# Additional Studies on Interface Temperatures and Bonding Mechanisms of Ultrasonic Welds

## Bonding is a mechanical disruption of surface layers and the presentation of nascent surfaces to each other, thereby creating metal-to-metal adhesion wherein there may be some grain boundary diffusion across the bond interface

BY T. H. HAZLETT AND S. M. AMBEKAR

ABSTRACT. The beginning of ultrasonic welding of metals, as the process is recognized today, has been attributed to the Germans during World War II. In the early 1950's considerable effort was spent on developing methods of utilizing this process, and a number of rather fundamental research programs were undertaken and their results reported in the literature. Basic studies of the bonding mechanism have been seriously considered during the past ten years, and the literature abounds with references in this area. There is considerable evidence to indicate that four basic bonding mechanisms may occur, depending upon the material combination involved:

1. Melting of the interface.
2. Mechanical interlocking.
3. Interfacial atomic forces (nascent bonding).
4. Interfacial chemical reactions, which often result in diffusion.

The presently reported study was undertaken to shed more light upon the maximum temperatures achieved during this welding process as well as to identify more positively at least one or more of the bonding mechanisms involved.

Temperature rise during the welding cycle was determined by utilizing the Seebeck (thermocouple) effect by measuring the voltage produced between the two dissimilar metals being joined and thereby measuring the average temperature over the welded area. Material combinations of aluminum, brass, copper, stainless steel and nickel were welded in various combinations to determine their response to this approach. It was concluded that a higher output voltage was required despite the fact that the instrumentation used consisted of a 1,000:1 preamplifier and a very sensitive recording oscillograph.

Standard iron-constan and copper-constantan thermocouple wires of 0.021 in. diameter were cold-rolled to a strip thickness of 0.002 inches. It is recognized that this resulted in a non-uniform cold-worked condition across specimen width; however, every effort was made to locate the welds in the center of the strip produced which was the area of maximum cold work.

The effect of power input to the transducer on the average interface temperature was measured. No attempt was made to determine shear strength of the welds prodcced, but a peel test was used as the criterion of a "good" weld; a "good" weld is defined as one in which a nugget is pulled from one of the base metal foils. It was found that there was a minimum average temperature over the weld interface and corresponding minimum power input for a particular clamping pressure required to obtain a satisfactory weld. This measured temperature was 345° F for iron constantan, and 325° F for copper constantan. The clamping pressure in all cases was 50 lb.

This minimum temperature was obtained under two conditions for each material combination:

1. Low power input and long weld times (4 seconds).
2. High power input and short weld times (approximately 0.5 seconds). Metallurgical bonds were produced under both sets of conditions. Representative specimens produced under each of these conditions were cross-sectioned and scanning electron micrographs were made at several magnifications varying from ×270 to ×30,000.

These electron micrographic studies indicate that, for the particular alloy systems studied, there is limited evidence of grain boundary diffusion across the bond interface and there was mechanical interlocking of the two alloys. Microcracks are produced at the interface under certain welding conditions. It must, therefore, be concluded that for the specific cases studied the bonding mechanism is primarily that of mechanical disruption of surface layers and the presentation of nascent surfaces to each other, thereby creating metal to metal bonding which may be termed adhesive in nature. Further, there may be grain boundary diffusion across the bond interface. Irrespective of the bonding mechanism, a minimum average temperature must be reached in the bond area to achieve a "good" weld.

T. H. HAZLETT is Professor of Mechanical Engineering and S. M. AMBEKAR is a former Graduate Student, University of California, Berkeley, Calif.

Paper presented at the AWS 51st Annual Meeting held in Cleveland, Ohio, during April 20-24, 1970.

### Introduction

The potential effect of ultrasonic energy on the mechanical properties and joining of metals have been recognized for two decades, and meaningful studies have been made in depth during the past 10 years to apply this energy source to other production processes. During this time numerous investigators have examined the probable mechanisms responsible for the ultrasonic bonding of metals. One school has studied the area of contact of the mating surfaces using elastic or plastic analysis to estimate the area of physical contact where the bond is formed.[1–6] Others have approached the problem from a thermal activation point of view.[7–12] It is generally agreed by all that there is a significant temperature rise at the interface during welding.

