problem of establishing the mechanical impedance of the wire. It would be advisable to develop a dimensionless description of wire impedance so that the design of impedance transformers or horns could be greatly simplified. Such a development would permit the die, wire, and transducer to be readily matched with each other. Another problem of great importance is that of radial excitation of the die. The results described in this report indicate that this mode of vibration could now be developed quite easily, either alone or in conjunction with the longitudinal mode.

The next logical step would be to press toward the achievement of the largest reduction possible. According to Hoffman and Sachs (p. 168) without friction in the die the maximum reduction in section should be 63%.[1] In order to achieve this maximum reduction, it would probably be necessary to develop a self-tuning system which would adapt itself to small ambient changes. It would also be necessary to arrive experimentally at a means of tuning multiple transducer assemblies for use where greater power densities are required.

Although it has been demonstrated that the draw force can be reduced by ultrasonic vibration of the die, no information has been obtained concerning the surface condition of the wire, or for that matter, the physical or metallurgical state of the wire. This information could easily be obtained from appropriate standard tests.

Neither the state of wear nor the rate of wear of the die has been considered at all in this study. No proven means of establishing this parameter has been developed, but several means are worthy of consideration. The use of isotopic tracers or the value of a magneto-inductive surface study might well be considered.

APPENDIX

A. CHRONOLOGY

In order to accomplish the aims of this study it was necessary to investigate the various means and methods for the production of ultrasonic energy. Devices applicable to the vibration of a die were, of course, given the most consideration. It was apparent from the outset that the use of magnetostrictive transducers would be required in order to produce the necessary power density. The ultrasonic power equipment available at that time included a commercial 350-watt Sheffield-Cavitron unit and a 1000-watt unit built at The University of Michigan for another project.

The preliminary wire drawing experiments were made with aluminum wire, an old tungsten carbide die, and the 350-watt unit. The apparatus at that time was crude but the results indicated graphically that reductions in draw forces could be expected as a result of ultrasonic vibration of the die. Furthermore, it became apparent that when ferrous materials were to be drawn, a considerably larger source of power would be required. On the basis of this early experience and an analysis based on Hoffman and Sachs (p. 163), and with the idea of providing some power reserve, design was started on a transducer capable of handling power levels of from 2 to 3 kw for short periods of time. At the same time, a search was made for a source for an appropriate power amplifier. A supplier for the power amplifier was found, but none was found for the transducer.

The transducer design finally selected was somewhat unusual. Since it was necessary to pass the wire down the center of the system, a toroidal-shaped transducer was envisioned. The outside diameter of the transducer was 3-15/16 in. and the inside diameter 2-9/16 in. The core itself was wound with nickel-cobalt alloy foil 3 in. wide, 0.0045 in. thick, and long enough to produce the desired core. Six 3/8-in.-wide slots were milled radially along the core to accomodate the electrical windings. The laminated core was then silver-soldered to a straight, half-wavelength section of stainless steel which had a hole down its axis to pass the wire and receive the die. The assembly when completed (See Fig. 5) was mounted in the broach and a series of tests were run on each of the wire types provided. The results of this series of tests is illustrated in Fig. 6. With the equipment operating properly, the program was advanced to attempt to establish an appropriate mechanical impedance match by increasing the amplitude of the die vibration.

The first step in the search for more effective operation was the design of a horn transformer with a ratio of four to one: this was the straight tapered device shown in Fig. 7. At this point difficulties were encountered due to the use of two-dimensional equations on a three-dimensional system. In essence, the discontinuity produced by the change in section developed reflections within the horn, and these reflections in turn shifted the resonance point for the system, greatly reducing its efficiency. Several horns were subsequently designed and tried in an effort to overcome the three-dimensional effects. The most effective approach incorporated the use of radial saw slits in the horn itself.

At about this time it was found that the silver solder joint between the nickle and the horn was no longer continuous. A motional impedance study and plot indicated that the horn and transducer assembly was no longer usable, which forced a change in plans for additional work.

Three distinct approaches to the problem were under consideration:

1. That the original magnetostrictive system be completely failed and subsequently cemented with an epoxy to a new horn system.

2. That the use of transducers be re-evaluated in the light of recent improvements in ceramic materials.

3. That magnetostrictive unit of standard design be developed and produced as a back-up for the first unit and a possible replacement for it.

Attempts to break the toroidal core from the horn were unsuccessful, and plans to remove the core by machining the horn away were postponed because of the danger of damage to the electrical windings.

