Ultrasonic Longitudinal Mode Welding of Aluminum Wire

Basic principles and operation of a new ultrasonic welding method are described in a preliminary study

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ABSTRACT. This research program was carried out in the Sonic Power Laboratory of The Ohio State University for the purpose of determining process parameters which control a unique ultrasonic welding process. This process was discovered accidentally in the laboratory while investigating sonic riveting. The process has given indications of (1) being capable of welding relatively thick sections of metal, (2) being able to utilize fixed frequency, rotating (rather than electronic) power supplies, (3) delivering relatively high energy densities to the faying surface intermittently, and (4) requiring only a minimum deformation of the faying surface to produce a solid state bond. This unique process has been described as ultrasonic LM bonding.

An ultrasonic solid state longitudinal mode (LM) metallic bonding process may be distinguished from the conventional ultrasonic bonding process by the mode of acoustic energy transfer to the work surface from the transducer or sonic probe. In the ultrasonic LM bonding process, this mode is longitudinal. In conventional or commercial ultrasonic bonding processes, the mode may be shear, compressional or torsional. The bonds may also be distinguished by metallographic examination. The ultrasonic power supplies utilized in LM bonding are unique in that they require no adjustability of frequency.

The objective of this program was to determine experimentally the configurations of ultrasonic transducer, power source, deforming die and supporting structure that would produce the unique type of solid state bond previously observed, on a repeatable basis, using lap joining of two aluminum wires as a work configuration. Evaluation of the welded joint was to be based on examination of the faying surfaces using metallographic techniques.

The ultrasonic system that was utilized required intermittent rather than continuous contact between the working die and the supply of vibrating energy. This intermittent contact made possible the increased levels of sonic energy at the work surface and the use of relatively low cost per Kw power supplies. The intermittent contact system was applied to the lap welding of aluminum wires through the medium of a hollow tapered die. To evaluate the bond by metallographic means, it was necessary to sectionalize the die as well as the aluminum wires that had achieved a solid state bond.

The parameters that were controlled in making this experimental investigation of ultrasonic LM bonding included the natural frequency of resonance of the driving transducer in comparison to the power supply frequency, the exciting voltages applied to the piezoelectric transducer, the power input during the work cycle, the pressure-time schedule during the work cycle and the duration of the work cycle. Tests were carried out with two types of hollow tapered dies in which the aluminum wires were inserted. Various taper angles were tried and various die lengths and die materials were employed.

Examination of the metallographic studies indicated that the bonding process was not similar to the conventional shear-mode ultrasonic bond described in the AWS Welding Handbook. The differences are clear both in the faying surface microstructure and the percent deformation measured in the die used to produce that microstructure. A unique microdeformation or metal turbulence was observed in the metallographic studies, indicating metal flowing across the interface in both directions in an eddy or whirlpool pattern.

As a result of this experimental program it has been established that the welding of aluminum wires is possible with a deformation rate significantly lower than required in conventional cold welding processes and with significantly less static force required. The ultrasonic welding of

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aluminum wires of 0.125 in. diam has been demonstrated, both with precleaning by wire brushing and without cleaning. The development of this type of ultrasonic system, for the welding of various configurations of metallic surfaces, will require additional research and development.

Introduction

Volume 3B of the current American Welding Society's *Welding Handbook* describes three different methods of producing ultrasonic welds through the use of conventional equipment, which is available commercially. These processes differ essentially by the mode in which vibrational energy is applied to the work area, either at sonic or ultrasonic frequencies. The three methods are described as: shear mode, torsional mode and compressional mode. In each case, an electromechanical device known as a transducer is used to supply the vibrational energy utilized for welding.

The equipment required and the power sources for ultrasonic welding are as follows: First, commercial 60 cycle ac electrical power is transformed into high frequency ac power using an electro-magnetic converter. Second, this energy is transformed by the transducer into mechanical vibrations. Third, the vibrational energy is applied to the work surface (by various configurations of tools, probes and anvils) in such a way as to create sonic or ultrasonic welds. In anti-nodal welding, the point of contact between the work surface and the sonic transducer is located at the point of maximum vibration (and minimum stress) in the transducer. This point is identified as the vibration-amplitude anti-node of the transducer; hence the term anti-nodal welding.

In most of the commercially available ultrasonic welding processes, the transducer is continuously coupled, at its anti-node, to the work surface through a sonic probe. A feedback-controlled electronic power supply unit is necessary for each transducer in order to provide the desired exciting energy under the varying load conditions, with a continuously coupled system.

As described in Volume 3B of the *Welding Handbook*, these ultrasonic welding processes are limited by certain parameters which include ductility and hardness of the base metals, thickness of the piece to be joined, and certain metallurgical qualities of the work surface including recrystallization properties and grain growth characteristics (Refs. 1-4).

The ultrasonic or sonic equipment and the bonding process described in this paper differ from those described in the *Welding Handbook* in these ways: (1) The equipment described herein is experimental and not now available as a standard commercial system, (2) the process described is unique from an acoustic viewpoint, and (3) the welds produced bear little resemblance, in metallographic studies, to those produced by commercial ultrasonic processes.

This new welding process, and its necessary sonic or ultrasonic equipment, is identified as ultrasonic LM bonding. The initials identify the process as longitudinal mode, as contrasted to shear, compressional or torsional mode processes which are used commercially. The power supply is of fixed frequency and may be rotating or electronic, as desired; neither variable frequency supplies nor feedback controls of frequency are required. The mode of acoustic coupling between the transducer and work surface is intermittent rather than continuous as employed in commercial ultrasonic welding processes. This intermittent coupling is made possible through the use of a mechanical element, described as a "bouncing mass."

The intermittent coupling system used in ultrasonic LM bonding was developed at The Ohio State University during the course of a research program on sonically assisted riveting of aeroplane aluminum materials (Ref. 5). During this program, ultrasonic LM bonding was discovered; this led eventually to the research program described herein.