The earliest reported studies on the possible bonding mechanisms were made by Winter and Neilson[11] who proposed that any one or a combination of four mechanisms may be responsible:

1. Melting—as possibly evidenced in a lead-tin couple, but the results were not conclusive.
2. Mechanical interlock—as evidenced in copper-silver and copper-nickel couples where the interface reaction seemed to be one of turbulence and disruption.
3. Interfacial atomic forces (nascent bonding)—as evidenced in the aluminum-aluminum and the copper-

copper bonds in which the interface quickly disappeared.

4. Interface chemical reaction—as shown in the copper-zinc and titanium-molybdenum bonds which indicated diffusion with a consequent full range of phases present.

These speculations were deduced from studies of ultrasonic bonds of similar and dissimilar metal couples whose cross-sections were examined metallographically.

More critical evaluation of these specualtions would be aided if the maximum interface temperatures reached during welding could be determined. Previous investigators[5,13] have used thermocouples at the interface in an attempt to determine these temperatures, but this technique is recognized as being questionable for any of the following reasons:

1. The presence of a thermocouple at the interface is a foreign object with different mechanical and physical properties which may produce an unknown effect. It could either raise the indicated temperature above the actual maximum, or conduction through the thermocouple wires could lower the indicated temperature, even though the wires are very small in diameter.

2. The thermal emf generated at the hot junction may be shorted through the relatively colder base material or on the anvil, thereby causing a low indication.

3. The precise location of the thermocouple relative to the center of the faying surfaces during welding is questionable since it may move during the welding cycle.

Lewis, et al,[10] Winter and Neilson,[11] and Jones et al[13] depended upon the use of equilibrium phase diagrams to deduce temperatures from the metallurgical reactions that were observed after welding was completed. However, ultrasonic bonding is far from being an equilibrium process; it is an exceedingly dynamic process. Consequently, the temperatures thus determined may be greatly in error. Lewis used the $\alpha$-$\beta$ transus for titanium to conclude that the weld interface may be at or near the melting point. He also found alloying when Type 316 stainless steel was welded to titanium while Gencsoy et al [12] showed that diffusion definitely occurs across the interface of a Ti-Cu weld.

These studies show conclusively that diffusion is one of the effective mechanisms that activate bonding during ultrasonic bonding of some dissimilar metal combinations. However, it is not clear as to whether this is the only operative mechanism or whether the reported interface temperatures are reasonably accurate.

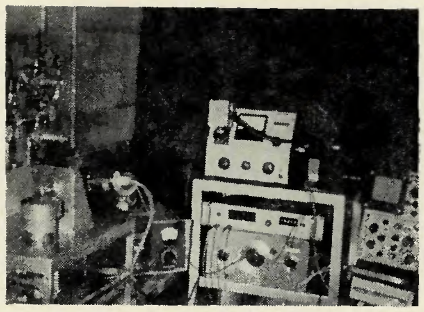

Fig. 1—Complete experimental equipment

The investigation reported herein was designed to minimize some of the questions regarding the validity of previously reported interface temperature measurements and attempt to shed more light on the other bonding mechanisms that may be operative.

## Experimental Procedure

The welding equipment, necessary associated controls and instrumentation are shown in Fig. 1. The energy source consisted of a power supply rated at 250 watts which fed into a nominal 20 kc transducer which converted the electrical to mechanical energy. The transducer was stationary mounted at an antinodal point on the amplifying horn, the horn being made of a titanium alloy and double cylindrical in shape. Force was applied between the faying surfaces of the metals being joined through a pneumatically actuated ram which moved upward towards the fixed welding tip. The welding tip itself was mounted at the end of the transducer horn and made from hardened tool steel with a radius of 0.134 in. A relatively massive anvil was used which was also of hardened steel. This is shown in more detail in Fig. 2.

Although the power supply was equipped with a feedback sensing system to lock the frequency of the power supply to the resonant frequency of the coupled system, this was not found to be satisfactory. Accordingly, it was necessary to decouple this mode of operation and utilize an auxiliary external oscillator to tune the system to its resonant frequency. This resonant frequency was determined by the maximum power input. However, this resonant frequency changed with clamping force, the materials being joined, weld time, and power level, since the force transducer system increased in temperature due to adsorbed energy. A power meter was placed between the output of the power supply and the input to the transducer.

