WELDING AND BRAZING

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WELDING AND BRAZING SPACE AGE METALS

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Introduction

To achieve the performance desired in future aircraft, missiles and spacecraft, it will be necessary to use structural materials and alloys which have the highest possible strength to weight ratio at the temperatures of operation. These materials will include newly developed metals or alloys, such as, beryllium, titanium, high strength steels, nickel-base alloys and the refractory metals, columbium, molybdenum, tantalum and tungsten. The development of these alloys requires a corresponding development in joining methods which will provide joints with properties that match as closely as possible those of the parent metal. The efficient utilization of an alloy in a structure or component will often require that the joints be made by welding or brazing. The new alloys have presented more difficult problems in welding and brazing and have made it desirable also to investigate new and unconventional joining methods, such as, ultrasonic, electron beam and explosive welding. The use of sandwich construction, likewise, has created additional requirements for new brazing methods and materials. A continuing research and development effort is required to solve these problems and to establish the optimum welding and brazing procedures for the construction and repair of aerospace equipment.

A discussion of some of the major problems was presented at the Materials Symposium held in Dallas, Texas, 10 July 1958. Since that date new developments have been made and new problems have been encountered which make this discussion appropriate.

Applicable Processes

Before proceeding with the discussion of the problems involved in the joining of specific alloys, it is desirable to review briefly the welding and brazing processes which are used frequently in the aerospace industry, and to mention recent developments in joining that may have application in the aerospace industry.

Welding Processes

Manual gas welding and metal arc welding were the first fusion welding processes to be used by the aerospace industry. These processes are still in current use but they have been replaced to a great extent by the inert-gas metal-arc welding process. The latter process when compared with gas and metal-arc welding has an important advantage: there is no reaction between the inert gas and the weld metal. In gas or metal-arc welding, the gas or slag reacts with the molten pool of the active metals. This characteristic restricts the use of these processes to welding of the less reactive metals, iron, nickel, and aluminum. The inert-gas shield permits arc welding of all the metals and alloys, including the reactive metals titanium, columbium, molybdenum, tantalum and tungsten. Arc spot welding, a modification of the inert-gas metal-arc welding, is being used in many more applications. This process allows spot welds to be made when the joint is accessible from only one side. The inert-gas metal-arc process is readily adaptable to automatic welding in which all variables are closely controlled. Elaborate devices have been developed for controlling the important variables associated with the process.

Electron beam welding is one of the more recent processes of great interest. This process consists of accelerating electrons to a high velocity in a vacuum and allowing them to strike the joint where a weld is desired. The electron beam can be focused within a very small diameter spot which produces a weld with deep penetration and a very narrow fusion zone. The high vacuum required for the electron beam reduces contamination in the weld to a low level. The major disadvantage of this process in its present state of development is that the part to be welded must be completely enclosed in the vacuum chamber. Possible methods of overcoming this disadvantage are under investigation in programs supported by the Air Force. The electron beam process will be suitable for welding in space environments in the future. A high vacuum exists in outer space which eliminates the need for a chamber to enclose the electron gun and the parts to be welded.

The plasma-jet has been proposed as a new welding method, but some of the recent investigations indicate that this method is more suitable for metal spraying or surfacing on parts requiring a minimum of penetration into the parent metal.

Resistance spot and seam welding has been used successfully in the aerospace industry for joining all of the weldable alloys. The recent trend toward the use of refractory alloys will present a serious problem of avoiding tip pickup. Possible solutions to this problem include the use of projections to concentrate the current at the interface, while a flat tip is used at the outer surface to distribute the welding current over a larger area where the tip is in contact with the sheet. Other resistance welding processes of interest to industry include flash welding for making butt joints in sheet, bar stock, tubing and similar joints and the high frequency welding which is used in the manufacture of tubing.

There has been an interest in the more recent processes which probably involve solid state bonding. These processes include ultrasonic welding, friction welding, diffusion bonding, and explosive welding. Ultrasonic welding has been successful in joining aluminum to aluminum and also dissimilar metals such as aluminum to copper or aluminum to steel. Further development is required to make this process suitable for joining the high strength alloys or the refractory metals. Programs have been initiated with the objective of developing ultrasonic equipment with a greater power output which may extend the range of materials that can be welded. Friction welding appears suitable for making butt welds in tubing similar to those produced by flash welding. More data on friction welding is required to determine the advantage of this process. Diffusion bonding has been used in the manufacture of fuel elements and has promise as a method of joining difficult combinations of alloys when other joining methods are not adequate.

