Walther N. KOHL
Consultant, Materials, Techniques and Devices
Belmont Massachusetts, USA

Joining techniques: soldering and brazing *

1. INTRODUCTION

Joining materials of all kinds is a fundamental pursuit of modern technology, just as it has been trhoughout the history of civilization. The production of various artifacts often calls for the joining of different materials, although the joining of two components of the same material may present a challenging problem at times. One is thus confronted with a wide range of joining techniques that have been developed for different applications; these include mechanical joints achieved by reveting and roll-peening, adhesive joints, widley used in the aerospace industry, diffusion joints, welding, and soldering and brazing. As the title of this lecture indicates, the latter two techniques are the main concern of this presentation, but since Brazing falls In the general category of Welding, a few words should be said about this important group of joining techniques.

Welding Processes: In its most general application, the term "Welding" covers the joining of metals by any procedure that results in a metallurgically sound joint. On the other hand, the American Welding Society (AWS) defines Welding as "a metal-joining process wherein coalescence is produced by heating to a suitable temperature with or without the application of pressure, and with or without the use of filler metal". Cold-Welding, a process widely used in the vacuum-tube industry for pinching-off metal exhaust tubulations without the application of heat, is thus a contradiction. Similarly, Resistance-Welding, Ultrasonic Welding, and Friction-Welding do not require en external heat source, although high temperatures are being produced at the interface by the nature of_these processes.

The "Chart of Welding Processes" published by AWS makes some allowance for these discrepancies by listing as major categories

Gas Welding
Arc Welding
Resistance Welding
Brazing
Solid State Welding
Other Processes

*Presented at the International Summer School on subject electronics materials (Herceg-Novi 1975)

The first two entries, Gas Welding and Arc Welding, are the processes that we generally associate with the activities of a welder who produces a fusion joint between alinged parent metals by heating them to the molten state with the aid of an external heat source whereupon a solid ioint results on coolina.

Gas Welding is usually a manual operation, although in can be automated. The operator uses the familiar welding torch to which a mixture of gases is fed that burns at the tip and produces the heat required to melt the metal. A filler metal rod is usually melted into the joit. Most ferrous and nonferrous metals can be gas welded, but the oxy-fuel gas mixture must be carefully chosen to produce the desired flame temperature, heat transfer intensity, and composition of the flame atmosphere. Oxy-acetylene welding is being widely used for repair and maintenance work and for flame cutting; the flame temperature exceeds 3000°C (6000°F).

Arc Welding: Fourteen conventional arc welding processes are currently in use; they differ principally in the way harmful gases are excluded from the weld area. Depending on the material to be welded and the desired weld charactericties, the following main categories exist.

Shielded-Metal-Arc Welding is a manual process in which the heat for welding is generated by an arc established between a flux-covered consumable electrode and the work. The electrode tip, weld puddle, arc, and adjacent areas of the work piece are protected from atmospheric contamination by a gaseous shield obtained from combustion and decomposition of the flux covering. Additional shielding is provided for the molten metal in the weld puddle by a covering of molten flux (slag). Filler metal is supplied by the core of the consumable electrode, and, with certain electrodes, from metal powder mixed with the electrode covering. Metals most easily welded are carbon- and low-alloy steels, stainless steels, and heat-resisting alloys. The end of the electrode must be close enough to the work to insure that molten metal from the electrode will be transferred directly and accurately into the weld puddle. In general, arc length should not exceed the diameter of the electrode core wire.

Flux-cored Arc Welding utilizes a tubular consumabie electrode within which the flux is contained. The electrode may therefore be supplied in the from of flexible, continuous wire that can be coiled in distinction to the "stick electrodes" used in shielded metal arc welding.

Submerged-Arc Welding is a fast welding operation restricted to the joining of fairly heavy stock, more than 3/16 in. thick, while the faying surfaces are maintained in a horizontal position. A layer of granular and fusible flux is deposited along the gap that may be contoured to retain it, and one or more bare metal consumable electrodes plow through this granular track and establish an arc (or arcs) between their tips and the base metal. The layer of fusible flux blankets the molten weld metal and the base metal near the joint and thus prevents atmospheric contamination. The process is most frequently applied to the joining of ferrous metals, but difficulties arise with high-alloy steels, and cast iron is excluded.