The employment of a bouncing mass or an intermittent energy transmitting device of a mechanical nature is necessary to the LM bonding system. This mass is located between transducer transmission tip and work surface. It acoustically isolates the resonantly vibrating transducer from the detuning effect of the load. This insures the continuous and optimum supply of energy to the transducer as the work load varies. Theoretical work done at The Ohio State University has further shown that the amount of energy which "flows" into the work load at each impact is related to the average forward and rebound velocities of the small bouncing mass utilized in an intermittent acoustic coupling of this type (Ref. 6).

With this coupling system, the incremental deformation of the work surface depends upon (1) the kinetic energy stored in the bouncing mass at the instant of impact with the work surface, (2) deformation characteristics of the workpiece and (3) impact frequency of the bouncing mass. Since the work surface is deformed plastically immediately after each impact with the bouncing mass, work hardening or strain relieving may occur in the workpiece. Each succeeding impact will then deform the piece under a quite different condition (Ref. 7). A detailed analysis of the successive steps in such a deformation process is beyond the scope of this paper.

This research effort was directed toward the application of longitudinal mode ultrasonic vibration in metallic bonding, and to the development of the necessary dies, jigs, fixtures and means of applying ultrasonic energy, to join a specific work surface configuration. The acoustic generator utilized in this research was developed at The Ohio State University in prior research programs, including the model P-7 piezoelectric transducer having a nominal resonant frequency of 10 kHz and a no-load Q of approximately 1000.

Metallographic studies were carried out to examine and evaluate all the welds attained in this process. Examination of the metallographic studies indicated that evidence of good bonding is not similar to conventional shear mode ultrasonic bonds described in the AWS *Welding Handbook*. The differences are clear both in the faying surface microstructure and the percent deformation measured.

A unique microdeformation or metal turbulence was observed in the metallographic studies, indicating metal flowing across the interface in both directions in an eddy or whirlpool pattern.

Experimental Procedure

Prior to this research, a preliminary investigation of anti-nodal welding was done on a limited experimental basis. Conclusions reached in this study, and prior welding observations during the sonic assisted riveting research program, led to the use of a forming die in the ultrasonic LM bonding of two wires.

This forming die serves two purposes: (1) as a holding device for the wires during and after deformation by the impact ultrasonic energy, and (2)

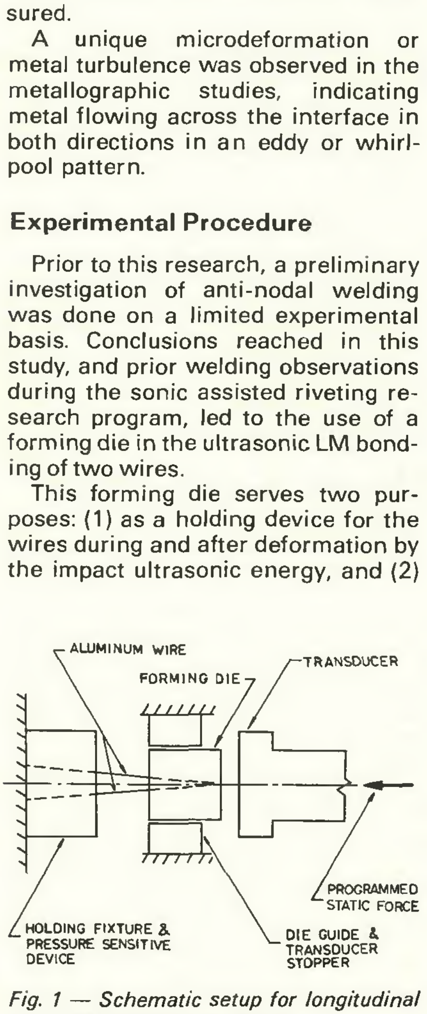


Fig. 1 — Schematic setup for longitudinal mode (LM) ultrasonic welding

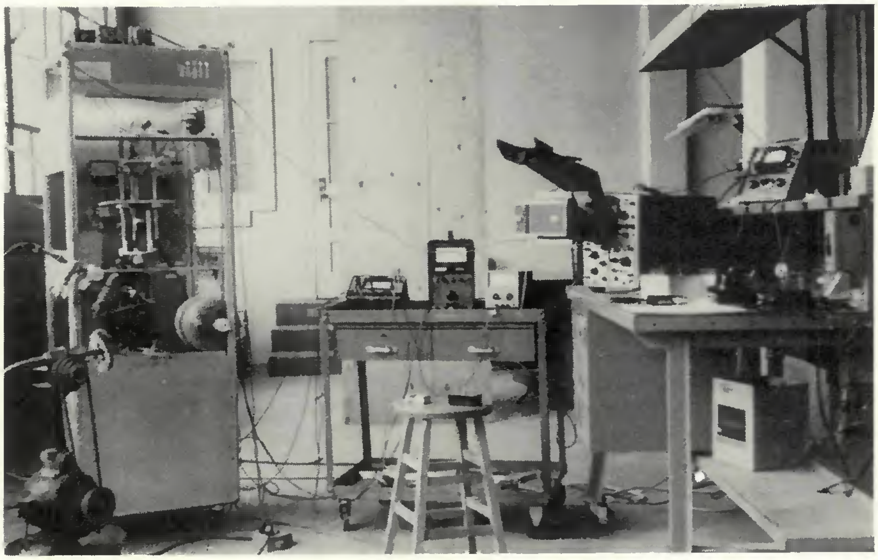


Fig. 2 — Laboratory setup for LM ultrasonic welding

as an energy transmission medium between the energy source (the ultrasonic transducer) and the load (the wires). Figure 1 schematically shows the transducer, the forming die and the workpiece in relative position. Tests were carried out using 1100-0 aluminum wires of 0.125 in. diam throughout the entire program.