Explosive welding is a new process which was discovered accidently in explosive forming. A limited investigation completed recently indicates that small plates of similar and dissimilar alloys can be bonded with explosives. Sufficient data is unavailable on this process to determine useful applications. Possible applications may include bonding dissimilar combinations or welding at remote locations; explosive welding may be useful in the assembly of future space stations.

Brazing Processes

Many components in the aerospace industry are fabricated by various brazing processes. Brazing is used in the fabrication of liquid rocket engines, heat exchangers, jet engine components, hydraulic lines, fittings and similar parts. Brazing of these components require some development effort to obtain the optimum procedures, brazing filler metals, and atmospheres. The major effort however, in recent years has been aimed at developing techniques and brazing alloys which will be suitable for the fabrication of brazed

sandwich panels. The brazed honeycomb sandwich panel is an ideal structure but presents difficult problems in fabrication.

Sandwich Structures

Progress has been made toward the solution of problems encountered in the fabrication of brazed sandwich panels. This progress is the result of extensive research and development programs supported by the Air Force and the aerospace industry. A number of different brazing methods have been investigated in an effort to reduce the time required for brazing. The methods include the use of the conventional furnace, radiant furnace, electric blanket and the quartz lamp radiant heating. The Air Force has recently sponsored projects on the development of radiant furnace and quartz lamp radiant brazing methods. Additional work with the electric blanket method is included in the program on the development of the B-70 airplane. While all methods may have some application on future aircraft, the electric blanket method or modifications of this method appears to have the greatest utility. The major part of the PH 15-7 Mo steel panels for the B-70 airplane have been brazed with the electric blanket method. This method has a number of advantages over furnace brazing: (1) the time for brazing is shorter (2) the amount of handling can be reduced since the panel can be brazed and heat-treated in the same fixture (3) distortion during brazing and heat treatment can be controlled with less difficulty as the panel is held in the jig throughout the cycle. The quartz lamp radiant heating also has promise as a method of reducing the time required for brazing. This method has successfully produced panels of PH 15-7 Mo steel with flat, single curvature and complex curvature surfaces. Another form of radiant heating which uses a Globar furnace was successful in brazing honeycomb panels, 12" x 12" x 1/4", made of both Inconel 702 and Haynes No. 25 alloy.

Progress has been made in controlling the flow of the brazing alloys in PH 15-7 Mo steel sandwich panels. In all brazing methods, contamination of the surfaces is avoided by carefully cleaning the parts and then placing the assembly in an envelope which is filled with a high purity inert gas. A small amount of lithium, about 0.2 percent is added to the brazing alloy to improve wetting by removing residual surface oxides. The composition of the brazing alloy is adjusted so that its flow temperature will be compatible with the heat-treatment cycle. A silver base alloy containing 7 percent copper and 0.2 percent lithium is frequently used for the attachment of the cover sheet to the core. Modifications of this alloy include the addition of palladium and indium which lower the thermal conductivity of the alloy or the use of the alloy in a nickel sponge to reduce the drainage of filler metal to low places. The silver-copper-lithium alloy has produced brazed joints with satisfactory fillets and soundness for the attachment of the cover sheet to the core in PH 15-7 Mo steel panels. This alloy, however, has not been satisfactory for the edge attachments on the panel because of the formation of voids at the interfaces of the lap joint. The major cause of the voids is probably the high vapor pressure of the lithium addition. The voids have been reduced by using another silver alloy containing 32.5 percent copper and 5 percent nickel.

In recent years some of the effort on the development of brazed sandwich panels has been shifted from PH 15-7 Mo stainless steel to the super alloys and the refractory metals. The work on sandwich panels of super alloys, and refractory metals is part of the effort to develop structures that will withstand the high temperatures of re-entry into the atmosphere. In a program sponsored by the Air Force, procedures were developed for brazing panels of both Inconel 702 and Haynes 25 alloys. The brazing of similar panels of molybdenum - 0.5 percent titanium alloy in this program was not successful.