· Gas Metal-Arc Welding (GMA) or Metal Inert Gas Welding (MIG): The heat for welding is generated by an arc between a consumable electrode and the work metal. The electrode, a bare solid wire that is continuously fed to the weld area, becomes the filler metal as it is consumed. The electrode, weld puddle, arc, and adjacent areas of the base metal are protected from atmospheric contamination by a gaseous shield provded by a stream of gas, or a mixture of gases, fed through the electrode holder. Argon (Argon-arc welding) or helium (Heli-arc welding) were originally used for shielding almost exclusively, but carbon dioxide has now also been widely accepted as a shielding gas. Oxygen and carbon dioxide are often mixed with the inert gases to stabilize the arc and improve the metal transfer characteristics, but deoxidizers are then added to the electrode. Argon is preferable to helium for the welding of thin sections, whereas helium is preferred for thick sections.

Gas Tungsten-Arc Welding (GTA Welding) or Tungsten Inert Gas (TIG Welding) utilizes a nonconsumable tungsten electrode. As in MIG welding, an arc is struck between the electrode and the work, and shielding is provided by a stream of gas. A weld can be made by fusion of the base metal without the addition of filler metal, or a filler metal may be fed into the joint is required. Direct-Current, straight polarity is most widely used for TIG welding which implies that the tungsten electrode is connected to the negative pole of the power supply. In the case of reverse-polarity welding, the work piece is connected to the negative pole. Reverse polarity D.C. produces a flat, wide bead with shallow penetration.

Percussion Welding is a versatile welding process that permits the joining of similar of dissimilar metals of widely varying cross-sections by means of a capacitor discharge across an air gap. A shallow layer of metal on the contact surfaces of the work pieces is melted by heat of the arc produced between them; one of them is impacted against the other, extinquishing the arc, expelling molten metal, and completing the weld. The ends of wires can be butt-welded to each other in this manner, one wire having as small a dia. as 0.005in. Large-area joints to composite contact surfaces are also possible. The welding currents are extermely large but of very short duration.

There exists a large body of literature on all aspects of welding. Volume 6 of the Metals Handbook of the American Society for Metals [Ref.3], the Welding Handbook of the American Welding Society [Ref.5], Process Specifications published by the American Society For Testing and Materials (ASTM), numerous publications by NASA [Ref.6] are some of the sources that should be consulted for further details.

The application of welding to the construction of vacuum devices have been discussed by Sullivan et al. [Ref.7] and by Verfuss [Ref.8]. Espe [Ref.9] deals with these questions in Vol.1 of his series on "Materials of High Vacuum Technology", and Kohl's Handbook [Ref.10] contains two lengthy chapters on Soldering and Brazing. Manko [Ref.11] has published a book on "Solders and Soldering".

2. SOLDERING

It is not so long ago that "Soldering" was looked upon with some disdain as "the Plumber's Art" that was practiced by the Romans when they made water pipes from lead sheet and joined them by soldering with lead, Later they added tin to the lead and created the socalled "Wiping Solder" that is being used for this purpose today.

Incidentally, lead/tin solders were known to the Egyptians more than 3000 years ago, although no tin ores were available in the Mediterranean basin; they were brought to Egypt along mysterious trade routes from as far as Conwall in the West and The Caspian Sea in the East. No wonder that pure tin was looked upon as a precious metal and used for coins at one time.

The skill of the craftsman that relies on techniques accumulated over centuries and was passed on from one generation to the next has served well in the creation of works of art, but it has lost its dominant role in modern soldering technology. Scientific disciplines aiming at an uderstanding of the principles that underlie the formation of a reliable joint now provide important guide-lines in practical operations.

The materials engineer must now command knowledge in a number of fields that bear on this subject. Among these are not only Physics. Chemistry, and Metallurgy, but also Surface Physics, Stress Analysis, Electrochemisty, and Vacuum Technology. The "Plumber's Art" hast thus developed into a sophisticated pursuit of solutions to problems whose existence was not apparent in earlier times. The reasons for this growing complexity have their roots in the following developments.

The demands for quantity production of soldered assemblies have necessitated a high degree of m e c h a n i z a t i o n and a much closer control of individual operations. Where a torch was formerly manipulated by hand and the gas mixture adjusted by the operator, a whole battery of torches may now be mounted on the periphery of a rotating platform on which the workpieces are placed and the gases are fed to each torch position and their proper mixture is controlled by flow meters. Similarly the flux and solder may automatically be fed to the joint from dispensers. Even the soldering iron, where it is still being used, has its built-in heat sensor and a time controller, both of which can be adjusted to meet the existing requirements. Solder may applied to the joint by electroplating or by using preforms that can also be automatically dispensed in some cases.