Transducer Console and Instrumentation

A console was built, consisting of a metal framework in which the necessary elements are supported. These include (1) a stepup transformer to supply the required high frequency excitation to the transducer, (2) a pneumatic system which controls the application of static force to the transducer, (3) electrical power supply circuits, and (4) instruments to monitor system parameters. A pressure sensitive strain gage is employed to monitor the controlled static force applied through the transducer to the forming die. Figure 2 shows the working console, together with the pneumatic system and the instruments employed.

Forming Die Configuration

During the course of this research, various modifications were carried out on the forming die. A hollow, tapered, forming die was finally adopted. This die has a single tapered hole through which the wires are fed into the forming cavity. Various taper angles and die neck diameters were tested throughout the research program. A forming die design having a taper angle of 5 deg, with neck diameter D, of either 0.228 or 0.221 in. was finally selected. Figure 3 lists the percentage deformation of the work calculated for these two neck diameters, as well as other physical characteristics of the die design.

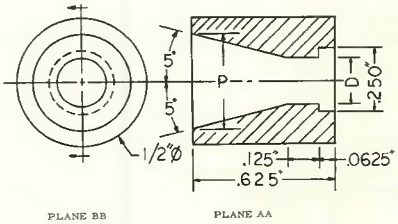
Experimental Approach

The three control parameters of the process being studied experimentally include (1) high frequency electrical power level which is accepted by the transducer, (2) the operating time (time during excitation of the transducer) and (3) the external static force applied by the pneumatic system to the transducer during excitation. The amplitude of the supply voltage (from a rotating MG set) is fixed at a preset value. An electronic timer is employed for the purpose of controlling the operating time, or the duration of the deformation of the work surface.

A special system was built to regulate the applied static force by controlling the air pressure supplied to a pneumatic cylinder. The transducer is connected at its nodal plane to the piston of the pneumatic cylinder. Compressed air is piped into a tank (of about 1 cu ft capacity), from which air pressure is introduced into the pneumatic cylinder. The static force can thus be increased gradually or programmed during the working cycle until a constant value is finally attained. This constant value may be selected and preset. The actual buildup of static forces is illustrated in Fig. 4 along a time base. Various preset values of force are indicated in different curves.

A working cycle, and the preset values of excitation and pressure are programmed as follows:

1. Prior to the initiation of the working cycle, the transducer is brought lightly into contact with the forming die which holds the working wires. The initial static force, which the transducer applies to the work surface, can be measured through the use of the pressure sensitive strain gage prior to excitation.



DESIGN	D	P	AVERAGE MASS	PERCENT DEFORMATION
6-1	.228 IN	.305 IN	11.3 GM	8.8
6-2	.221 IN	.298 IN	11.4 GM	11.6

Fig. 3 — Design data for two forming dies. Percent deformation (of the wire workpiece) = 100 (2W - D)/2W, where W = wire diameter and D = die neck diameter

2. During the working cycle, the transducer applies ultrasonic energy to the work for a limited time period. During the excitation period the static force applied to the work surface by the transducer will increase steadily. The applied static force will finally reach a steady level which corresponds to a preselected air pressure value (preselected by setting the air-input pressure regulator).
3. Electrical power input to the transducer and work-cycle duration are measured and recorded on a storage type oscilloscope. The final static force which was applied at the end of the work cycle by the pneumatic system is ascertained from the static force vs time curves shown in Fig. 4.
4. During the work cycle, the transducer is impacting the die with steadily increasing frequency of impact (as the static force increases).
5. As the steel die is being impacted, the work surface (a pair of aluminum wires) is forced gradually into the tapered recess in the die. Constraint forces are induced between the working wires, which increase as the wires progress into the die.
6. The die and the working wires receive ultrasonic energy. Ultrasonic LM bonds are developed between the faying surfaces of the wires which are enclosed within the die.

Preparation of Metallographic Samples

After the wires welded together within the die, the die together with the working wires was sectioned, mounted and polished. The polished surfaces to be studied were etched with Keller's solution. Microscopic studies of the etched samples were performed both on Section AA and BB (see Fig. 3).

Results

Various die configurations have been tested during the course of the research program. Only those which achieved satisfactory welds are reported here.

Single Hole Die with Programmed Static Force

Two die designs were used with programmed static force in this research program. These two single hole designs, #6-1 and #6-2, have the same tapered angle of 5 deg, with neck diameters of 0.228 and 0.221 in., respectively. This corresponds to 8.8 and 11.6 % deformation of the working wires, as shown in Fig. 3.

Test results are given in Tables 1 and 2. A total of nineteen samples, in which the wires were not precleaned, were tested using designs #6-1 and #6-2. Six of the samples were found with welds between wires. Micrographs of two of the welds are shown in Figs. 5 and 6. In Fig. 5, clean base metal has apparently been brought into intimate contact along the faying line. Figure 6 shows a rather zigzag line of interface, where many microdeformation spots are located. It can be seen from Fig. 6 that the interface has been eliminated in some areas where welding has occurred. The bond line is discontinuous, and the presence of aluminum oxide is evident.

Precleaning the Work Surface

In many cold welding applications, precleaning the base metal surface is very important. In this research program, however, bonding has been made possible without precleaning the working wires.

To determine the effect of precleaning on percent welds produced, two series of tests were run employing design #6-1 dies. In one series of tests, the wires were precleaned with a stainless steel wire brush. In another series of tests, the wires remained uncleaned and untreated. Tables 3 and 4 show the results of these tests. In Table 3, the data show that for precleaned wires six samples out of eight were found to be welded. In Table 4, three out of nine untreated samples were found to be welded.

