Numerical Simulation of Solder Solidification

The interface effects at a solder/base metal joint are shown to be more dependent on base metal surface condition than on solder composition and temperature when using a numerical model to simulate the unidirectional solidification of Pb-Sn solder against a brass plate

BY DELCIE R. DURHAM

ABSTRACT. The development of a numerical model to simulate the unidirectional solidification of lead-tin alloy solder against a brass plate was accomplished. The computer program included a set of finite difference equations specifically developed for solidification heat transfer, incorporating variable compositions of the solder encompassing the entire range of lead-tin alloys, variable thermophysical properties for the alloy, and variable values concerned with the condition of base plate, and degree of superheat of the molten solder.

The interface effects at the solder/base metal joint are shown to be greatly dependent upon the condition of the surface of the metal plate, and to a lesser degree on the composition of the solder and the temperature of the solder.

Wettability and the thermal conductance at the interface are directly related to these same parameters.

Introduction

There has been considerable progress made in recent years predicting the solidification patterns in ingots, sand-castings and die-castings, of both pure metals and long freezing range alloys, using numerical simulation techniques.[1-4] Analytical methods have been successfully used to predict peak temperatures and cooling rates in the heat-affected zones of welds,[5] but very little attention has been given to the prediction, or even to the measurement of rates of solidification or cooling rates within the weld metal itself.

Welding, brazing, and soldering researchers are acutely aware of some of the effects of these parameters on the quality of the weld. In particular, the work of Adams[6] and Savage[7] and their colleagues has indicated how both weld microstructure and macrostructure can be manipulated by controlling the speed of welding, arc energy and the lateral movement of the heat source. This, in turn, affects both the rate of freezing and the temperature gradient of the weld pool during solidification.

In the case of brazing or soldering, the widest range of sound joints is obtained when the joint design and the method of heating permit rapid melting and unidirectional flow of the brazing or soldering alloy.[8] The ability of the molten solder to flow over, or wet, the base metal is dependent upon several parameters. Shipley[9] discusses the effects of surface rugosity, solder composition and flux usage upon the wetting characteristics in soldering, in an effort to optimize the soldering process. The temperature of the liquid solder also has a considerable impact upon the wettability.

Paper prepared while DELCIE R. DURHAM was a Graduate Teaching Fellow, Department of Mechanical Engineering, University of Vermont, Burlington, Vermont.

Effect of Solder/Base Metal Interface Air Gaps

It is apparent that the difficulties inherent in the soldification of most metals are present in the particular case of solder solidification. Many solder materials exhibit shrinkage upon solidification and cooling, and this leads to a phenomenon commonly found in casting solidification which is the formation of an air gap between the solidifying metal and the metallic mold. In casting, this air gap affects the heat transfer and thus the solidification parameters in the cast part. In soldering, it will strongly reduce the strength of the joint by limiting the contact between the solder and the base metal. The formation of the air gap depends upon the surface rugosity of the base metal as investigated by Prates, Fissolo and Biloni;[10] it also depends on the cleanliness of the base metal, and the degree of superheat of the molten metal which has been shown to affect both the fluidity and the shrinkage by numerous researchers.

The presence of any air gap at the mold/metal interface affects the heat transfer both across the interface and in the solidifying metal. In the simulation of casting solidification, the heat transfer equations at the interface include an air gap thermal conductance term (the reciprocal of the resistance which the air gap provides to heat transfer), which is often referred to as the interfacial heat transfer coefficient. If there were perfect thermal contact, then the conductance value, h, would be infinite. In actual practice, it has been found that h has a wide range of values depending upon the particular metals involved, and the other parameters previously mentioned.

An investigation was previously made into the role of the mold/metal interface during solidification and its effects upon the solidification parameters for a pure metal against a metallic chill using a finite difference model for computer simulation of unidirectional solidification.[11] It was found that the greater the thermal conductance, the more rapid the solidification rate and the finer the microstructure.