One of the major problems in the brazing of these materials is the development of brazing alloys and procedures which will reduce erosion of the thin sheet and embrittlement of the alloy. A nickel base alloy containing 19 percent Cr and 10 percent Si was adequate for the Inconel 702 and Haynes 25 alloy panels but no satisfactory alloy was found for the molybdenum - 0.5 percent titanium alloy panels which were suitable for temperatures above 2000°F. This investigation included nickel-base and cobalt-base brazing alloys. Additional development work is desirable to obtain the optimum procedures and filler metals for brazing the super alloys and the refractory metals. The current effort in this area includes an investigation to determine the feasibility of using volatile elements such as indium, in brazing alloys to lower the flow temperature. After brazing, the element is volatilized to raise the remelt temperature. Other work covers the development of brazing alloys for columbium and tungsten as will be described later. Consideration is also being given to the extension of the work on radiant brazing methods to include refractory metals.

Joining Problems in Aerospace Metals

The problems encountered in joining specific alloy groups will now be discussed. The alloy groups will include beryllium, titanium, high strength steels, precipitation hardening stainless, high temperature alloys and the refractory metals. Magnesium and aluminum will be omitted since the Air Force has no current development projects in this area.

Beryllium

The problem of joining beryllium was mentioned briefly in the previous materials symposium. It was stated that a program had been initiated to investigate possible methods of joining beryllium along with other problems associated with the application of beryllium in useful structures and components. The program sponsored by the Air Force includes the conventional welding and brazing processes.

Prevention of cracks at fusion welds is a major problem. One possible cause of cracking is the low ductility of beryllium at room temperature combined with the high thermal stresses produced in welding. When the product of the modulus of elasticity and the coefficient of expansion is used as an indication of the ease in which the thermal stresses can be produced, beryllium occupies an unfavorable position in a comparison with other metals. When the common metals are arranged in order of increasing product, table 1, it is noted that beryllium has the highest product while columbium has the lowest. Beryllium is also among the metals having the lowest ductility. The high product combined with the low ductility indicates that beryllium must be fabricated with procedures that produce a minimum of thermal stresses.

Another possible cause of the cracks is hot tearing which is due to the formation of low melting point constituents in the grain boundaries. This conclusion is supported by the results obtained in the present program. It has been shown that the susceptibility to hot tearing in beryllium fusion welds is increased by increasing the aluminum content in and above the range found in commercially pure beryllium, up to several percent aluminum. Other residual impurities in beryllium may contribute to cracking in a different manner. As an example, in beryllium, iron forms intermetallics which have lattices different from that of beryllium. The difference in lattice structure may produce stresses in beryllium and increase the tendency to crack at the welds. The major impurity, BeO, in beryllium appears to have no effect on cracking when present in amounts less than 2 percent. Another condition which probably increases the cracking tendency is the large grain size in the fusion welds.

Progress has been made in the development of procedures for fusion welding of beryllium. The inert-gas arc-welding process has produced crack free welds in laboratory specimens with sheet thicknesses under 1/4 inch. Small components made of beryllium have been welded successfully. Cracks are minimized by avoiding thermal shocks and by using low welding currents and slow welding speeds. More refinements in procedures are required for welds in thick plates or large structures where the joint is under more restraint. Other problems in fusion welding are: mechanical properties of the weld are lower than those of the parent metal, satisfactory penetration is difficult to obtain because of the high heat conductivity of beryllium combined with the requirement for low welding current, and excessive grain growth is difficult to avoid in the weld and heat affected zones. Solutions to these problems must be found to extend the use of fusion welding. Techniques such as roll planishing to improve the strength are now being attempted with some success. Other fusion welding processes such as elctron beam welding may provide additional improvement.

Ultrasonic welding of beryllium sheet ranging in thickness from 0.010 to 0.013 inch is under investigation. Sound welds have been made without an accompanying increase in the grain size in the weld area. The cracking tendency at the weld is reduced by using short periods of power application, usually less than 0.5 second. The short time interval requires an increase in the power level to make the weld and limits the maximum thickness that can be welded with the available equipment. To reduce the power requirements, an investigation was initiated to determine the effects of welding through foil interleafs of various metals such as aluminum, zirconium and gold. The technique of using foil interleafs shows definite promise but more data are required to make a complete analysis.