One difference between cleaned and uncleaned interface is illustrated by comparing Figs. 7 and 8; a weld was observed in the former but not in the latter case. In neither case was microdeformation present. Notice in Fig. 7, the base metal of both wires had been brought very close together during the process cycle, but failed to form bonds, whereas in Fig. 8, base metal of both wires contacted and formed bonds along the interface line.

Microdeformation on Faying Surface

Metallographic studies indicated that bonding of the wires within the forming die was not similar to that of the conventional shear-mode ultrasonic processes described in the AWS *Welding Handbook*. Unique microdeformation or metal turbulence was observed, indicating that metal flowed across the faying surface in both directions, in an eddy or whirlpool pattern.

Figure 9 shows an example of this unique whirlpool-like metallic turbulence. Figure 10 shows metallic microflows induced along the faying surface.

In the examination of plane AA (Fig. 3) of the welds attained, it is very interesting to notice that there are always many isolated areas of bonding occurring along the interfacial line, instead of one continuous weld. Bonding of the wires is always formed at these spots of microdeformation. One of the samples (Fig. 6) has six such microdeformation areas distributed along the interfacial line. Figure 11 gives another example of this unique distribution of microdeformation areas.

Table 1 — Welding Data, Die Design 6-1

Sample	Detuning time, sec	Maximum static force, lb	Maximum power input, W	Bonding
6-24-1	6.5	62 (a)	500	—
6-24-2	2.5	62 (a)	550	yes
6-25-3	1.5	62 (a)	550	— (b)
6-25-4	2.0	62 (a)	550	—
7-1-11	2.6	62 (a)	550	—
7-1-12	2.3	62 (a)	550	—
7-1-13	1.5	62 (a)	450	—
7-2-1	8.0	25	350	yes
7-2-2	13.0	39	575	—
7-2-3	14.5	41	500	—
7-2-4	6.5	30	550	yes

(a) Static force was increasing rapidly without using air tank as regulator.
(b) Metallographic study was not carried out to this sample.

Table 2 — Welding Data, Die Design 6-2

Sample	Detuning time, sec	Maximum static force, lb	Maximum power input, W	Bonding
7-1-1	1.5	45(a)	450	yes
7-1-2	1.0	45(a)	400	—
7-1-3	1.3	50(a)	400	yes
7-1-4	1.5	50(a)	400	—
7-1-5	14.0	25	450	—
7-1-6	14.0	20	400	yes
7-1-8	8.0	17	400	—
7-1-9	4.0	— (b)	400	—
7-1-10	2.0	— (b)	400	—

(a) Static force was increasing rapidly without using air tank as regulator.
(b) No information available.

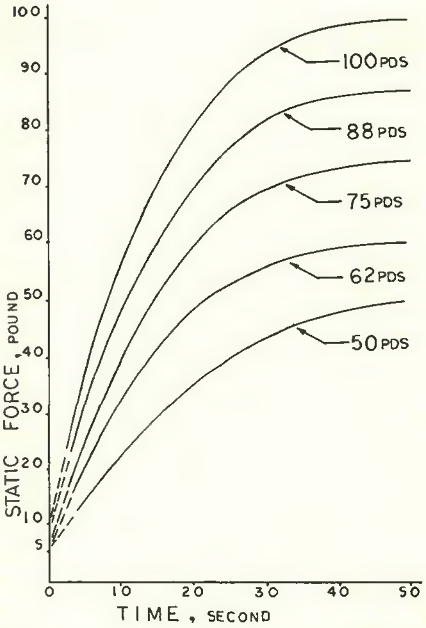


Fig. 4 — Curves showing the buildup of force with time of application for five different force settings

Fig. 5 — Photomicrograph of joint in Sample 7-1-1, plane AA, X400, reduced 32%

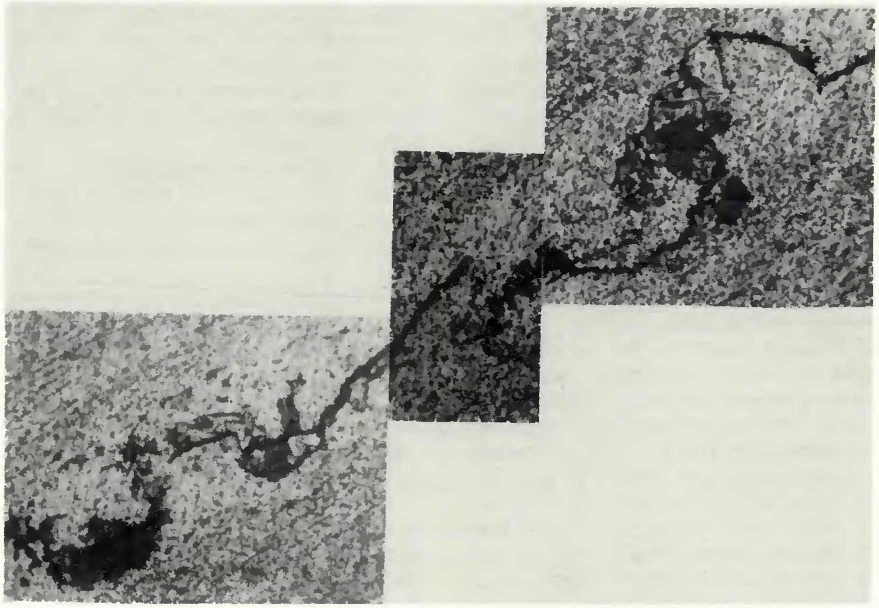


Fig. 6 — Sample 6-24-2, plane AA, showing microdeformation and partial elimination of bond line, X300, reduced 44%

Table 3 — Welding Data, Die Design 6-1 (Wires were precleaned)

Sample	Detuning Time, sec	Maximum static force, lb	Maximum power input, W	Bonding
7-12-1	18.0	45	420	—[a]
7-12-2	17.0	43	450	—
7-12-3	9.5	32	500	yes
7-12-4	14.0	40	420	yes
7-12-3	3.0	15	500	—
7-12-11	13.7	48	500	yes
7-12-12	10.0	40	500	yes
7-12-13	15.0	50	500	yes
7-12-14	11.7	43	480	yes

(a) Metallographic study was not carried out to this sample.