A set of four Acoustica "multipower" transducers were procured and used with various horn configurations in an attempt to achieve results comparable with the original results. The most successful horn and mounting assembly is pictured in Fig. 8. It was concluded that in general, however, the power level at which the ceramic units could safely operate was insufficient for purposes of this study. One final attempt to utilize the ceramic transducers was made concurrently with completion of the punch and die for the magnetostrictive transducer laminations. A set of four magnesium horns (See Fig. 9) was designed by Professor Colwell after the equations developed by Neppiras of Mullard Laboratories.[2] At the time the magnesium horns were being made, an identical set was made of steel. The magnesium horns were planned for use in a quadruple array and were to be compared with the steel horns identically mounted, as shown in Fig. 10. Individual tests on these magnesium horns showed that insufficient power was being developed (despite the observance of proper electrical polarities in making connections to the power amplifier), since the activity could be completely damped and absorbed with the fingers. The magnetostrictive units showed great promise, however, and were more active than any unit previously tested. Results in the combined array were poor, apparently due to unexpected loading from the die holder. Since there was not enough time for the slow and tedious tuning process necessary to achieve the desired results, the array approach was abandoned.

As an interim measure while another transducer assembly was being completed, the magnetostrictive double-step horn pictured in Fig. 11 was tested. Essentially the configuration was identical to that used in drawing the aluminum wire at the beginning of the study. The system did function satisfactorily, but since the results obtained from another unit overshadowed those obtained from this one, the data are not displayed here.

Figure 12 pictures the assembly which was used for the most significant of the tests run. It is basically a double-step horn with a mirror image of the last step section extended to produce a dumbbell-shaped assembly. Most of the data collected on this system is described in the main body of this report.

An additional series of tests was run with the dumbbell system in which two parameters were varied. In studying the standing wave behavior of the system it appeared logical to run a series of tests wherein not only the length of the wire used would be varied, but the initial distance from the jaws to the die would be varied in uniform steps. Figure 13 illustrates the manner in which the pertinent measurements were made. In general the results were not as clear-cut as desired, due (as can be seen from the traces in Fig. 14) to the position which the die was assigned within the horn. Once again, however, the presence of standing waves was evident, and the quarter-wave spacing of the final dip appeared.

Because of difficulties in measuring the actual distance from the die to the cross head, it was not possible to prove experimentally the influence of the fixed reflection on the standing waves. The basic difficulty involved in this measurement was caused by the method of clamping the wire. Clamping was accomplished by wrapping the wire around a clevis pin, and then with a bolt and washer arrangement fastening the free end parallel with the lead. Other techniques were tried in an effort to prevent slipping, but were unsuccessful. In any case, it was apparent that the actual location of the critical nodal point could not be established with any certainty. As an additional complicating factor, the length of the wire changed as it passed through the die.

B. TEST PROCEDURE AND MEASUREMENTS

For the most part the measurements made during the course of this study were conventional in nature. The micrometer and steel scale hardly require description, but the measurements concerned with forces, displacements, and accelerations were in some cases unique and are worthy of description.

Force measurements were made with a dynamometer designed around the Kistler Quartz Load Cell. This device has high sensitivity and linearity, and has an exceptional range of frequency response. Because of the very high resonant frequency of the Kistler Load Cell, it is possible to measure forces with frequency components nearly as high as 100,000 cps. This extreme response was not utilized in all tests because the recording device, a two-channel Sanborn recorder, is limited to frequencies somewhat below 100 cps. In making adjustments to the system, it was necessary from time to time to view the loads applied with a cathode ray oscilloscope where the full frequency response was utilized. The load cell is pictured along with the die end of the quadruple horn assembly in Fig. 15.

During the work on horn development it was necessary to make measurements of the amplitude of motion of the end of the horn. A capacitance-type micrometer was used for this measurement because contact with the horn would have disturbed the operation of the system. When lower power tuning operations were being undertaken, the Kistler Accelerometer was occasionally used.

Although each series of tests had a specific purpose within the framework of the study, the test procedure was basically the same throughout. Figure 16 shows the equipment used in place at the test site. Preliminary measurements such as diameter, length, and lead length were, of course, taken before the wire was drawn. With the preliminary information (including wire type and coating recorded in the data along with an identifying number) the wire lead was passed through the die, secured to the clevis pin, and then anchored. If ultrasonic vibration was to be used, the generator was turned on prior to the start of the draw; it was tuned for resonance and the frequency was recorded in the data. The tests were all run at a speed of approximately 2-1/2 inches per second, primarily because this was the slowest speed at which the broach would operate. Slow speed was necessary so that the operator could perform all the required functions during the test run. At the conclusion of a test the wire was removed from the machine and tagged, the recorded Sanborn trace was identified and filed, and the final measurements were entered on the data sheet.

The same procedure was followed when ultrasonic vibrations were not used except that the generator was not disturbed.