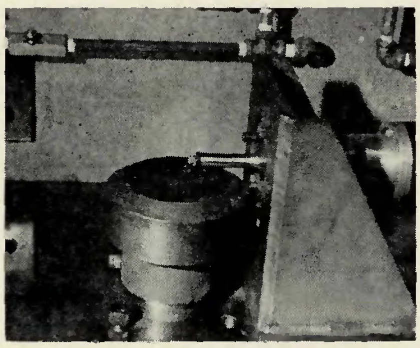

Fig. 2—Transducer, amplifying horn, welding tip and anvil

The moveable ram assembly was so designed that the ram approached the work pieces slowly with a low level of air pressure, but the clamping force at the time of welding was independently controlled. All tests were made with a final clamping force of 50 lb, but preliminary exploratory work was carried out at both higher and lower values. The ram force was not monitored during the actual welding cycle but was accurately calibrated prior to initiation of the tests.

Length of weld time was controlled by an electronic timing circuit capable of controlling within 0.1 second increments.

Temperatures were measured by utilizing the Seebeck effect in which the voltage difference between two dissimilar metal junctions was calibrated in terms of the actual temperature of the junction, i.e., the thermocouple effect. Output emf from the members being welded was channeled through a 1000:1 d-c pre-amplifier and into a recording oscillograph to measure the temperature rise.

In the initial stages of this study, different materials and combinations thereof were utilized including aluminum, brass, copper, stainless steel, and nickel. It was found that soft metals with good solid solubility such as aluminum, copper, nickel, and brass, were readily welded under a wide range of clamping pressures, welding times and power inputs. Heat-resistant alloys such as titanium, molybdenum, zirconium, and Inconel were also welded, but it was difficult to obtain good weld strengths in these materials. This difficulty was attributed primarily to their hardness and higher yield strength at elevated temperatures, but the limited power capacity of the equipment was undoubtedly also a factor.

The principle objective of this investigation was to determine the temperature rise in the weld zone, relate it to the weld structures produced and, hopefully, better understand the bonding mechanisms involved in the ultrasonic welding of some dissimilar metals. Since most of the original dissimilar metal combinations investigated produced very low voltages, the