Table 4 — Welding Data, Die Design 6-1 (Wires were not precleaned)

Sample	Detuning time, sec	Maximum static force, lb	Maximum power input, W	Bonding
7-12-6	18.0	46	500	yes
7-12-7	16.5	44	500	—
7-12-8	16.5	44	500	—
7-12-9	18.0	46	500	yes
7-12-10	18.0	46	500	—
7-12-15	14.5	49	500	—
7-12-16	11.5	42	480	—
7-12-17	14.0	48	500	—
7-12-18	15.0	50	500	yes

Tables have been prepared which might disclose any relationship existing between the system parameters when this unique phenomenon occurred. Table 5 gives the system parameter readings for some of the samples in which this phenomenon was observed. So far, with the limited information available, no direct relation has been established between these parameters and the number, as well as length covered, of this unique microdeformation distribution.

Discussion

Forming Die

Before adopting the single hole tapered forming die, several different forming methods were tested. They included two-hole dies, different ways of feeding the wires, various taper angles, as well as different geometries and die materials. Although welding of the two wires was occasionally observed with these variations, difficulty was encountered in (1) buckling of the wires at a point adjacent to the die neck, (2) wires passing through the die neck completely, without welding and (3) welding of the wires to the forming die rather than to one another.

The single hole of the forming die used in this program has a taper angle of 5 deg. With this angle, buckling of the wires outside of the die has been eliminated or very much reduced. A die guide, as shown in Fig. 1, was also employed to reduce the buckling of the wires. The die guide limits the motion of the forming die to the direction in which the transducer tip vibration occurs.

The tapered hole of the die serves as a feeding cavity. Wire deformation can be calculated from dimensions of the wires and of the die neck, as shown in Fig. 3. The tapered feeding cavity serves mainly to create internal constraint force between the wires as they pass through the tapered hole. Constraint forces along the wire interfaces build up rapidly, as illustrated in Fig. 12, and eventually reach a value equal to yield strength of the base metal. Consequently, microdeformation along the faying surfaces is facilitated and surface films of both of the wires are finally broken.

Bonding Mechanism Analysis

The bonding mechanism in this process is unlike that in conventional ultrasonic shear mode welding in which two metallic surfaces are forced into a shear action, rubbing each other and forming a bond. In the process employed in this test series, a longitudinal mode process is utilized with a significant increase in energy density compared to the shear mode process. Another significant difference is that the percent deformation required in this process is much lower than that typical of shear mode ultrasonic welding. The microstructure of the bonded interface is significantly different in the two processes; however, they may both be categorized as solid state welding.

In this welding process, two wires are first forced into intimate contact with each other by the wedging action of the tapered die. The die is driven dynamically by intermittent contact with the transducer tip in a direction which forces the wires together. Constraint forces are therefore induced, which increase incrementally as the transducer continues to impact the forming die, as shown in Fig. 12.

Wires will therefore be deformed along both the wire-to-wire and the wire-to-forming die interfaces when these internal constraint forces exceed the yield point of the material. As the wires pass through the tapered section and into the die neck, the constraint forces keep building up incrementally and incremental deformation of both wires occurs. As elements of the work finally pass through the die neck, the constraint force is at its maximum value as is the total deformation. Thus the percent deformation is determined by both wire dimensions and the die neck diameter. The wires are retained within this dimension and are not separated even though excited by vigorous force impulses of the transducer.

Continuous application of ultrasonic energy in the form of force impulses facilitates microdeformation and/or microflows along and crossing the faying surface. Surface films on the wires are thus broken, and the base metals of the wires are thus brought into intimate contact with each other. A solid state weld is formed.

Figures 13 and 14 further illustrate weld formation along the interface. Notice that the bonding line has been eliminated where micrometallic flows have crossed the faying sur-

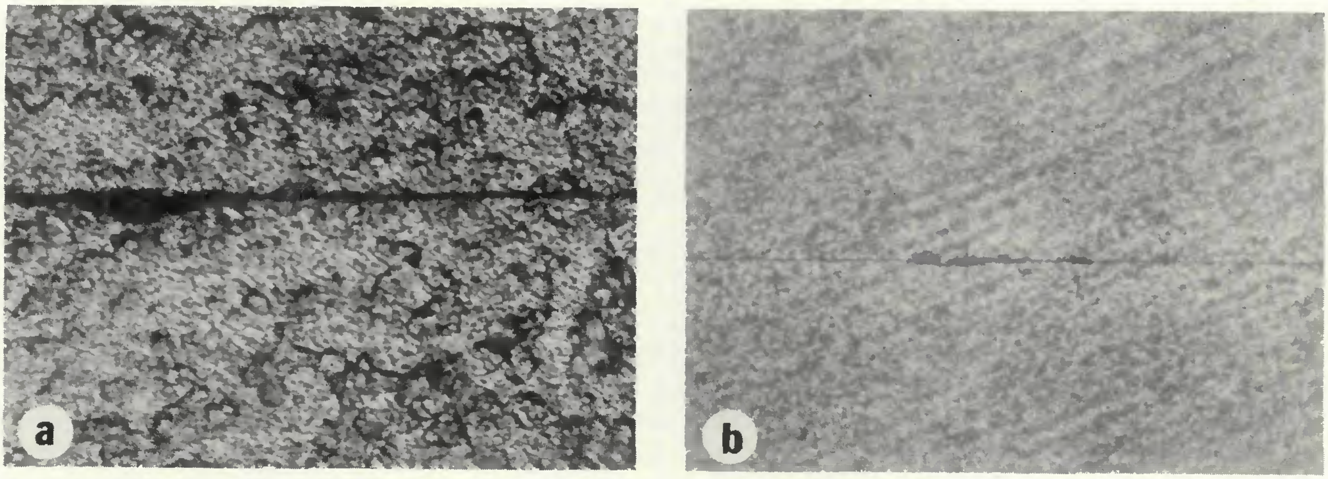


Fig. 7 — Bond line in Sample 7-12-14 (precleaned wires), plane AA. (a) X600, (b) X100, both reduced 9%