In the die-casting industry, die washes are used to protect the die surface and to facilitate ejection of the part. These washes, usually an oxide, provide greater resistance to heat transfer at the interface, and thus decrease the interfacial thermal conductance. The temperature of the die, while still cyclic, does not reach as high a value, and the solidification parameters of the part are altered considerably. This is directly opposite to the soldering process, where the surface is fluxed to remove oxides and the greater intimacy of contact is desired. The higher h value is now desired.

Scope of Investigation

An investigation was made to determine if a simulation model would be capable of predicting solidification parameters in the solder, and the intimacy of contact between the solder and the base metal. A variety of the most common commercial lead-tin solders—60/40, 50/50 and 40/60—were chosen. Experimental unidirectional castings and computer simulations were made and the results compared.

Simulation Model

A unidirectional solidification model has been developed to simulate the solidification of a column of pure lead or pure tin against a metallic, water-cooled chill.[11] A computer program was written to solve a series of heat transfer equations for the mold and casting metal in finite difference form over a period of time steps. The model specifically included an enthalpy-temperature relationship to allow for the discontinuity in enthalpy at the freezing point due to the latent heat of fusion, variable thermal conductivities in liquid and solid metal (Table 1), variable degree of superheat in the molten metal, and variable values of air gap thermal conductance at the mold/metal interface. Output from the simulation model included the temperature profiles at various locations in both the casting and the base plate, the solidification time at an array of points throughout the casting, and the local rate of solidification between these points. These results agreed satisfactorily with experimental data obtained for these two materials, as shown in Figs. 1 through 6.

To simulate the unidirectional solidification of a column of solder against a brass chill, the model had to be modified to handle binary alloys. The latent heat of fusion was distributed linearly over the finite freezing range of the alloy, thus altering the enthalpy term. The extents of progress at the beginning and end of solidification along the column were then determined from the respective enthalpy values.

Since various alloy compositions were to be simulated, a generalized alloy program was developed where the enthalpies and thermal conductivities were based upon the alloy compositions read in from a data file. In this way, simulations of the solidification of various alloys were accomplished with the same basic program.

Experimental Work

The three commercial lead-tin solders—60/40, 50/50, and 40/60—were unidirectionally solidified in a stainless steel cylindrical mold against a water-cooled brass chill, as shown in Fig. 7. The mold was wrapped in insulating material, and the interior coated with refractory wash. The contact area on the chill was well polished, and either coated with lampblack, coated with Nokor-ode flux paste or left bare. The mold and chill were assembled and preheated to the temperature of the molten solder. This assured that, during solidification, heat transfer occurred only through the chill, and not through the sidewalls.

The assembly was placed upon a stand similar to that used in a Jominey End Quench, and the solder quietly poured into it. Duration of solidification was measured from the time that the water flow was initiated. Glass capillary tubes were used to locate the solid-liquid interface as time progressed. These tubes were used because of their small diameters. They did not interfere with the structure of the solidifying material or act as heat sinks.

Two pouring temperatures of 30 and 55 K (54 and 99 F) superheat were chosen to monitor the effects of temperature on the rate of solidification. A distance solidified vs. time curve was established for each pour.

Simulations

Data files were created for each of the solder alloys, including alloy compositions, thermal properties of both the chill and the solder, pouring temperature and interfacial heat transfer coefficient, h. Simulations were run corresponding to each of the experimental pours, and the h value adjusted until the output matched the data obtained experimentally.

The experimental and simulated data for 60% tin-40% lead solder poured at 30 K (54 F) superheat against a polished brass plate are shown in Fig. 8. The simulation run with an h value set at 0.1 cal/cm sec °K provided the best agreement with the experimental results. In Fig. 9, the data for 60% tin-40% lead solder poured at 55 K (99 F) superheat, again against polished brass, indicate that an h value of 0.15 cal/cm sec °K gives the best correlation. In examining the column of solder cast against the brass plate, it was found that partial wetting occurred. However, the "joint" was quite weak and easily pulled apart.