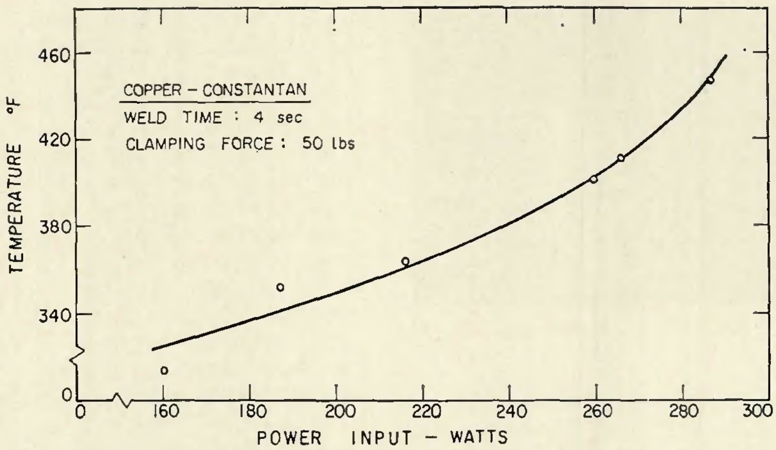


Fig. 3—Maximum average interface temperature vs. power input

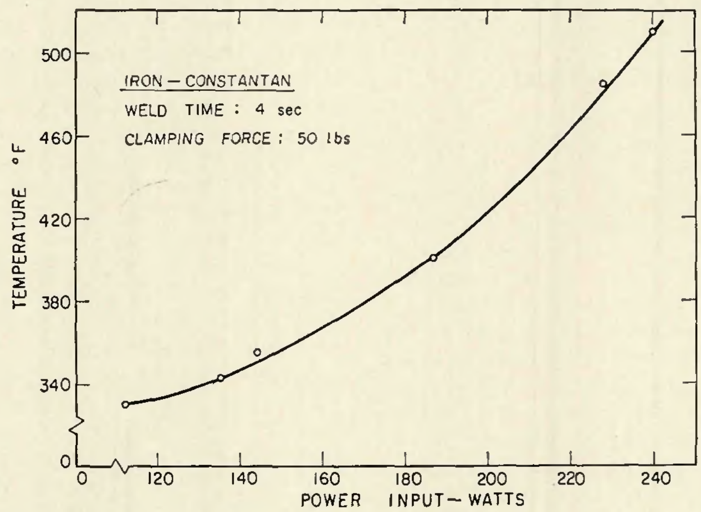


Fig. 4—Maximum average interface temperature vs. power input

Fig. 5—Copper-constantan bond at short time and high power. X14,000 reduced 40% on reproduction)

Fig. 6—Copper-constantan bond at short time and high power. X14,000 (reduced 40% on reproduction)

values of which were considered unreliable, standard thermocouple alloys were used. Two combinations, iron-constantan and copper-constantan, are reported herein. Standard wires of 0.021 in. diameter were rolled flat to a strip thickness of 0.002 in. It is recognized that this resulted in a non-uniform cold worked condition across the specimen width. However, every effort was made to locate the welds in the center of the strip which was the region of maximum cold work. Cleaning consisted only of degreasing the foils with alcohol prior to welding.

No attempt was made to determine shear strength of the welds but a peel test was used as the criterion of a "good" weld; a "good" weld is defined as one in which the whole nugget is pulled, leaving a similar sized hole in the other member being joined.

The maximum welding time was selected as four seconds, since this length of time was required for the temperature to level off or show a negligible rate increase at lower input levels.

Power input to the transducer was varied and maximum temperature noted to determine the minimum temperature and time required to produce a good weld. Consistency in the results varied considerably which may be attributed to unstable operating characteristics due to the fact that resonant coupling is extremely critical. Any frequency drift causes lower power input to the transducer and consequently results in lower temperatures. Results of stable temperature vs. power input are shown in Figs. 3 and 4 for the metal combinations studied.

The amplitude of vibration of the horn was determined by means of a stroboscope and microscope. Clamping forces in the range of 10–230 lb resulted in a relatively constant end-to-end displacement of the tip of 0.002 in.

Scanning electron micrographs were taken of cross-sectioned and etched "good" welds at magnifications varying from $\times 270$ to $\times 30{,}000$ in an effort to determine the operative bonding mechanisms.

## Results

It should be noted from Figs. 3 and 4 that the variation of maximum temperature with power input is not linear but the maximum temperature rises more rapidly as power is increased at the higher power levels.

Two micrographs of each metal combination are shown at different power input levels. The minimum temperature required for obtaining "good" welds were obtained by:

1. Low power and long weld times.
2. High power and short welding times.

Clamping pressure was maintained at 50 pounds in all cases.

Figures 5 and 6 show the interface between copper-constantan under conditions of short times and high power; both were originally taken at $\times 14{,}000$ from different areas of the same weld. It may be seen that fine microcracks appear extending into the base metal; micro-voids are also present although the weld pulled a "button." Undoubtedly such cracks are due to fatigue directly attributable to the welding process. This condition is enhanced by the fact that the base metals in both halves of the specimen were severely cold-worked prior to welding and the energy input level was high. If diffusion occurred across this interface, it is not evident from the photomicrographs, but rather, bonding appears to be a result of

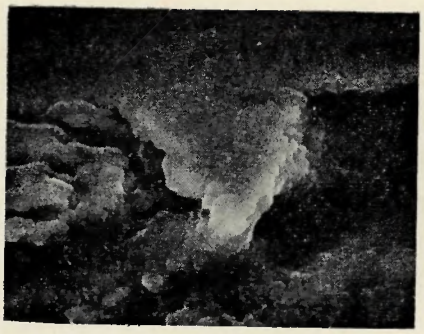

Fig. 7—Copper-constantan bond at longer time (4 sec.) and low power. X7,100 (reduced 40% on reproduction)

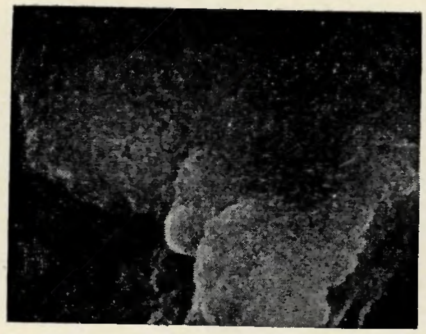

Fig. 8—Copper-constantan bond at longer time (4 sec.) and low power. X28,200 (reduced 40% on reproduction)

Fig. 9—Iron-constantan bond at short time and high power (4 sec.). X2,900 (reduced 40% on reproduction)

mechanical mixing.