An investigation of resistance butt welding and spot welding has been initiated. Some resistance butt welds were made in 5/8-inch diameter beryllium rod but additional tests are required to evaluate this process. Preliminary results of tests of spot welds in 0.040-inch sheet indicate that both preheating and postheating are required to eliminate cracking. The results are encouraging but more tests are needed for making definite conclusions.

Results reported by several investigators indicate that beryllium can be joined by brazing with silver base or aluminum base alloys. To date, brazing is considered as the most reliable method of joining beryllium. Brazing alloys have been developed which give a satisfactory bond with approximately 60 percent of base metal strength at room temperature. The program on brazing beryllium will be continued and the effort will be directed to the development of improved brazing alloys and procedures.

Titanium

Titanium and titanium alloys are joined by inert-gas-shielded metal-arc welding and by spot, seam, flash, and pressure welding. For arc welding, procedures have been developed which avoid contamination of the welds by oxygen and nitrogen from the air. These procedures include the use of large gas nozzles, trailing shields and backing bars with means for introducing the inert gas on the underside of the weld. Also, chambers filled with an inert gas are in use to provide shielding for parts that cannot be adequately shielded by other methods. The major problem is now the brittleness of fusion welds in the higher strength titanium alloys. The Air Force sponsored a program aimed at the development of more weldable medium strength titanium alloys having a yield strength of 130,000 psi but no alloys were obtained which have better weldability than current commercial alloys. The current alloys that are frequently used in welded structures include Ti-5Al-2.5Sn, Ti-6Al-4V and Ti-13V-11Cr-3Al,

representing respectively the alpha, alpha-beta and beta alloys. Although successful weldments have been made with these alloys, additional research and development is required to obtain the optimum properties in the welded joints.

Some progress has been made in the development of procedures and brazing alloys for the fabrication of brazed titanium sandwich panels. The procedures are similar to those used for stainless steel sandwich panels. Some modifications are required to make the brazing cycle compatible with the heat treatment cycle required for the titanium alloy. The brazing is accomplished near the solution temperature as part of the heat-treating operation. This requires that the brazing alloy have a flow point from approximately 1450°F to 1600°F. The most suitable brazing alloys at this date are silver base alloys containing 5 percent or 12.5 percent aluminum. Silver-lithium alloys have been investigated but the corrosion resistance of these alloys was found unsatisfactory. For a number of applications it is desirable to braze the titanium alloy at the aging temperature, usually below 1100°F. At this temperature, it has been difficult to obtain satisfactory flow of a brazing alloy on titanium. The present programs sponsored by the Air Force include the development of alloys for brazing titanium during the aging cycle.

High Strength Steels

The welding of high strength steels has been a subject of major interest to the aircraft and missile industry. Welding was first used by the aerospace industry in the fabrication of airframes, landing gears, engine mounts and similar components made of SAE 4130, 4140, or 4340 steels. The major development effort in recent years has shifted from welding these components to the welding of missile cases. New steels, 300M, X-200, D6A, H-11, and others have been added to list of aircraft steels. Also, the steels are heat treated to higher strengths. Yield strengths of 230,000 psi and higher are now being considered for steels in missile cases. The use of welding is essential in the fabrication of missile cases of high strength steels. A major effort has been directed to the development of filler wires and welding procedures which will produce welds of the desired strength, ductility and soundness. The inert-gas-shielded arc welding is the most frequently used process. Other processes, metal arc, submerged arc and resistance welding have also been used but less extensively. Development of filler wires which produce welds of the desired strength has been achieved. Filler wire of a composition similar to the parent metal is usually used so that the weld will respond to heat treatment in the same manner as the parent metal. The carbon content of the filler wire is often below that of the parent metal to reduce the cracking tendency and to improve the ductility. With this type of filler wire it is not difficult to obtain welds with strengths approaching that of the parent metal but welds with the desired ductility and soundness are not always obtained. Because of the difficulty involved in obtaining welds with the required soundness and ductility some fabricators have avoided the use of longitudinal welds and have used only girth welds on the missile cases. Progress has been made in improving the ductility and soundness of the welds.