When flux was applied to the surface of the brass chill, and experimental and simulated runs made, the h value was determined to be 15 cal/cm sec °K for a pour of 60/40 solder at 30 K (54 F) superheat.

Figure 8 shows the data. The magni-

0 K = −273 C (−459 F) where K represents degrees Kelvin.

Table 1—Values of Thermal Constants Utilized in Simulations

Material	Latent heat, cal/cm	Specific heat, cal/gm °K	Thermal conductivity, cal/cm sec °K	Density, g/cc
Lead				
liq.	5.84	0.0374−0.000003T	0.37+0.000045(T−600)	11.38
sol.		0.0271+0.00001T	0.0848−0.00003(T−273)	
Tin				
liq.	14.25	0.0698−0.000018T	0.0725+0.000049(T505)	5.90
sol.		0.0372+0.000053T	0.163+0.000091(T−273)	
70-30 brass				
sol.		0.092	0.306	8.54

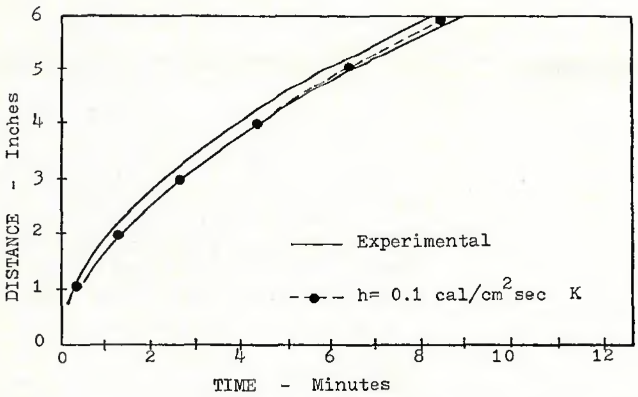

Fig. 1—Distance solidified vs. time for lead poured at 603 K (i.e., 330 C, 626 F)

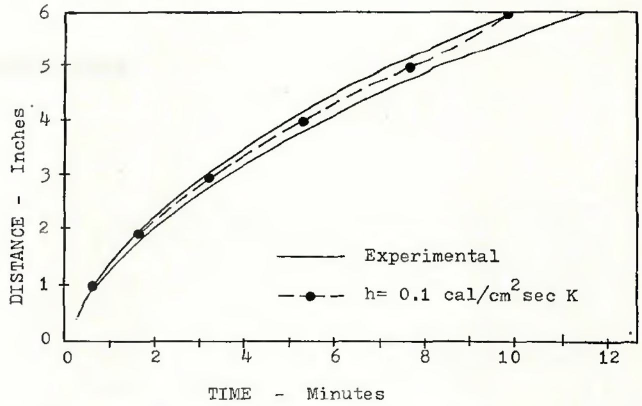

Fig. 2—Distance solidified vs. time for lead poured at 623 K (i.e., 350 C, 662 F)

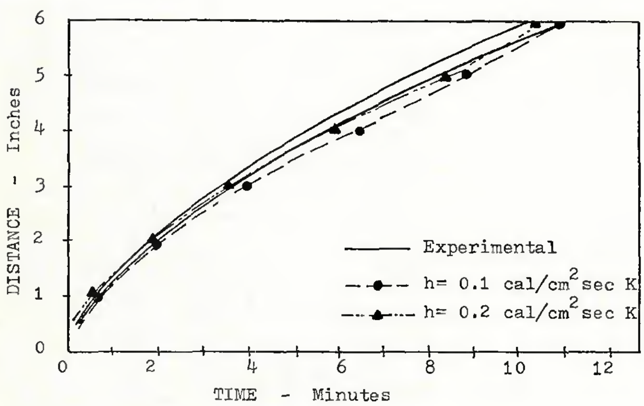

Fig. 3—Distance solidified vs. time for lead poured at 648 K (i.e., 375 C, 707 F)