C. HORN DESIGN

The length of an impedance transformer or horn is related to the velocity of sound in the material used in making the horn. This velocity of sound can be calculated from a knowledge of the modulus of elasticity and the density of the material. That is:

$$\bar{V} = \sqrt{\frac{E}{\rho}}$$

E = modulus of elasticity
ρ = density of material

For example, with steel:

$$E = 30 \times 10^6 \text{ lb-ft/in.}^2$$
$$\rho = .283 \text{ lb-in/in.}^3$$
$$g = \frac{\text{lb-in. in.}}{\text{lb-ft sec}^2}$$

$$\overline{V} = \frac{30 \times 10^6 \times 386}{.283} = \sqrt{4.09 \times 10^{10}}$$

$$\cong 200{,}000 \text{ in./sec}$$

Since the wavelength $\lambda = \overline{V}/f$, a full wavelength at 25,000 cps becomes

$$\frac{200{,}000}{25{,}000} = 8 \text{ in.}$$

Neppiras[2] suggests basing horn design on a general equation relating cross-sectional area, velocity, and frequency:

$$\frac{d^2\overline{v}}{dx^2} + \frac{d\overline{v}}{dx} \cdot \frac{d}{dx}(\ln A) + \frac{\omega^2}{c^2}\overline{v} = 0 \tag{1}$$

where

$\overline{v}$ is the velocity potential
A is the cross section at distance x
c is the velocity of sound in the material

Carrying the work one step further and involving strain:

$$\frac{\delta^2\xi}{\delta x^2} + \frac{\omega^2}{c^2\xi} = 0 \tag{2}$$

$$\text{where } \frac{\delta\xi}{\delta x} \text{ is proportional to } \frac{\delta V}{\delta x}$$

The boundary conditions for Eq. (2) require that $\frac{\delta\xi}{\delta x} = 0$ at $x = 0$ and also at $x = a + b$, where a and b are the lengths of the two quarter-wave cylinders. They also require that

$$S_1 \left(\frac{\delta\xi}{\delta x}\right)_b = S_2 \left(\frac{\delta\xi}{\delta x}\right)_c$$

where S_1 and S_2 are the cross-sectional areas of the two cylinders.

The solution of Eq. (2) then becomes $\xi = \xi_x \cos \omega x/c$. If $a = b = \lambda/4 = \frac{c\pi}{2\omega}$, $\xi = 0$ at $x = a$.

The transformation ratio becomes

$$\frac{\xi_0}{\xi_a} = \frac{S_1}{S_2}, \text{ the area ratio.}$$

The stored energy $K_1 = \frac{\delta \xi \omega^2 \xi_a{}^2}{16} \cdot S_1 \left(1 + \frac{S_1}{S_2}\right)$ where δ is the material density.

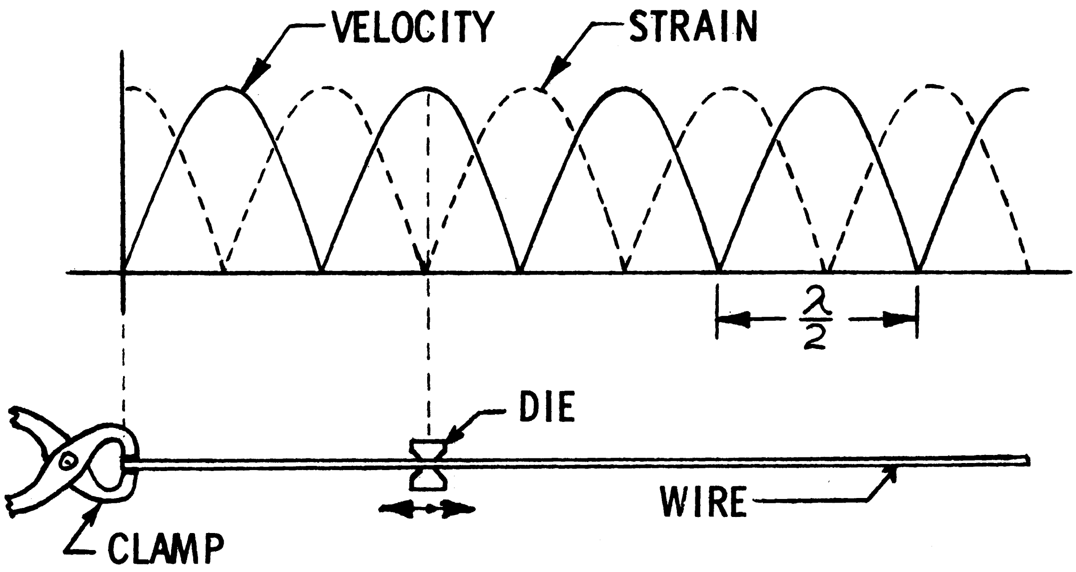


Fig. 1. Idealized velocity-strain relations in a longitudinally excited wire.