3. INDUSTRIAL APPLICATIONS

Sheet Metal Work
Cable Joints
Piping Installations
Automotive Body Repair
Automotive Radiators
Refrigeration Systems
Air Conditioning Systems
Food Preservation (Tin Cans)
Electrical Wiring
Printed Circuit Boards
Electrical Instruments

This partial list of industrial activities where Soldering is practiced on a large scale indicates the commercial importance of this joining process. Many of these applications call for special solder compositions and a careful selectio of fluxes. In electronic applications, strict limits must be imposed on the impurity and gas content of solders, as these would adversely affect performac While Standard Agencies in various countries have established limits on chemical composition, gas content is rarely mentioned. "Vacuum-cast solders" are available from a number of suppliers, but users have found them to have widely varying quality. In view of their relatively high vapor pressures, solders are generally not permitted "to see" a vacuum environment, especially in a sealed-off device.

Wave Soldering is being widely used in the production of Printed Circuit Boards (PCB) and has reached a high degree of automation. This technique essentially is a modified version of Dip Soldering where the board with its many exposed "lands" or "pads" is horizontally fed through the crest of a solder wave that is produced by an elongated orifice mounted just below the surface of liquid solder in a suitable container. The solder is continually circulated by a pump so that the wave always contains fresh, uncontaminated solder. Cleaning, Preheating, and Fluxing positions often precede the immersion of the board in the solder wave in a linear array and are followed by Post-Heating and Post-Cleaning stations, so that a wave-soldering machine may extend over a legth of 20 feet or more, depending on the number of operations that are incorporated. Different widths of boards can be accomodated by adjustable rails.

Printed Circuit Boards were developed in Great Britain during W,W., II and their technology rapidly advanced in USA. At that time, boards were acually printed on insulating substrates by applying conductive inks through suitable stencils. The term PCB has now taken on a generic meaning and covers the technique of removing unwanted copper from a copper-clad insulating board (subtractive method) by electrolytic etching or adding the circuit pattern to a bare insulating board (additive technique). Great advances have been made in the past decades. The line width and spacing currently achieved in the industry range from 15 to 20 mils (0.38-0.51 mm) and the size of the boards from 100 to over 1000 cm^2. High reliablility and amenability to mass production have made PCB's the backbone of electronics in computers, space vehicles, missiles, and increasingly also in the entertainment industry, such as radio and television.

The highly sophisticated technology that is required for the production of PCB's has been discussed in numerous publications and at international conferences. It would go beyond the frame of this presentation to enter into any details beyond emphasizing the extreme importance of the utmost cleanliness in all operations Ref.12, 13 and the need for strict process control.

Solderability Tests: The balance of forces that prevails between liquid solder and substrate is determined by the respective surface energies and the resulting contact angle which should not be much greater than 60 degrees for good wetting and spreading. Invisible tarnish of the surfaces and adsorption of impurities contained in the solder will have a harmful effect and cause poor wetting or dewetting unless a sufficiently active flux removes such contamination. In electronic assembiies, however, only mild, rosintype fluxes are permitted. It is therefore important to be able to measure the compatibility of the involved components and thus to evaluate, preferably in a quantitative manner, the effects of process variables, storage times, and choice of materials.

A number of solderability tests have been evolved over the years and one or the other are prescribed in military and civilian specifications. Among these are the "Twisted Wire Test", the "Spread Test", the "Globule Test", and the "Edge Dip Test".

The earliest of these tests is based on the Wilhelmy film balance for surface tension measurements and was applied to kinetic measurements in the Kollagraph in 1945 by Earle. In recent years, the instrumentation for this method has been greatly refined in independendent developments by Companics in Europe (Philips, Marconi, G.E.C., Ericsson) and USA (NL Industries). The G.E.C. version in being marketed in USA by Hollis Engineering Inc. in Nashua, N.H. under the tradename "Meniscograph". To quote from their literature..." it has been used to show differences between component leads at various stages of semiconductor device manufacture, to evaluate cleaning procedures for improving the solderability of nickel/iron leads on reed relays and to illustrate the difference between fluxes used on nickel/silver realy springs".