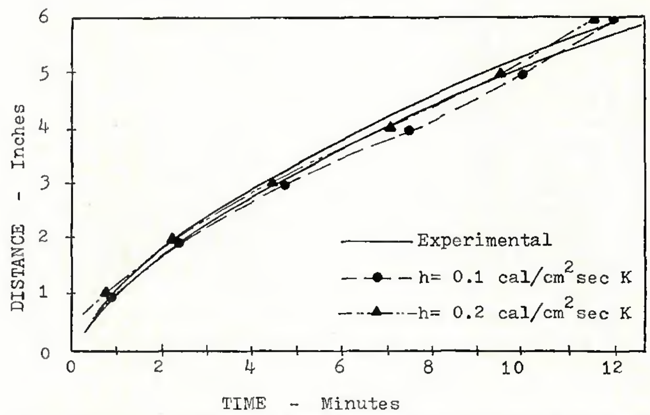

Fig. 4—Distance solidified vs. time for lead poured at 673 K (i.e., 400 C, 752 F)

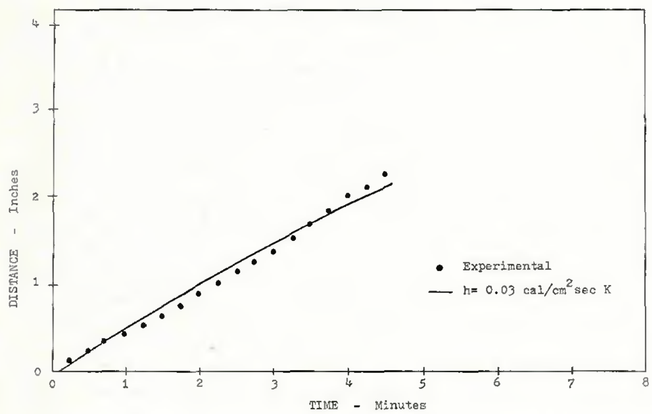

Fig. 5—Distance solidified vs. time for tin poured at 533 K (i.e., 260 C, 500 F)

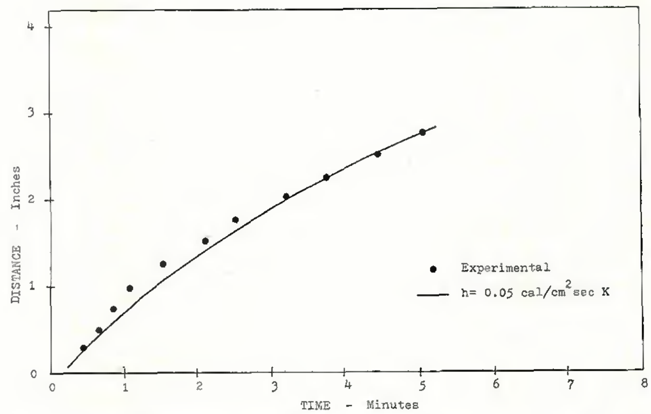

Fig. 6—Distance solidified vs. time for tin poured at 560 K (i.e., 287 C, 549 F)

tude of the air gap thermal conductions is 100 times greater for the fluxed surface than for the polished surface, indicating the greater thermal contact of the solder against the brass when flux is used. In fact, the column of solder was firmly joined to the brass plate and could not be removed. The resulting joint was typical of good wetting.

When the surface of the brass plate was coated with lampblack before pouring, the thermal contact was greatly reduced. In comparing experimental and simulated data for a run at 30 K (54 K) superheat, the best h value was found to be 0.01. The column of solder did not adhere to the brass whatsoever, indicating no wetting of the surface.

The results of the 40% tin-60% lead commercial solder follow much the same pattern as the 60/40 alloy. The test with the fluxed surface shows a much higher wettability and the respective simulation indicates a high h value. Again, the interfacial thermal conductance is increased by a factor of 100 when the polished brass surface has a flux applied.