Figures 7 and 8 illustrate the same alloy combinations but welded under conditions of longer times and lower power levels. In both welds, a maximum temperature of 325° F was recorded by the method previously described. Figure 7 illustrates the boundary at a magnification of ×7,100 and rather severe mixing of the interface is evident. However, it is difficult from this photograph or from Fig. 8, which was taken at double that magnification, to see any clear evidence of diffussion. The shading shown in the protrusions are attributed to the difference in reflectivity rather than diffusion between the alloys being joined.

Figures 9 and 10 are of two different magnifications (×2,900 and ×14,800) of the same general area of an iron-constantan weld made under conditions of short times and high power. It appears again that no diffusion has occurred across the interface, but the weld is formed by either nascent bonding or mechanical mixing. Evidence for the latter is particularly evident in Fig. 9. As contrasted to Figs. 5 and 6 there is no evidence of cracking of the base metal or of voids at the interface even though the amount of cold work was severe.

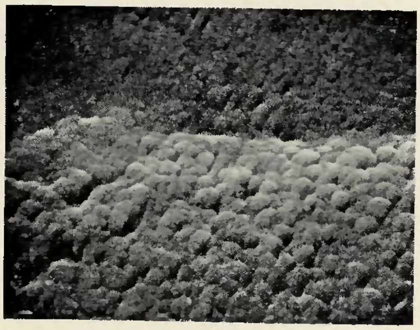

Fig. 10—Iron-constantan at short time and high power (4 sec.). X14,800 (reduced 40% on reproduction)

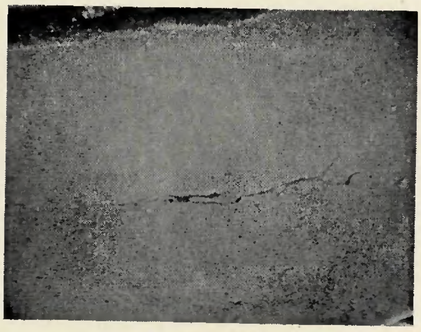

Fig. 11—Unetched bond between iron and constantan. X750 (reduced 40% on reproduction)

A low power scanning electromicrograph of an unetched bond (×750) is shown in Fig. 11 which shows lack of bonding at the edge of the weld zone and some lack of bonding toward the center of the weld itself. The weld shown in this photomicrograph, as well as that in Figs. 12 and 13, were made under conditions of low power input and longer time (4 seconds). Maximum recorded temperature stabilized at 345° F. The bonded areas are shown in Figs. 12 and 13 at much higher magnifications (×8,000 and ×16,000). It may be seen that there is a distinct metallic bond area, but some diffusion may have occurred along a grain boundary of one of the two alloys being joined.

## Discussion

A study of the scanning electron micrographs (Figs. 5-13) confirms findings of previous investigators and indicates that there are probably at least two of the postulated mechanisms occurring insofar as bonding of these specific alloy couples by ultrasonic energy is concerned.

The work of Gencsoy et al proves conclusively that diffusion across the interface can occur in the case of the bonding of some dissimilar metals. However, the temperatures measured by the writers are very low, indicating that normal diffusion processes associated with relatively high temperatures and long times are not necessarily required for this particular bonding process.

It is recognized that the temperatures measured in this study represent an average over the entire contact area and not the maximum. However, it is believed that the maximum temperatures do not exceed three of four times that of the measured average, and thus is still far below those that would be expected for diffusion in the very short length of times involved.

Langenecker and his staff through many studies, [14,15] as well as Lewis et al [10] have shown that basic material properties may be altered when subjected to ultrasonic vibrations. Thus, it is likely that the severely cold-worked base metal used in this study was recrystallized during the burst of ultrasonic energy applied during the bonding process.