Completed joints can be evaluated by a number of destructive and non-destructive tests, such as Pull Tests, Peel Tests, X-Rays, Ultrasonic Scans, I.R. Spectroscopy, Optical and Acoustic Holography, and Acoustic Emission. All too frequently, however, the inspection of soldered joints relies on visual examination, and detailed guidelines have been established for the number and type of fault permissible on PCB's.

Design Considerations: Apart from the compatibility of the joint components and the effect of environmental conditions, it is important to remember that solders generally have low mechanical strength and low thermal and electrical conductivity. Ultimate Tensile Strength (U.T.S.) at room Temperature (R.T.) ranges from 5 - 10 ksi (0.7 - 1.4 kp/mm^2) for commonly used solders, and electrical conductivities are about 10% IACS (International Annealed Copper Standard). Soldered joints must therefore be mechanically anchored when exposed to stresses in service, and electrical by-paths must be provided to avoid overheating by excessivly high currents. Brazing alloys also have a wide range of resistivities, but the interface between abutting surfaces is usually much thinner than it is for solders, of it may disappear altogether in diffusion seals. In metallized and brazed ceramics, losses in the brazed interface at high frequencies can be a cause of failure in waveguide windows and similar structures.

Table 1

INTEGRATIVE PLANNING FOR SOLDERING AND BRAZING

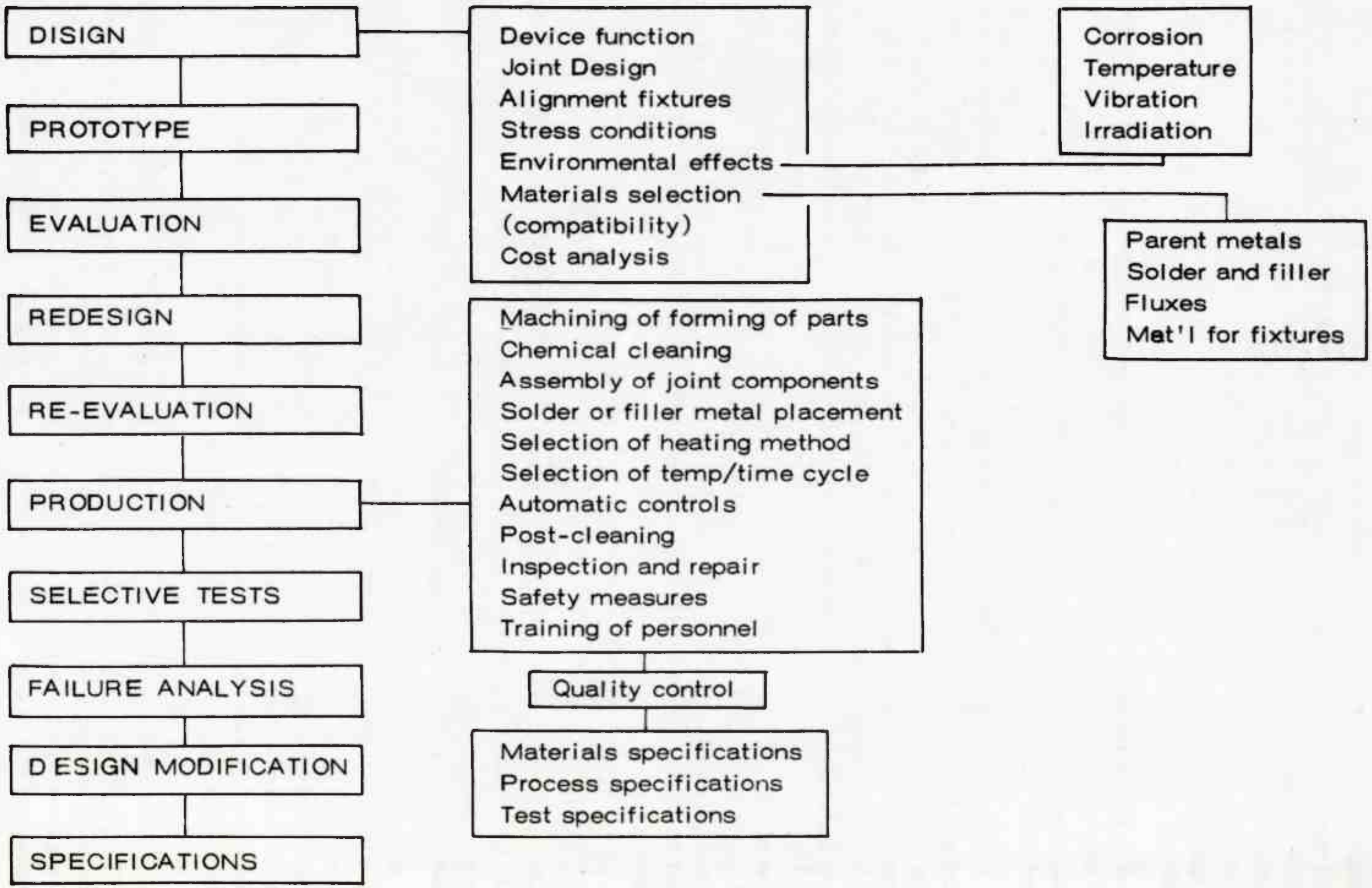

Table 2

TYPICAL SOLDER COMPOSITIONS AND APPLICAT'S

Sn/Pb/other (%)			Solldus/ /Liquidus (°F)		Solidus/Liguldus (°C)		Applications
95	0	5 Sb	452	464	234	240	Food Equipment
95	0	5 Ag	430	473	221	245	Electr.Instr. (High Temp,)
80	0	20 Zn	390	518	199	271	Aluminium Joints
70	30	-	361	378	183	192	Metal Coating
60	40	-	361	370	183	188	Electronics and Instrum'ts
50	50	-	361	414	183	212	Sheet Metal and GI Purpose
40	60	-	361	460	183	238	Wiping Solder and GI Engg.
30	70	-	361	496	183	257	Automobile Radiators
20	80	-	361	536	183	290	Automobile Body Work
10	90	-	435	576	224	302	Cryogenic Applications
5	93.5	1.5Ag	565	574	296	301	" "
1	97.5	1.5Ag	588	588	309	309	" "
2	98	-					Tinplate Can Side Seams