Run	Die Location From End, in.	Wire Diameter, in.		Wire Length, in.	
		Initial	Final	Initial	Final
48	Flush	0.1000	0.097	15	15.91
50	1/2	0.0999	0.097	15	15.87
52	1	0.1000	0.097	15	15.87
53	1-1/2	0.0998	0.097	15	15.84
54	2	0.0998	0.097	15	15.91
55	2-1/2	0.1000	0.097	15	15.87
56	3	0.0999	0.097	15	15.84
57	3-1/2	0.0997	0.097	15	15.91
59	4	0.0997	0.097	15	15.84
61	4-1/2	0.0999	0.097	15	15.91
49*	Flush	0.1000	0.097	15	15.84

*Run 49 was made without ultrasonics.

Fig. 2. Die locations and tabulated data. (Bright, annealed C-1010 wire; die No. 13; bearing 39%; approach 19%; diameter 0.0975 in.)

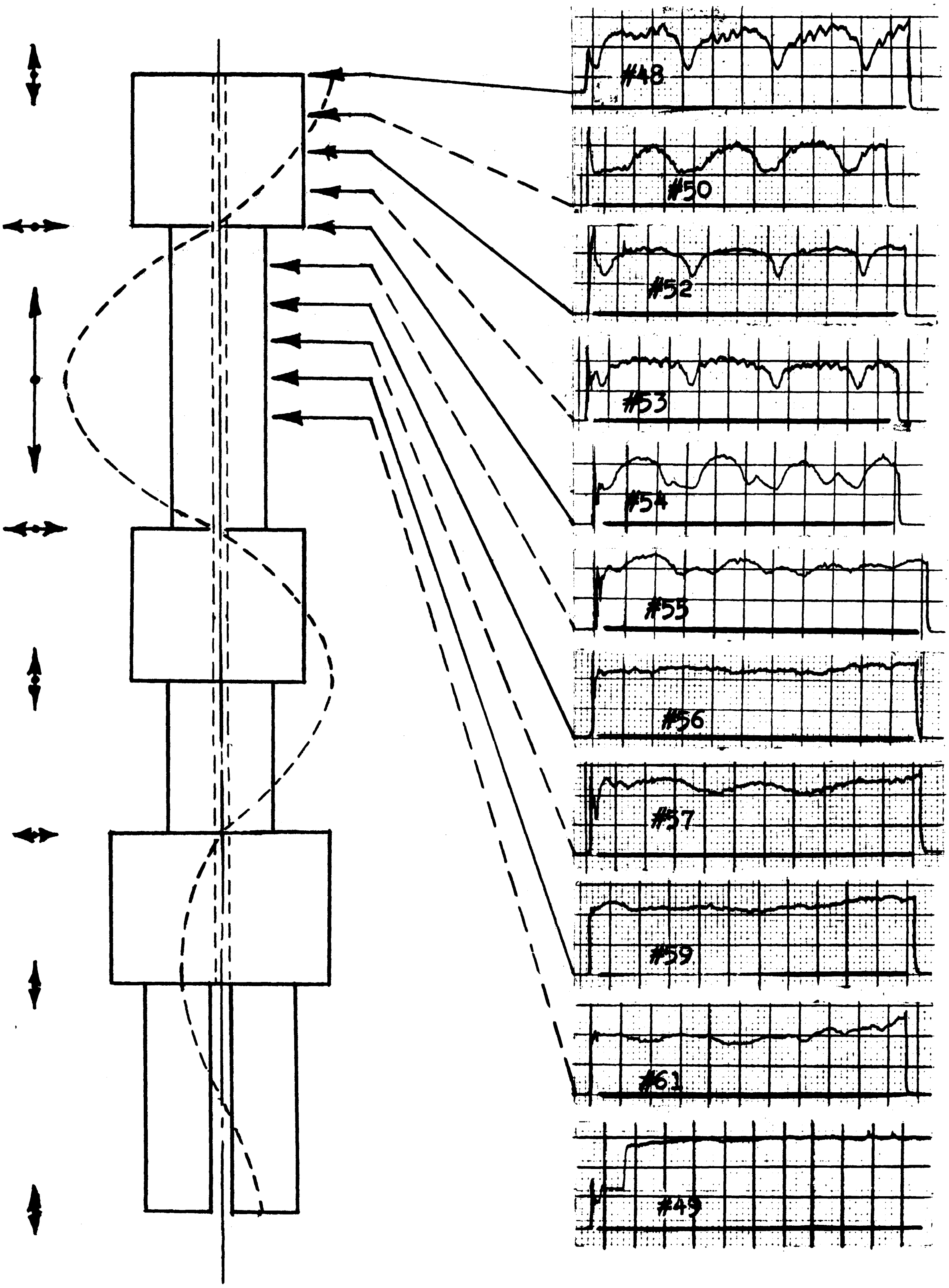
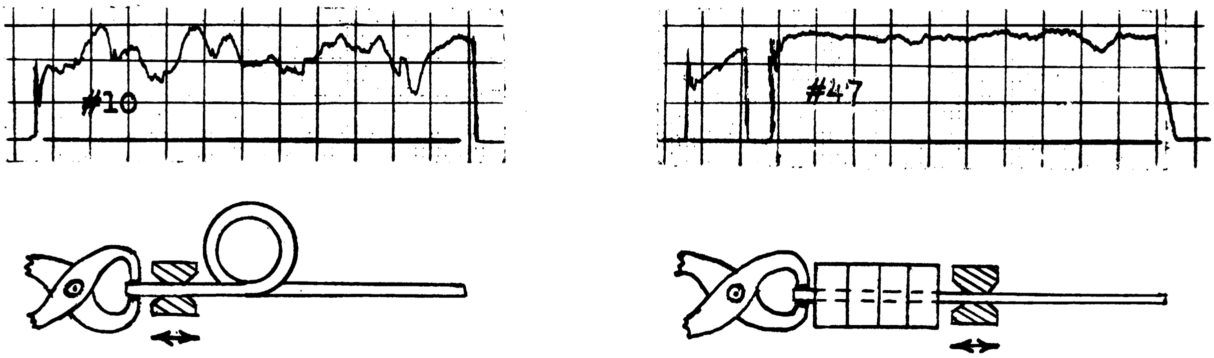