The reduction of hot cracking has improved the soundness of the welds. Results obtained in recent programs show that sulfur and phosphorus in amounts allowed by commercial specifications for steels can contribute to hot cracking. The results of a typical study are presented in figure 1 which shows the detrimental effects of sulfur on the hot ductility of SAE 4340 weld metal. Lowering the sulfur content from 0.031 to 0.012 percent increases the temperature at which there is a sharp drop in hot ductility. Similar results have been obtained for the effects of phosphorus. Based on these results many specifications for filler wire now require very low sulfur and phosphorus. Further progress in avoiding weld cracks has been made by using the optimum temperature for preheating and

post-heating. The isothermal transformation diagrams are useful in the determination of the optimum preheating and postheating procedures. An analysis of these diagrams for SAE 4340 and 300M steels (figure 2) indicates an optimum preheating and postheating temperature of 600°F. Temperatures above 600°F require longer times for the austenite to bainite transformation. At temperatures below 575°F martensite forms. Longitudinal bend tests of welds made with a 600°F preheat and postheat, show much better ductility than similar tests of welds made with higher or lower preheat and postheat temperatures. Good fixtures and proper cleaning of the filler wire and parent metal are also helpful in the prevention of cracks and porosity in the welds. Another essential part of the procedures is to avoid contact between the hot weld metal and the copper backing bars. Cracks can be caused by rapid cooling when the hot weld metal contacts the copper bars.

These procedures are effective in improving the weld soundness but do not always produce the desired ductility in the weld metal. Procedures which will improve the ductility of welds are of major interest. As mentioned previously the use of filler wires with lower carbon content is effective in improving the ductility. Additional improvement is obtained by heat treatments which refine the austenite grain size in the weld metal and heat affected zones. A number of research laboratories have proposed investigations of various possible methods of improving the ductility and soundness of welds. These methods include magnetic stirring of molten pool, pulsing of the welding current and the application of vibrations to the molten pool. An existing program includes the development of improved filler wires and procedures for welding the hot work die steels. Other possible programs of interest in the welding of missile cases are the development of more sensitive methods of nondestructive inspection. Many failures in rocket cases started at weld flaws which were not detected in the nondestructive inspection.

Precipitation Hardening Stainless Steels

The manufacturers and users of these steels have developed filler wires and welding procedures which produce welds with better ductility without a serious drop in strength. An important part of the procedures is the adjustment of the chemical composition of the weld metal so that the required amount of delta ferrite is formed in the weld metal. A small amount of delta ferrite, about 15 percent, is required in PH 15-7 Mo weld metal to obtain the optimum physical properties when the part is heat treated after welding. The inert-gas tungsten-arc welding process is used most widely on these steels. This process provides efficient protection of all the alloying elements and allows close control of the chemical composition of the weld metal. The solution to another problem is required before the precipitation hardening stainless steels can be used efficiently in aircraft structures of the future. One proposed design for these structures requires the assembly of brazed honeycomb panels by welding the edge attachments, figure 3. The joints will be used in the as welded condition. The control of warpage and residual stresses at the welded joints may be a serious problem in the assembly of the large rigid structures. The residual stresses in these structures may contribute to brittle failures or they may increase the susceptibility of the alloy to stress corrosion cracking. Residual stresses have been shown to be a contributing factor to brittle failures in large welded structures of low carbon steels.

High Temperature Alloys

The problem of major interest in welding these alloys is cracking at the welds in the age hardenable alloys, such as, A286, Inconel X and Rene 41. These alloys have additions of titanium and aluminum to obtain higher strengths by heat treatment which includes a solution treatment at a relatively high temperature, usually from 1650°F to 2200°F,

followed by an aging treatment usually between 1200°F to 1600°F. The physical properties of these alloys are adequate for a large number of applications, but the additions of aluminum and titanium tend to lower their weldability. Progress has been made for production welding of these alloys and in understanding their behavior from a metallurgical standpoint. However, welding problems still arise in production welding of these alloys, and more development of the process is required. Sound fusion welds can usually be made in the high nickel alloys, Inconel X and Rene 41, when they are in the solution heat-treated condition. With the alloy in this condition, cracking during or immediately after welding does not appear to be the major problem. However, during the subsequent heat treatment, they have a serious tendency toward strain age cracking when the part is heated through the aging period temperature range. In the A286 alloy, most of the cracking occurs during or immediately after welding. It appears that there is a hot short range just below the melting point of the alloy. The Air Force is sponsoring a program to obtain more information on the mechanism of cracking and to develop procedures which will reduce the tendency to cracking in these alloys.