Brazing is distinguished from soldering by its being conducted at a higher temperature, usually above 400°C, so that the joint can correspondingly be exposed to higher temperatures in operation. As long as a suitable filler metal is chosen, even refractory metals with very high melting points can be joined by brazing. In all cases, both for soldring and brazing, the formation of brittle intermetallic compounds at the interface of the parent metals must be avoided, since their presence would seriously interfere with the mechanical strength of the joint. However, this remark cannot entirely be taken at its face value, since a small amount of interface may be necessary for effective bonding; it is the excessive build-up of interfacial compound layers at the interface that is objectionable.

Apart from compound formation at the interface. it has also been found that carbon films may form the surface of the parent metal by diffusion of excessive carbon content which then seriously interferes with the wettability of the surface by filler metals. Such a case has recently been described by Larson and Korbitz [Ref.14], following an observation by Hauber [Ref.15].

A gray tarnish film developed on a sample A of Monel 400* (64% Ni, 33% Cu, 2% Fe, 1% Mn) on exposure to a temperature of 800-900°C in a vacuum furnace (10^{-5} Torr) but not on a different sample B. Auger electron spectra established the tarnish film to consist of carbon, and bulk chemical analysis showed that the carbon concentration in sample A was 0.153 wt% and that of sample B 0.109 wt%. As Hauber has pointed out, the carbon content of sample A was high enough to produce a supersaturated state at the brazing temperature with the result that the carbon diffused to the surface. Sample B, on the other hand, was not saturated with carbon and therefore did not produce a carbon film. The conclusion reached is that Monel has good wetting characteristics for carbon concentrations of less than 0.109 wt% C.

Of the various types of Monel currently in use, Monel 400, Monel 401, and Monel 404 have specified maximum carbon contents of 0.30, 0.10, and 0.15% respectively. It would thus appear that only Tupe 401 satisfies the above-stated requirement, although both Type 401 and Type 404 are being used in electronic applications. Type 404 Monel was developed some 15 years ago to replace Type 403; it has a much lower content of Manganese (0.10% max.) and can therefore be brazed in wet hydrogen at a higher Dew Point (+24°C). Trace amounts of aluminum, silver, and titanium that cause oxide formation in poorly controlled hydrogen atmospheres are also kept at a very low level in Type 404 Monel.