Fig. 3. Dumbbell horn assembly and force traces for various die locations in the assembly.



Run No. 10. Made with wire coiled to break up reflections from free end.

Frequency:		23,300 kcs
Diameter:	(initial)	0.1000 in.
	(final)	0.0970 in.
Length:	(initial)	15.02 in.
	(final)	15.94 in.

Run. No. 47. Made with four rubber stoppers to absorb reflections from draw end.

Frequency:		23,300 kcs
Diameter:	(initial)	0.1000 in.
	(final)	0.0968 in.
Length:	(initial)	15.00 in.
	(final)	16.00 in.

Fig. 4. Sketches and traces for Runs Nos. 10 and 47.

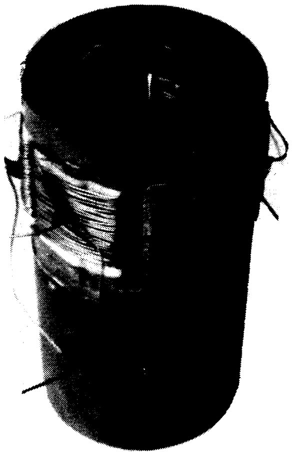


Fig. 5. Original transducer assembly.

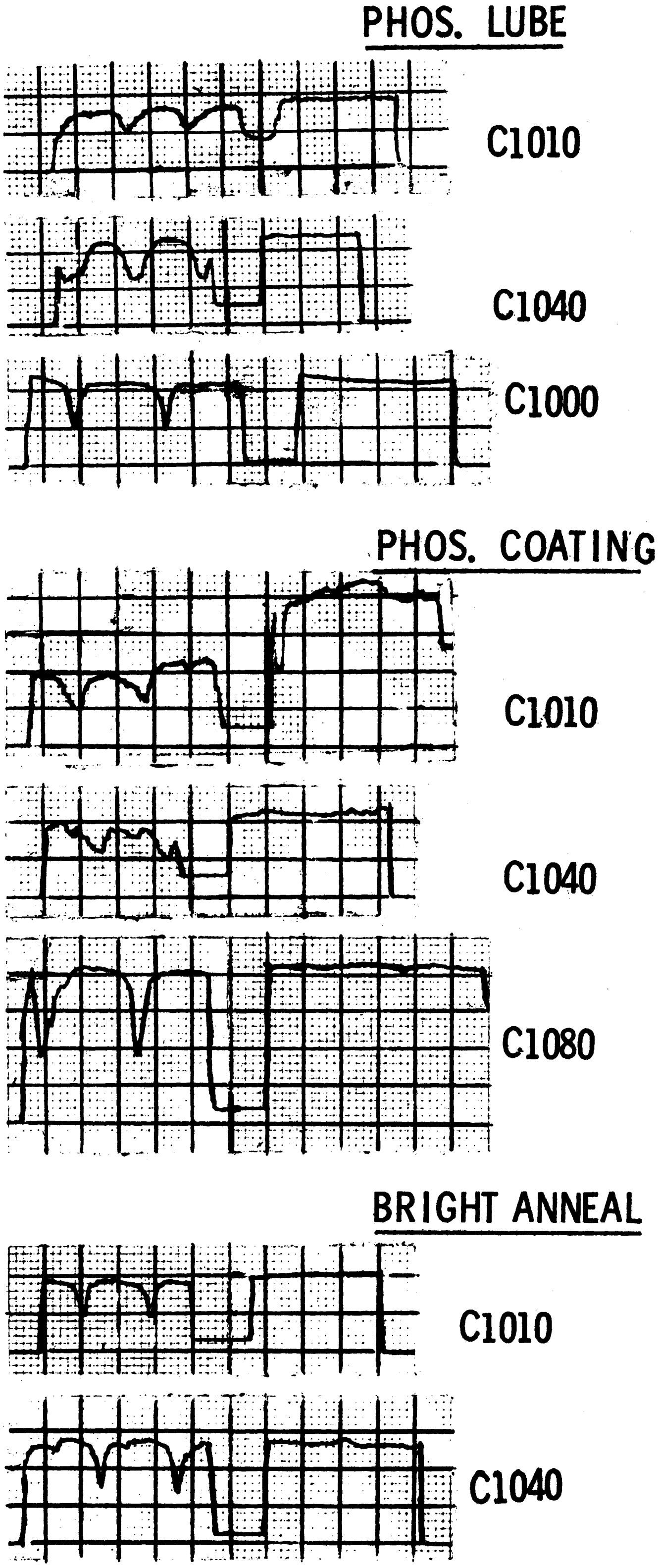


Fig. 6. Test results with die (15 Feb. 62).
(Die No. 15; bearing 49%; approach 17°; diameter 0.0975 in.)

Fig. 7. Straight tapered horn.

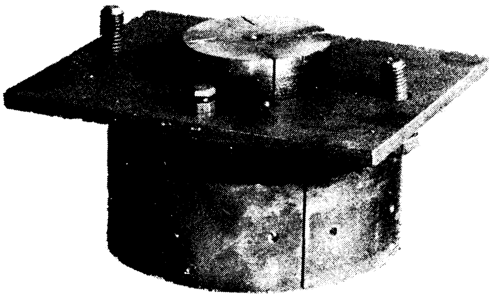


Fig. 8. Double-cylinder horn and mounting plate designed for use with 4 ceramic transducers.

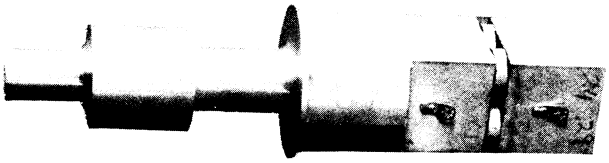


Fig. 9. Ceramic transducer mounted on magnesium double-step horn.

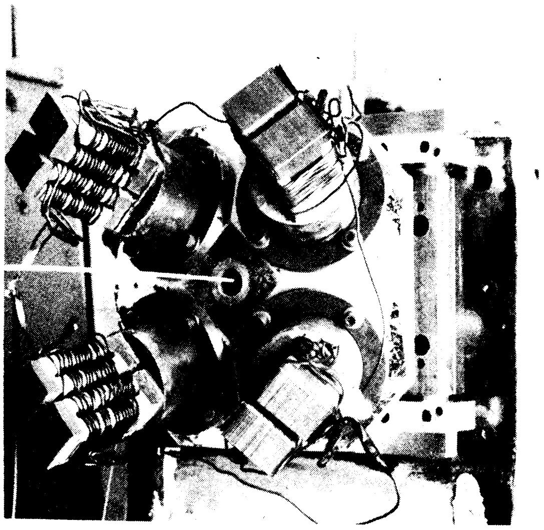


Fig. 10. Quadruple magnetostrictive transducers mounted with wire passing through plate and die.