Figure 11 shows an interesting phenomenon. Here, both experimental data and simulation results are shown for the unidirectional solidification of 60% tin-40% lead and 40% tin-60% lead, both poured at 55 K (100 F)

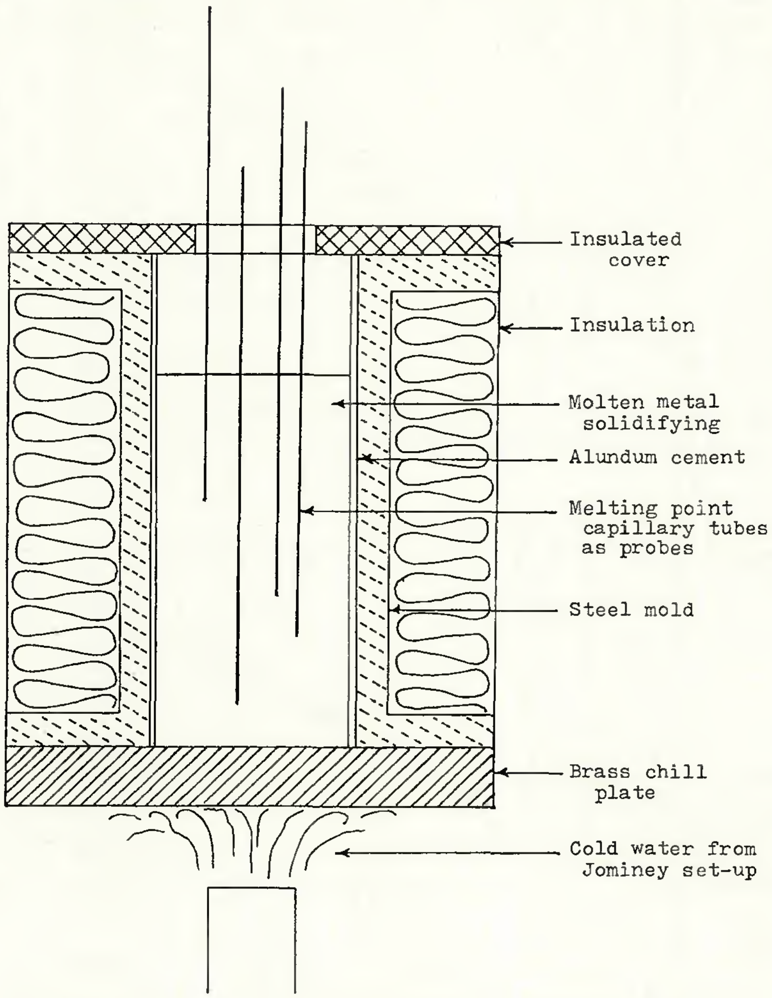

Fig. 7—Experimental setup for the unidirectional solidification of a metal or alloy

superheat. The best simulated runs in each case indicate appropriate h values of 0.15 cal/cm sec °K. However, the rate of solidification is faster for the 60% tin-40% lead alloy. This may be explained by considering the thermophysical properties of these materials. The thermal diffusivity of pure lead is approximately one-third that of pure tin; thus, the thermal diffusivity of an alloy high in tin will be greater than that of the alloy lower in tin. This difference in the values of thermal diffusivity, when incorporated in the heat transfer equations involved, affect the solutions of these equations, that is, the solidification time of these alloys.

If the h value for these two runs had changed significantly, then the question of the relative wettability and reflectivity values of lead and tin would assume some importance. However, since h = 0.15 cal/cm sec °K satisfied both sets of data, obviously the effects at the interface are of lesser importance than the composition of the alloy itself, all other parameters remaining constant.

Conclusion

The simulation of the unidirectional solidification of lead-tin solder, including the interface phenomena which occurs between the solder and the base metal, has been accomplished.

The composition of the solder has been incorporated as a variable within the computer program allowing the simulation of the solidification of the entire range of lead-tin solders.