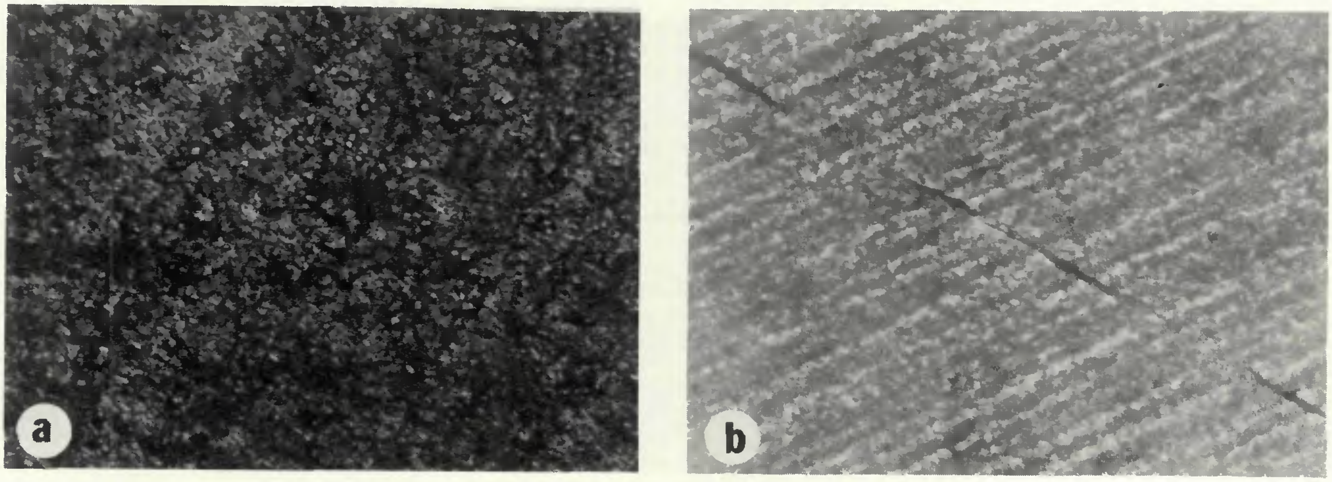


Fig. 8 — Bond line in Sample 7-12-16 (wires not precleaned), plane AA. (a) X600, (b) X100, both reduced 9%

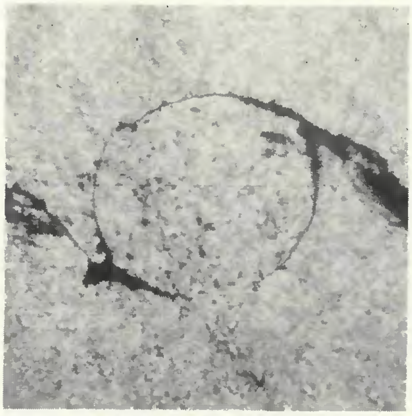


Fig. 9 — Typical metal turbulence, Sample 7-12-11, plane AA, X400, reduced 23%

Fig. 10 — Typical metal flow along faying surface, Sample 7-12-12, plane AA, X400, reduced 26%

face. These welds can, of course, be "strengthened" when subjected to postheat treatment.

Cause of metal turbulence and metallic flow along the interfacial line is probably an effect of the ultrasonic energy being concentrated at the faying surface. Detailed analysis of the formation of these phenomena is beyond the scope of this program.

Not only are the wires deformed along the wire-to-wire interface; they are also deformed along the die-to-wire interfaces. Some of the welds achieved earlier in this program were destroyed purposely to examine the interface deformation and the surface roughness condition of the working wires. It is interesting to note that black rings were always found surrounding the die-to-wire interfaces. These black rings, as illustrated by the right-hand wire in Fig. 15, suggest the presence of aluminum oxide which had been forced out of the interface when die wall and wire surfaces were in contact with each other.

Control Parameters

Electrical power input to the transducer, static force applied by the transducer to the die or working piece, and the time of excitation are three control parameters of the process. Theoretically, the energy density at the work surface is increased as the electrical power input increases. The determination of the energy density, however, depends upon the resolution of the overall efficacy which has yet to be determined.

The static force, which the transducer exerts upon the die, is one of the factors determining the rate at which ultrasonic energy is transmitted to the work surface, where the intermittent coupling system is employed. The total energy transmitted into the work is related to time of transducer excitation, as well as the input power level of the transducer. tion, as well as the input power level of the transducer.

Static Force Applied to the Work. Prior to the employment of programmed static force, tests were performed at the relatively low value of 10 lb. Welds were occasionally formed under these conditions. When the programmed force technique was used, most welding of wires occurred when the maximum static forces selected was between 40 to 50 lb, as indicated in Tables 1 through 4. In this series of experiments, the limit was 50 lb because of the transducer detuning caused by continuous contact between the transducer and the work. Only a few welds were formed when the maximum static force was below 40 lb. This implies that a higher maximum static force, which relates to a higher electrical input, is favorable to this welding process.

Electrical Power Input. With the limited information available, it can be seen that an increase in percent welds obtained was always related to higher power input. Of the total welds attained in this series of tests, as indicated in Tables 1 through 4, only one weld was observed at electrical power input lower than 400 W, while the rest were found at electrical power inputs from 400 to 550 W.