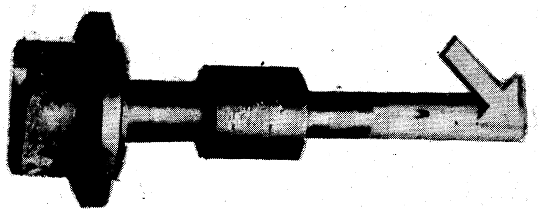


Fig. 11. Double-step steel horn with slotted half-wave extension. (Die located at arrow end)

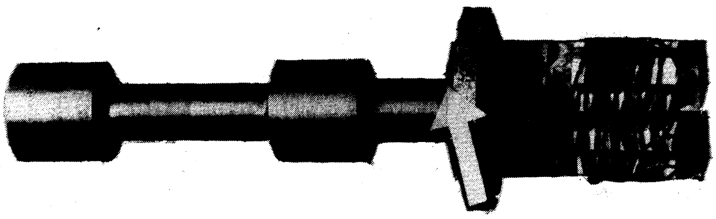


Fig. 12. Magnetostrictive transducer mounted on single-step horn with additional extension section giving dumbbell appearance. (Arrow points to mounting flange)

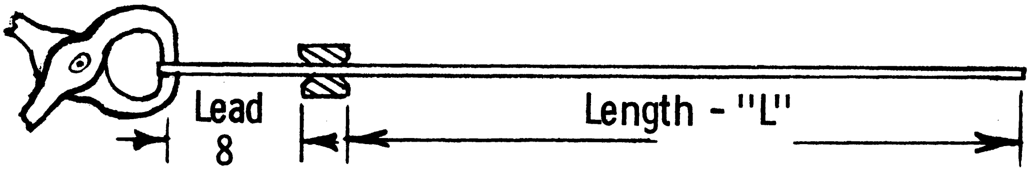
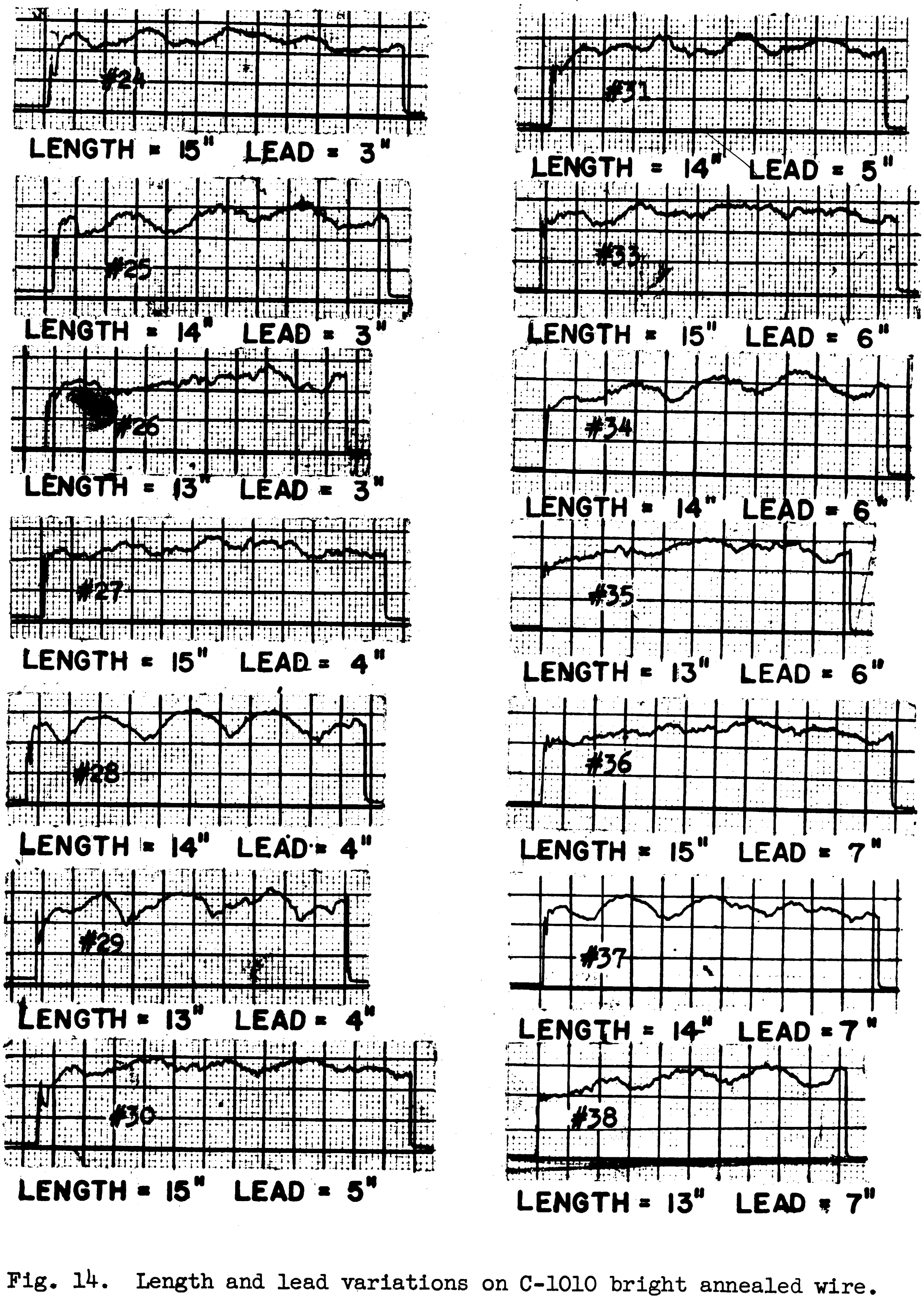


Fig. 13. Critical wire measurements.