The value of the air gap thermal conductance at the solder/base metal interface, as determined from the correlation of experimental and simulated data, is shown to be strongly affected by the condition of the base metal surface prior to solidification, by the composition of the solder, and by the temperature of the liquid solder before solidification.

The condition of the surface had the greatest affect upon the thermal conductance value, with the determined h value at the solder/fluxed surface interface being one hundred times greater than that at the solder/bare surface interface, and approximately one thousand times greater than that at the solder/graphite coated surface.

The strength of the joint and the thermal conductance are both related to the preparation of the surface. Total wetting and high h value occurred with the fluxed surface, partial wetting and lower h value occurred on the bare surface, and no wetting and very

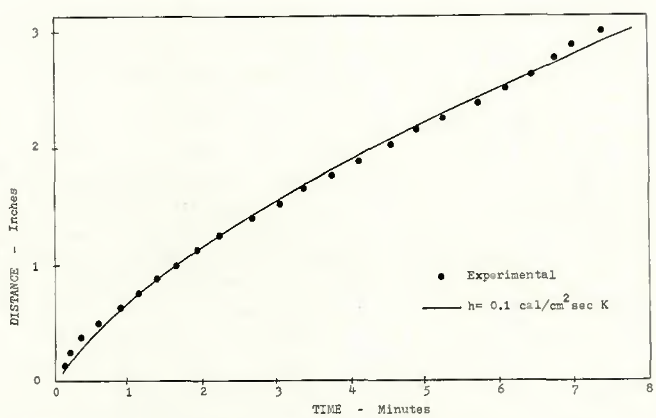

Fig. 8—Distance solidified vs. time for solder (60% tin-40% lead) poured at 30 K superheat, polished surface, no flux

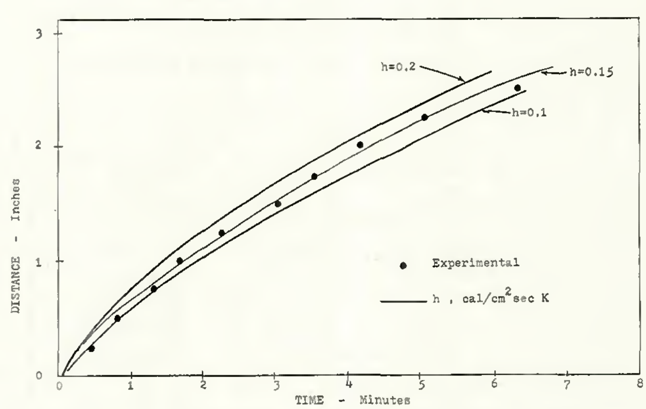

Fig. 9—Distance solidified vs. time for solder (60% tin-40% lead) poured at 55 K superheat, polished surface, no flux

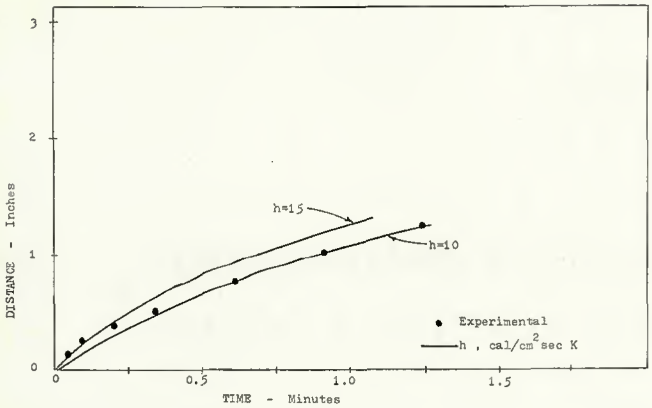

Fig. 10—Distance solidified vs. time for solder (60% tin-40% lead) poured at 33 K superheat, with flux