Table 5 — Microdeformation Distribution[(a)]

Sample	Bonding spots, no.	Length covered, microns	Maximum static force, lb	Maximum power input, W	Detuning time, sec
6-24-2	6	260	62	550	2.5
7-12-3	5	315	30	500	9.0
7-12-4	4	305	40	420	14.0
7-12-11	3	85	45	500	8.0

(a) All samples were pre-cleaned except 6-24-2.

Excitation Time. The excitation time, with programmed static force, equals the time interval between the instant the transducer touches the die until the moment the transducer detunes due to continuous (not intermittent) contact with the die. Alternatively, the transducer may detune from striking the stopper. The stopper, as illustrated in Fig. 1, is to prevent the transducer from hitting the wires. It protects the welds already formed.

The time interval is therefore the time required for the gross motion of the die, or the time for the wires to travel the required distance within the die neck. This time is determined by several factors, but it is not a prescribed interval. To some degree, a higher power delivery to the die means a shorter time of excitation, and vice versa. The total energy delivered is, of course, the product of time of excitation and power delivered.

The data indicate no correlation between the time of excitation and the number of welds attained.

Summary

In most current deformation welding processes, a minimum of 25% deformation is required to create a bond as strong as the base metal (Refs. 8-10). For some materials, as high as 70% deformation is necessary. High forces are thus demanded to achieve the required amounts of deformation in such processes.

It is also true that in many cold welding applications the base metal surfaces should be cleaned before bonding to give best results. For metals like aluminum, which has high negative electromotive potential, this surface preparation plays an even more important role.

In conventional ultrasonic welding processes, a piece of thin metal plate or wire can be joined successfully to a metal which may be either thin or thick. The relative motion between

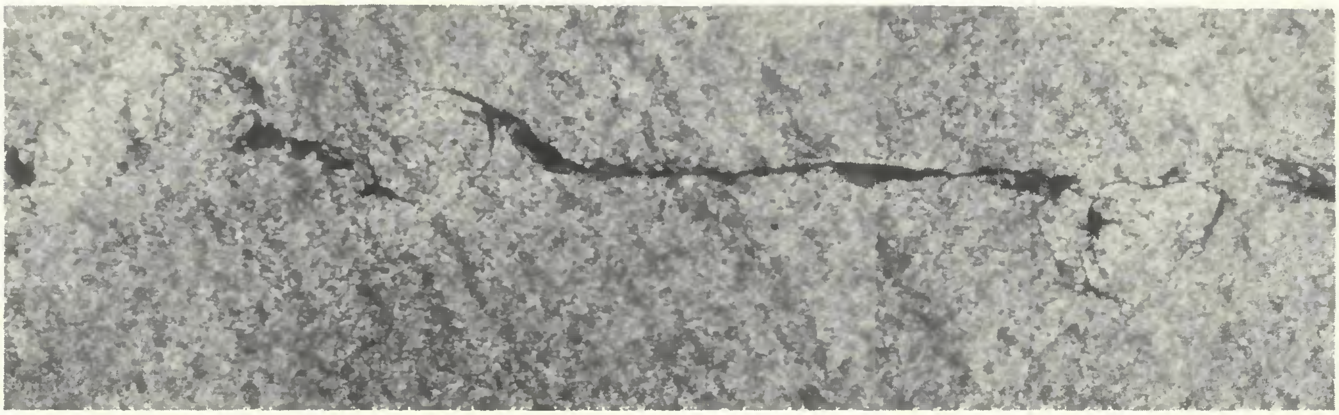


Fig. 11 — Microdeformation spots along faying surface, Sample 7-12-11, plane AA, X200, reduced 16%

these two plates disperses the oxide films of the faying surface and brings a metal-to-metal contact. However, the thickness limitation of the thinner piece in the currently available ultrasonic welding processes is 0.040 in. (Ref. 11). This thickness limitation is due primarily to the damping effect of the base metals, which disperses most of the applied ultransonic energy.

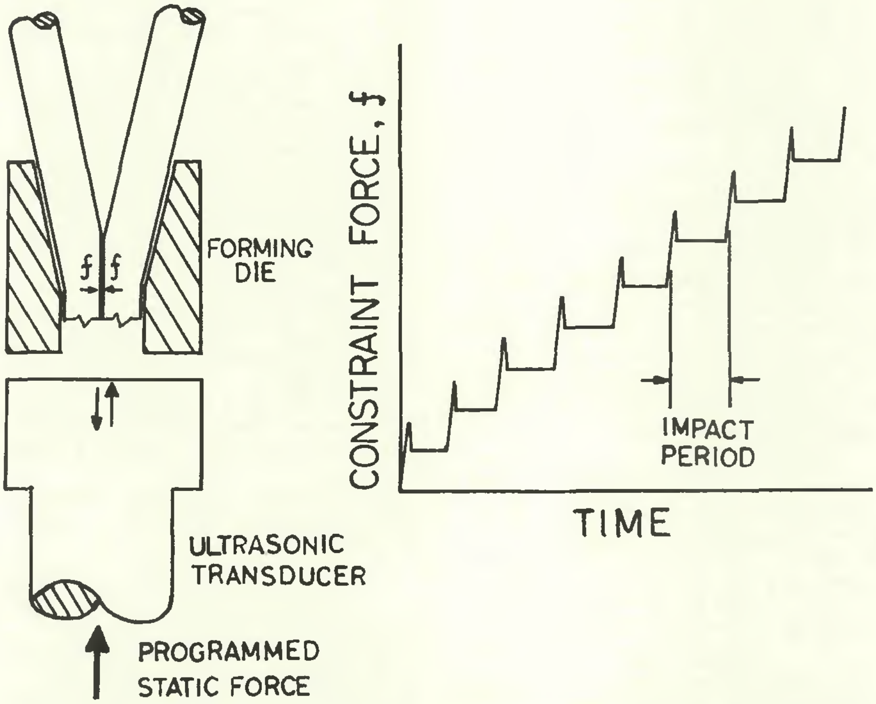


Fig. 12 — Position of wires in forming die with chart showing incremental buildup of constraint forces during welding cycle