LENGTH = 15" LEAD = 3"

LENGTH = 14" LEAD = 3"

LENGTH = 13" LEAD = 3"

LENGTH = 15" LEAD = 4"

LENGTH = 14" LEAD = 4"

LENGTH = 13" LEAD = 4"

LENGTH = 15" LEAD = 5"

LENGTH = 14" LEAD = 5"

LENGTH = 15" LEAD = 6"

LENGTH = 14" LEAD = 6"

LENGTH = 13" LEAD = 6"

LENGTH = 15" LEAD = 7"

LENGTH = 14" LEAD = 7"

LENGTH = 13" LEAD = 7"

Fig. 14. Length and lead variations on C-1010 bright annealed wire.

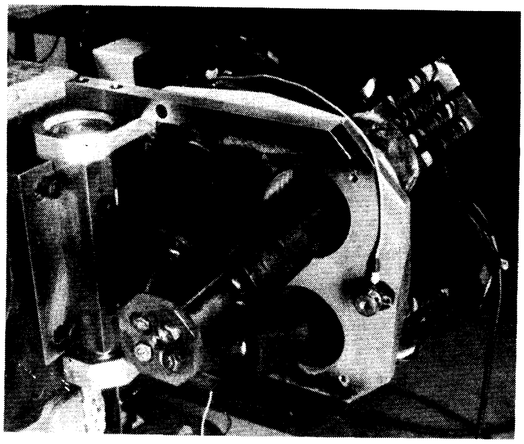


Fig. 15. Quadruple assembly showing horns converging at die holder. (Load cell is located to the right of the horns)

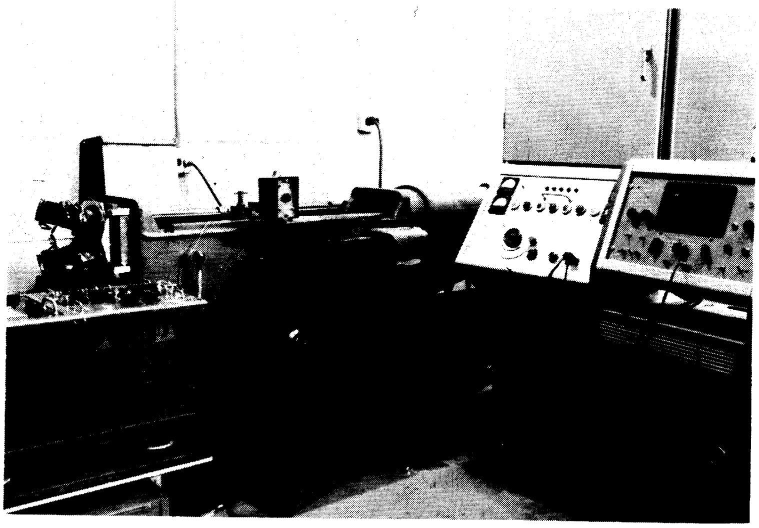


Fig. 16. Test equipment in place.

REFERENCES

1. Hoffman, O., and Sachs, G., Introduction to the Theory of Plasticity, New York, McGraw Hill, 1953.

2. Neppiras, M., The Design of Ultrasonic Machine Tools, Research Report, Mullard Laboratories, Great Britain.

See also:

Balamuth, L., IRE Convention Record, Vol. 3, Pt. 9, 1955, 89.

Cleaver, F. T., and Miller, H. J., Wire Drawing Technique and Equipment, Institute of Metals: Symposium on Cold Working, Monograph No. 12, 1952.

Leslie, F. M., "The Relative Output from Magnetostriction Ultrasonic Generators," Journal of the Acoustical Society of America, 22, 1950, 418.

Mason, W. P., and Wick, R. F., "A Barium Titanate Transducer Capable of Large Motion at an Ultrasonic Frequency," Journal of the Acoustical Society of America, 23, 1951, 161.

Tarpley, W. B., and Kartluke, H., Ultrasonic Tube Drawing: Niobium, Zircaloy-2, and Copper, AEC Report NYO-10008, 1961.