Refractory Metals

Molybdenum was the first metal of this group to be considered for use by the aircraft industry. Initially, molybdenum and its alloys were investigated as a material for use in ramjet and turbojet engines. More recently, molybdenum alloys are being considered for the construction of hot structures on re-entry vehicles. All of these applications require that molybdenum be joined by some method, preferably by welding or brazing. With the shielded inert gas arc welding processes, sound welds can be made in molybdenum by exercising a high degree of process control but the ductility of the weld at room temperature is usually less than that desired for airframe structures or engine components and the weldments are very notch sensitive. The ductility is lowered by the recrystallization in the fusion and heat affected zones. A similar enbrittlement will occur in brazing when molybdenum is heated above the recrystallization temperature. Extensive research and development programs have produced data which show that minute quantities of oxygen, nitrogen and carbon contribute to the enbrittlement. Thus, the major effort in the welding of molybdenum has been directed toward the elimination of these impurities from both the weld and the parent metal which has been accomplished by the use of ultra-high-purity molybdenum as the base metal, and by welding in dry boxes which have been vacuum-purged and filled with an inert gas of high purity. Other methods of improving the ductility of molybdenum welds include postweld heat treatments, cold working of welds, high welding speeds and stressing the weld at elevated temperatures. Even with these methods, the desired ductility in molybdenum fusion welds is difficult to obtain. More recent developments include the use of the Mo-50 percent Re alloy as the weld metal to lower the ductile to brittle transition temperature of the weld bead and the use of electron beam welding to reduce the contamination of the weld and also the width of the heat affected zone.

The Air Force is sponsoring a program on the electron beam welding of molybdenum and tungsten. These developments may provide additional improvement in the ductility of molybdenum fusion welds. Low ductility is also obtained in resistance spot welds joining molybdenum. Another problem in spot welding molybdenum is sticking of the electrodes. Because of these problems, the Air Force sponsored an investigation of ultrasonic welding which included the joining of molybdenum. Sticking of the tip to molybdenum was also a problem in ultrasonic welding. A more serious problem was the cracking at the edges of the welds, figure 4. To obtain an ultrasonic weld, it is necessary to apply the vibrations of the tip in a plane paralled to the sheet surface. This requirement creates the problem of transferring the energy from the tip to sheet surface, then through the sheet thickness to the interfaces where the weld is desired. In soft alloys, similar to aluminum, sufficient

energy can be transferred to make a weld without cracking, but in the hard metals, such as molybdenum, the transfer of the required energy becomes more difficult. Investigators report varying degrees of success in ultrasonic welding of molybdenum. Variations in welding equipment and procedures may improve ultrasonic welds in molybdenum but the problem of transferring energy to the interface will certainly limit the practical use of this process to the thinner sheets of molybdenum.

Since the discovery of large deposits of columbium ore, this metal and its alloys have been investigated for possible use in structures and components in which a higher operating temperature is desired. The current investigations include welding and brazing along with other investigations connected with the application of columbium. Tungsten arc welds with good ductility can be made in unalloyed columbium if reasonable care is exercised to avoid atmospheric contamination. Nitrogen and oxygen can embrittle columbium but its tolerance for these impurities is much greater than in the case of molybdenum. Although most of the wrought form higher strength columbium alloys are ductile at or below room temperature, the welding operation produces a zone of fused metal and a recrystallized heat-affected-zone of greatly reduced ductility. A precipitation process may contribute to the embrittlement. The addition of alloying elements to columbium can raise the ductile to brittle transition temperature. Some elements, vanadium, tantalum, titanium, hafnium and zirconium can be added in fairly large amounts without raising the transition temperature. Small additions of other elements, such as tungsten, molybdenum and chromium cause a rapid rise in the transition temperature. Thus, the development of weldable columbium alloys requires a careful consideration of the effects of alloying elements on the ductility of the welds.