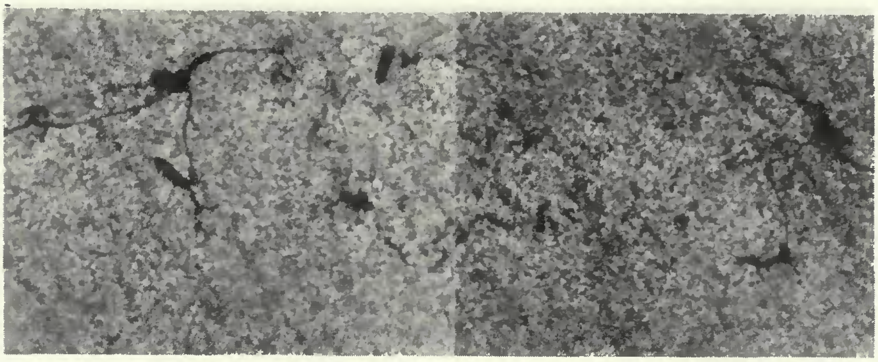


Fig. 13 — Weld formation along interface showing partial elimination of bond line with metal flow across faying surface, Sample 7-12-4, plane AA, X150, reduced 33%

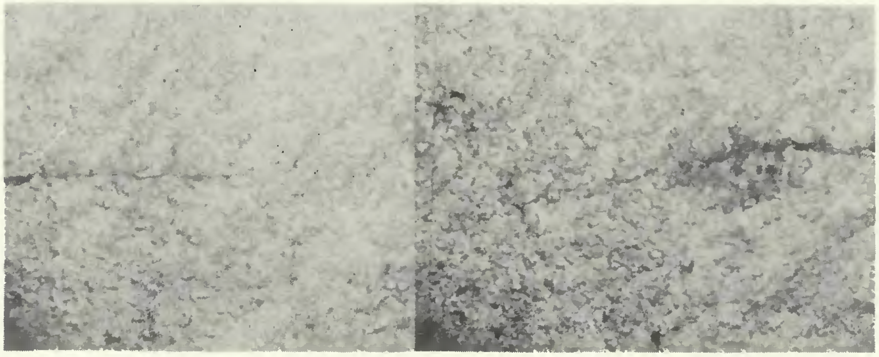


Fig. 14 — Condition similar to that of Fig. 13, Sample 7-12-8, plane AA, X400, reduced 35%

The results of this research program show that welding of 0.125 in. diam aluminum wires is possible with the longitudinal mode ultrasonic welding process in which the intermittent coupling system is employed. Deformation has been induced along the wire-to-wire interface. Percent deformation of either 8.8% or 11.6% was obtained with the aluminum wires. This deformation is much lower than that of the current deformation welding processes, but is still in the same range as that of conventional ultrasonic welding processes, as cited by J. B. Jones (Ref. 11).

Static forces ranging from 10 to 50 lb were applied to the forming die. Static force was used to insure a good energy transmission ability in this coupling system, rather than to deform the aluminum wires to be welded. This force is therefore significantly lower than most cold welding processes. In most cold welding processes, the force is necessary either to overcome the yield point of the base material, or, in some cases, to hold tightly the metal pieces to be welded.

In this work, welding was made without precleaning the wires. Unique deformation types, such as metal turbulence and microflow, were present along the interface. This deformation of the metal surface can certainly break the heavy surface films of the wires and make possible metal-to-metal contact. However, like most of the processes in the cold welding family, precleaning of the base metals does accelerate the formation of bonding along the interface, as indicated in Tables 4 and 5.

The diameter of the wires employed throughout this research program, 0.125 in., is larger than the 0.040 in. thickness cited by Jones in the *Welding Handbook* as the normal limitation in the conventional ultrasonic welding processes (Ref. 11). Un-

Fig. 15 — Typical faying surface roughness, Sample 2-16-4, X10, reduced 24%. Left, wire-to-wire surface; right die-to-wire surface

doubtedly, more energy has been transmitted to the faying surface through the unique intermittent coupling system.

Prior to the employment of programmed static force, a series of tests were performed using fixed static force. Electrical power input ranging from 80 to 425 W was recorded (Ref. 12). With the programmed static force technique, this power input was significantly increased to an average value of 500 W as indicated in Tables 1 through 4. This implies that the energy transmission capability of the intermittent coupling system has been much improved. Latest developments in the Sonic Power Laboratory show that, under a fixed excitation voltage, the transducer resonant frequency will be varied accordingly as the static force applied by the transducer to the load increases. When this resonant frequency matches exactly that of the power supply during the working cycle, higher power input to the transducer is possible (Ref. 13).

Conclusion

Based upon the experimental results and the theory presented in this text, the following conclusions can be drawn:

1. Welding of the aluminum wires has been made possible with this unique process at a deformation rate significantly lower than that required in the conventional cold welding processes.
2. The average static force required to form a solid-state bond has been very much reduced, compared to the conventional cold welding processes.
3. Welding of aluminum wires of diameter as large as 0.125 in. by ultrasonic energy has been made possible with this process in which the unique intermittent coupling of the ultrasonic transducer to the work was employed.
4. Precleaning of the wires is not a fundamental requirement of this welding process.
5. Optimum use of the transducer to insure a maximum possible power input is made possible through the use of a programmed static force, as contrasted to a fixed static force.
6. Although this is not a commercial process, it shows promise for commercial development.

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