On a somewhat different scale, brazing of aluminum to stainless steel has often presented serious difficulties, partly because the filler metals do not wet the tightly adhering oxide film on aluminum, and partly on account of the formation of a brittle intermetallic compound between aluminum and iron. The oxide film can be broken up by ultrasonic agitation of the filler metal that

* Trademark, The International Nickel Company

then gains access to the bare substrate. The formation of the objectionable intermetallic can be circumvented by the application onto the S.S. of a barrier layer of titanium by vapor deposition in a vacuum over which a second layer of Al-Zr-Si is then deposited by vaporization. Reliable joints are then obtainec by conventional salt bath immersion.

Metallurgically sound and vacuum tight joints between S.S. and Al tubing, or other metals, have been produced by forcing an oversized mandrel through the inner tube, thereby expanding it against the inner wall of a coaxial outer tube and causing the metal to yield at room temperature. Explosive bonding techniques have also been employed for this purpose.

Burgess, Bryant, Neugebauer, and Babcock of the General Electric Company in Schenectady [Ref.1] have described an interesting technique for the joining of metals, or of metals and dielectrics, that circumvents the placement of filler metals between the components of the joint. By heating the assembly in a reactive gas atmosphere, a gas-metal eutectic is formed that wets the surfaces to be joined and establishes a strong bond on cooling. Copper, nickel, iron, cobalt, chromium, silver, aluminum, and their alloys, as well as stainless steel (S.S.) have been joined in this manner. As the bond exhibits low ohmic resistance, the technique lends itself to the fabrication of integrated circuits.

In many important applications, much higher temperatures than those mentioned in the preceding paragraphs are encountered. Energy conversion devices, nuclear reactors, and aerospace structures are examples. This field of "High-Temperature Brazing" has been very well covered in a fairly recent monograph by Pattee [Ref.2] and in a NASA "Technical Memorandum by Morris [Ref.16], who describes and tabulates eutectics and melting point minima for binary combinations of metals having vapor pressures below 10^{-10} Torr at 1500 K and 10^{-5} Torr at 2000 K.

Finally, it may be appropriate at he end of this summary to make a few remarks on the Management of Soldering and Brazing. Any enterprise that aims at the production of soldered of brazed assemblies, be they bicycle frames, car radiators, or aerospace structures, should be aware of the complexity of the task. An attached Flow Chart shows the iterative nature of the design process in the left-hand column and the details entering into the design and production operations in the main body of the chart. Many disciplines are involved and should therefore be represented on the staff. At least a Materials Engineer should be competent in the areas of Physics,

Table 2A

RANGES OF ROOM-TEMPERATURE TENSILE STRENGTH (U.T.S.) FOR VARIOUS MATERIAL - EXPRESSED IN UNITES OF 1,000 P.S.I.

Freshly drawn glass fiber (0.0001 in.dia.)	10,000
Boron fibers	350 - 1,000
Glass fiber Type S (65% R.H.)*	500 - 650

* R.H. - Relative Humidity

Glass fiber Type E (65% R.H.)	300 - 500
Tungsten fiber (0.0008 in. dia.)	582
Boron fiber (0.0045 in. dia.)	400
Alloy steels (H and T)**	98 - 345
Ultra high strength steels (H and T)	275 - 319
Graphite fibers (65% R,H.)	103 - 285
Carbon steels(H and T)	75 - 237
Sintered tungsten bar (1 mm dia.)	200
Sintered tungsten bar (5 mm dia.)	57
Nickel rod, as drawn	65 - 110
Copper, ETP - 85% Red.	55
Aluminium and its alloys (Sol.Tr. and Aged)	36 - 49
Pure iron, annealed	42
Copper, annealed	32 - 35
Gold wire, cold worked	32
Gold wire, annealed	18
Graphite	0.4 - 2

Tin, Lead, and their Alloys

Cast tin-lead antimony alloys	6.8 - 11.8
Cast tin and its alloys	2.8 - 8.7
Cast lead and its alloys	2.0 - 7.4
Extruded lead and its alloys	2.0 - 3.3

Chemistry, Metallurgy, Thermodynamics, and Electronics, and in Industrial Engineer should concern himself with Process Control, Electrical Engineering, Vacuum Technology, Specifications, Personnel Training, and Safety. In larger organizations, separate departments will take over these diverse functions. In that case, it is important to maintain communication between them, so that the left hand knows what the right hand is doing.

Data extracted from 1974 Materials Selector, Reinhold Publishing Corp., and supplemented from the author's "Handbook of Materials and Techniques for Vacuum Devices", Reinhold 1967.

Whiskers of alumina have tensile strengths in the range of 2000 - 3000 ksi Whether they have correspondingly high fatigue strengths is not known.