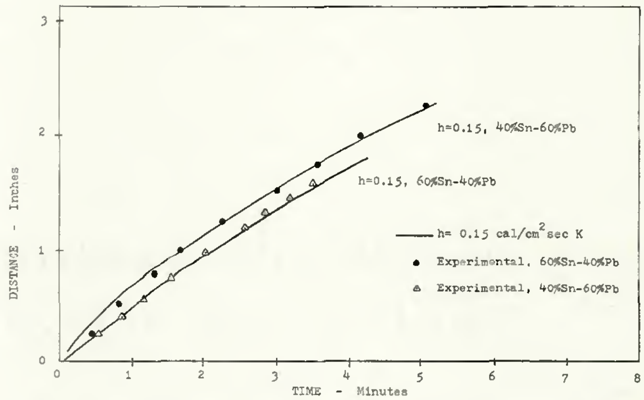

Fig. 11—Comparison of two lead tin solders: distance solidified vs. time at 55 K superheat with no flux

low h value occurred at the graphite coated surface.

The simulation of the solidification of solder against base metal can be an effective tool in determining good solder processing. The resulting h value serves as an indicator of the quality of the joint.

Acknowledgments

The author is most appreciative of the grant provided by the Welding Research Council in support of this investigation.

Particular thanks must be extended to Dr. John T. Berry for his guidance during the initial stages of this program, and also to Dr. Branimir von Turkovich, who then graciously assumed the responsibility of overseeing the project.

The author also gratefully acknowledges the use of the facilities of the Mechanical Engineering Department at the University of Vermont.

References

1. Henzel, J., and Keverian, J., *J. of Metals*, May 1965.
2. Pehlke, R.D., *et al.*, *AFS Cast Metals Research J.*, Dec. 1972.
3. Weatherwax, R.B., and Rieggers, O., SAE Paper #710600, June 1971.
4. Kaiser, W., Sander S., and Frost, P., Int. Die Casting Congress, Paper 5472, Oct. 1972.
5. Rosenthal, D., "Temperature Distribution and Shrinkage Stresses in Arc Welding," *Welding Journal*, 19 (9), Sept. 1940, Research Suppl., pp. 323-s to 331-s.
6. Brown, B., and Adams, C.M., *Trans. AFS*, Vol. 69, 1961.
7. Savage, W.F., Lundin, C.D., and Aronson, A.H., "Weld Metal Solification Mechanics," *Welding Journal*, 44 (4), April 1965, Research Suppl., pp. 175-s to 181-s.
8. Thomas, G.G., *Production Technology*, Oxford Univ. Press, 1970, p. 148.
9. Shipley, J.F., "Influence of Flux, Substrate and Solder Composition on Solder Wetting," *Welding Journal*, 54 (10), Oct. 1975, Research Suppl., pp. 357-s to 362-s.
10. Prates, M., Fissolo, J., and Biloni. H., *Met. Trans.*, Vol. 3, June 1972, pp. 1419-1425.
11. Durham, D.R., and Berry, J.T., *Trans. AFS.*, 1974, pp. 101-110.

WRC Bulletin 246
February 1979

Interpretive Report on Dynamic Analysis of Pressure Components

This interpretive report has been prepared by the Pressure Vessel Research Committee, Subcommittee on Dynamic Analysis of Pressure Components.

The intent in writing this report was to summarize, in one document, a brief background description of areas of concern to the Subcommittee as well as information currently available to industry and to assist in determining the course of research this Subcommittee will undertake in the future.

The Subcommittee in developing this report has associated the current topics with the Subcommittee Task Group assignments. Each topic has been written so that it can be read in its entirety without having cross references to other topics. This was done for clarity and to develop a procedure for inclusion of future work of the Pressure Vessel Research Committee, Subcommittee on Dynamic Analysis of Pressure Components.

Publication of this bulletin was sponsored by the Pressure Vessel Research Committee of the Welding Research Council.

The price of WRC Bulletin 246 is $10.00 per copy. Orders should be sent with payment to the Welding Research Council, 345 East 47th St., New York, NY 10017.