Additional problems that should be investigated include the effects of the interstitial elements on the physical properties and weldability of columbium alloys. Also welds in some of the commercial columbium alloys are reported to have low ductility. The Air Force has initiated a program to study the weldability of commercially available columbium alloys, FS 82, D 31 and F 48. The effects of various welding parameters including welding speeds, atmospheres, preheating and post heat treatments on the metallurgical and mechanical behavior of these alloys will be investigated.

Brazing is a subject of interest in the fabrication of structures from thin columbium sheets. Brazing alloys suitable for temperatures to 2500°F are usually desired for structures made of columbium alloys. Development of columbium brazing alloys is included in the current Air Force development programs. Brazing alloys under investigation include titanium, titanium-vanadium and binary alloys of columbium formed by additions of vanadium, titanium, zirconium and boron.

The welding characteristics of tantalum are similar to those of columbium. Tantalum can be welded with shielded inert gas arc welding, resistance welding and electron beam welding. The procedures are similar to those used in welding of molybdenum or columbium. The welds in pure tantalum have excellent ductility, however, because of its low strength to weight ratio, and because the development of tantalum base alloys was initiated only recently, it is of little interest in the aerospace industry.

Tungsten can be welded by the inert gas shielded arc processes. The procedures are similar to those used in the welding of molybdenum. The electron beam welding process can also be used. Sound welds can be made in tungsten but they are very brittle at room temperature. The problem of obtaining ductile welds is very difficult as the transition temperature of tungsten is approximately 600°F higher than that of molybdenum. The transition temperature of welded joints in tungsten is not appreciably higher than that of

the base metal. Programs are in progress on welding and brazing of tungsten. Specific areas of investigation in welding, cover the effects of interstitial content, tungsten arc, electron beam welding, and the use of tantalum as a filler wire. The brazing phase of the investigation will include the brazing of alloys suitable for service up to 3500°F. Binary alloys of tantalum, columbium and molybdenum which have additions of titanium, vanadium or other elements to lower the melting point will be investigated. The objective of this work is to gain a sound metallurgical insight into the physical metallurgy of joining tungsten by welding and brazing. The metallurgical reactions that occur during the joining process are to be evaluated so that procedures and filler metals can be developed for producing the best possible properties in the joints.

Summary

Major problems in welding and brazing aircraft and missile components have been reviewed and are indicated in table II. Progress has been made in welding beryllium but additional development is required to consistently make sound welds that are crack-free. Further improvements in the soundness and ductility of fusion welds in high strength steels and the high strength titanium alloys are desirable. The welding of brazed honeycomb panels to form an airframe structure is a challenge of major importance in the construction of Mach 3 aircraft. Cracking at the welds in the age hardenable high temperature alloys should receive additional attention. Welding of the refractory metals should also receive additional attention. The transition temperature of fusion welds in molybdenum is still too high for structural applications. New methods for joining molybdenum, such as diffusion bonding should be investigated. Additional work in the welding of columbium alloys is necessary to obtain satisfactory properties in the alloys of higher strength. Utilization of tantalum alloys in aerospace structures and components will require the development of weldable alloys of higher strength. Further refinements in welding techniques for joining tungsten are necessary to obtain sound welds consistently and to reduce the brittleness at room temperature. The brazing of all alloys mentioned in the preceding discussion should receive additional attention. Brazing alloys and techniques for the refractory metals are however, of special interest, while continuing research and development programs in welding and brazing must be continued to solve joining problems for the aerospace industry.