Table 2B

ROOM-TEMPERATURE TENSILE STRESS (U.T.S.) FOR COMMON SOLDERS (After P. A. Ainsworth, Tin Research Institute, (1971) expressed in units of 1.000 P.S.I)

General Engineering Solders:

Sn Pb 40	7.7
Sn Pb 50	6.5

** H and T - Strain hardened and Heat treated

Pb Sn 40	6.25
Pb Sn 30	6.25
Pb Sn 20	6.1
Pb Sn 50, Sb 2.8	8.1
Pb Sn 40, Sb 2.2	7.4
Pb Sn 30, Sb 1.7	6.95

Special Purpose Solders:

Pb Sn 2	4.05
Pb Sn 10	5.35
Pb Sn 1, Ag 1.5	4.05
Pb Sn 5, Ag 1.5	5.65
Pb Sn 40, Ag 1.5	10.1
Sn	2.03
Sn Ag 2	3.8
Sn Ag 5	8.5
Sn Sb 5	5.8
Sn Pb 30, Cd 18	6.2
Sn Zn 20	10.1

References

1. Burgess J., Neugebauer C.A.: Direct Bonding of Metais with a Metal-Gas Eutectic. U.S. Pat. 3, 744 July 10, 1973; see aiso
Guy L., Babcock et ai.: Method of Direct Bonding Metals to Non-Metallic Substrates. U.S. Pat. 3, Oct. 23, 1973, 766, 634

2. Pattee H.E.: High-Temperature Brazing. Buii. 187, 1973. Welding Research Council (345 East 47 th St., New York. N.Y. 10017)

3. American Society for Metals. Metals Handbook, 6, Welding and Brazing, 1971 (Metals Park, Ohio 44073)

4. American Welding Society, Brazing Manual 1975 (2501 N.W. 7 th St., Miami, Florida 33125)

5. American Welding Society, Welding Handbook 6 th ed. 1970

6. NASA: Welding, Brazing and Soldering Handbook. Sept. 1969, TSP, 69-10264
Welding for Electronic Assemblies. Technology Utilization Division, SP-5011, 1964
Applications of Aerospace Technology in Industry: Welding. Prepared by Abt Associates, Inc. under Contract NASW-2022, Sept. 1971
Most of the Nasa publications are available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

7. Sullivan J.J. et al.: Design Parameters For Inert Gas Welding and Vacuum Brazing of Vacuum Components. U.S. Army Electronics Command Nov. 1965 (AD 627 466; available from CFSTI)

8. Verfuss K.: Schweissen in der Vakuumtechnik. Presentation before the Austrian Vacuum Society. Vienna, Sept. 1970

9. Espe W.: Materials of High Vacuum Technology. 1: Metals and Metalloids. Pergamon Press Ltd. 1966. In the original German version, published in 1959, the pertinent Sections on Welding appear on pp. 724-755

10. Kohl W.H.: Handbook of Materials and Techniques for Vacuum Devices. New York 1967 Reinhold Publishing Corporation (now Van Nostrand-Reinhol Company, New York, NY 10001)

11. Manko H.H.: Solders and Soldering. New York. McGraw-Hill Book Company, NY 1964

12. NASA: Contamination Control Handbook SP-5076, 1969: available from CSFTI, Springfield, Va. 22151
Clean Room Technology NASA SP-5074, 1969: available from Superintendent of Documents, Washington, D.C. 20402

13. ASTM: Symposium on Electron Device Components and Materials: ASTM Special Technical Publication No. 246, 1959
Materials and Device Processing. ASTM Special Technical Publication No 300, 1969: available from ASTM, American Society For Testing And Materials, 1916 Race St., Philadelphia, Pa. 19103

14. Larson D.T., Korbitz F.W.: Surface Characterization of Nickel-Copper Alloy Displaying Poor Wettability During Brazing. J.Vac. Sci. and Technol. 12, 3, May/June 1975

15. Hauber J.R.: Surface Discoloration of High Nickel Alloys. Metals Engineering Quarterly, May 1975

16. Morris J.F.: Some Possible Filler Alloys With Low Vapor Pressures For Refractory-Metal Brazing. NASA TMX-68190, Feb. 1973: Lewis Research Center, Cleveland, Ohio 44135: Available from Aerospace Research Applications Center (ARAC), (Indiana University Foundation, Bloomington, Indiana 47401)