Prior investigators have also shown conclusively that the application of ultrasonic energy vastly enhances dif-

Fig. 12—Iron-constantan bond at low power and long time (4 sec.). X8,000 (reduced 40% on reproduction)

Fig. 13—Iron-constantan bond at low power and long time (4 sec.). X16,000 (reduced 40% on reproduction)

fusion rates. It is certainly conceivable that the application of bursts of ultrasonic energy used in this bonding process is a major contributing factor to both diffusion and recrystallization of severely cold-worked pure metals and alloys.

A study of Figs. 12 and 13 indicates that there may have been some diffusion along recrystallized grain boundaries, or these may be merely the grain boundaries themselves with some associated segregation. If it is grain boundary diffusion, this could account for the results reported by Gencsoy as well as others who have shown that diffusion occurs. However, in view of the very high magnification of these micrographs, this diffusion is very slight in depth. These results are not, however, inconsistent with the X-ray microanalysis performed at Osaka University between copper and titanium welds.

The presence of microcracks and microvoids shown in Figs. 5 and 6, when compared to the absence of such imperfections in Figs. 7 and 8, indicate that the intensity of power input has a very distinct bearing upon the type and quality of bond produced. It is impossible to determine from these four micrographs whether some melting and resolidification occurred, although in the opinion of the authors, such is not the case. Rather, the bond is considered to be primarily mechanical in nature.

On the other hand, Figs. 9 and 10 show no metallographic evidence of diffusion across the interface and every indication is that this is a nascent metal (chemical) bond.

Since no cleaning of the surfaces was performed prior to bonding, except to degrease with alcohol, the surfaces being joined had a surface film which had to be broken up by the ultrasonic energy. It must, therefore, be concluded that at the initial stage of energy application, surface films in the contact area between the components being joined are disrupted and at least partially removed—some into the base metal and the balance to the edge of the weld—thereby bringing clean metal surfaces into contact with each other. Thus a metallic bond is formed between nascent surfaces. As the contact area increases, the disruptive force is inevitably higher, but at a certain stage, the relative displacement of the two components ceases, and a major source of additional heat vanishes. The maximum interface temperature stabilizes at a constant value when the rate of heat produced is equivalent to the rate of heat lost.

Since plastic deformation plays an important role in this welding process, it is essential that the ultimate tensile or fatigue strength of the material not be exceeded during the vibrating time cycle. Annealed or soft materials with low moduli of elasticity, such as copper and aluminum, can generally withstand greater strains without failure than materials with higher moduli or with a small difference between yield and ultimate strengths. This may explain the relatively poor weldability of heat-resistant materials such as titanium, molybdenum, and zirconium. This view is supported by experiments of Weare and Monroe[16] who found that cracking occurred at the edge of the bond area where maximum stresses were developed when tip displacement exceeded about 0.002 in. This should also apply to severely cold-worked materials such as those used in the present study. This is supported by the cracks shown in Figs. 5, the voids evident in Figs. 6 and the partial bonding or fatigue cracking of Fig. 11. It is probable that the lack of bonding shown in the latter micrograph is due to fatigue rather than a lack of initial bonding. This is supported by the cracks which extend in a direction approximately 45 deg to the bonding plane.

## Conclusion

1. One of the most important parameters in determining static weld quality as determined by the "peel" test is the maximum average temperature attained in the contact area during ultrasonic welding. The heating is due to the combined effects of elastic hysterisis, plastic deformation, and friction between the various components.

2. Increase in weld strength with an increase in temperature may be attributed primarily to the larger area of seizure between the two components being joined; higher temperatures extend the zone of plastic flow. When maximum contact is established, the joint attains maximum strength and the bond strength becomes independent of temperature.

3. Some metallurgically sound bonds are due to mechanical mixing at the interface and the accompanying nascent metal bonding.

4. Metallurgically sound welds may be formed by nascent metal bonding without evidence of severe mechanical mixing.

5. Diffusion across the bond interface shown by previous investigators may be due to grain boundary rather than bulk diffusion.

6. Weld quality as measured by micro-cracks and/or micro-voids is a function of welding parameters. Relatively high power levels enhance the probability of such defects.


*Acknowledgements*

The authors wish to acknowledge the assistance of the Electronic Research Laboratory personnel, University of California, Berkeley, Calif. for taking the stereoscan scanning electron micrographs.


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