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TABLE 1

PRODUCT OF THE MODULUS OF ELASTICITY AND THE COEFFICIENT OF EXPANSION FOR SOME OF THE COMMON METALS

METAL	MODULUS OF ELASTICITY PSI	COEFFICIENT OF EXPANSION IN./°C	PRODUCT
COLUMBIUM	15×10^{6}	7×10^{-6}	105
TITANIUM	16.8×10^{6}	8.5×10^{-6}	143
MAGNESIUM	6.5×10^{6}	26×10^{-6}	169
TANTALUM	27×10^{6}	6.5×10^{-6}	175
TUNGSTEN	50×10^{6}	4.3×10^{-6}	215
CHROMIUM	36×10^{6}	6.2×10^{-6}	224
ALUMINUM	10×10^{6}	23.9×10^{-6}	239
MOLYBDENUM	50×10^{6}	4.9×10^{-6}	245
IRON	28.5×10^{6}	11.7×10^{-6}	334
COBALT	30×10^{6}	12.3×10^{-6}	369
NICKEL	30×10^{6}	13.3×10^{-6}	399
BERYLLIUM	37×10^{6}	12.4×10^{-6}	460

Table 2

Summary of Joining Problems

Beryllium - Prevention of cracking at welds.

Titanium - Low ductility of welds in high strength alloys.

Brazed honeycomb panels - Assembly of large structures by welding.

High strength steels - Better ductility in welds and more sensitive non-destructive inspection methods.

High temperature alloys - More data on hot cracking and strain age cracking at welds.

Refractory metals - Poor ductility of welds in both molybdenum and tungsten. More ductile welds in the high strength columbium alloys. Weldable high strength tantalum alloys.

EFFECTS of SULPFUR on HOT DUCTILITY, SAE 4340 WELD METAL

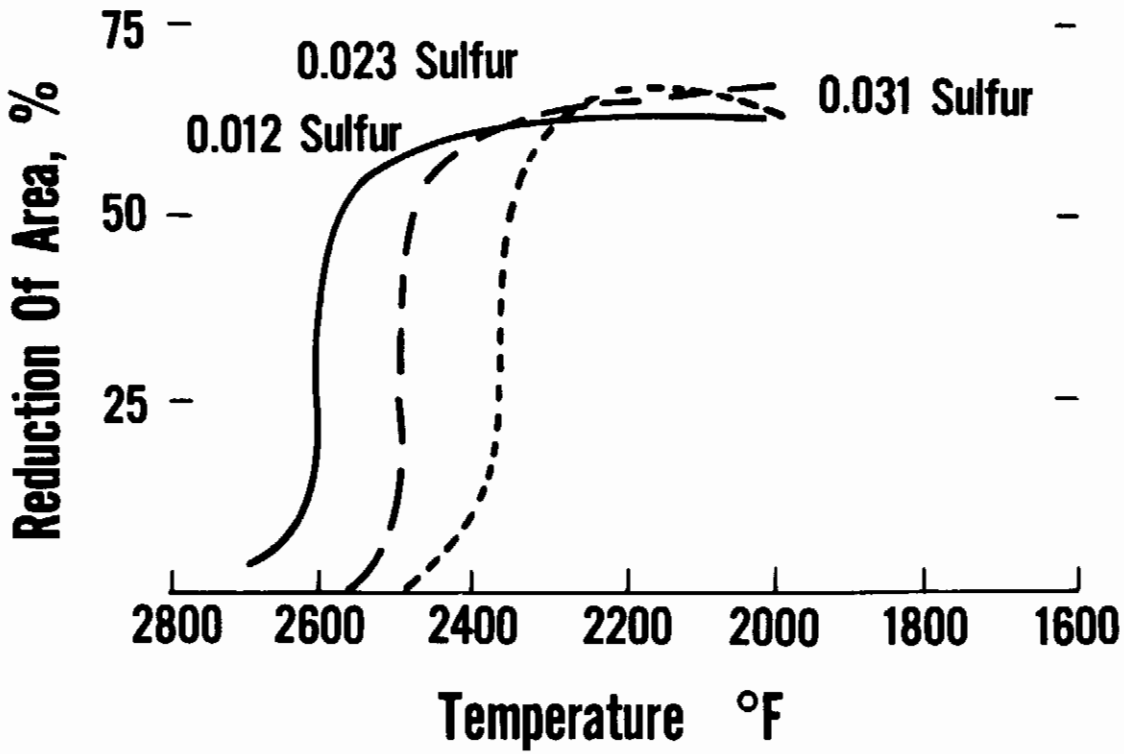


Figure 1.

TTT CURVES for 300M and 4340 STEEL

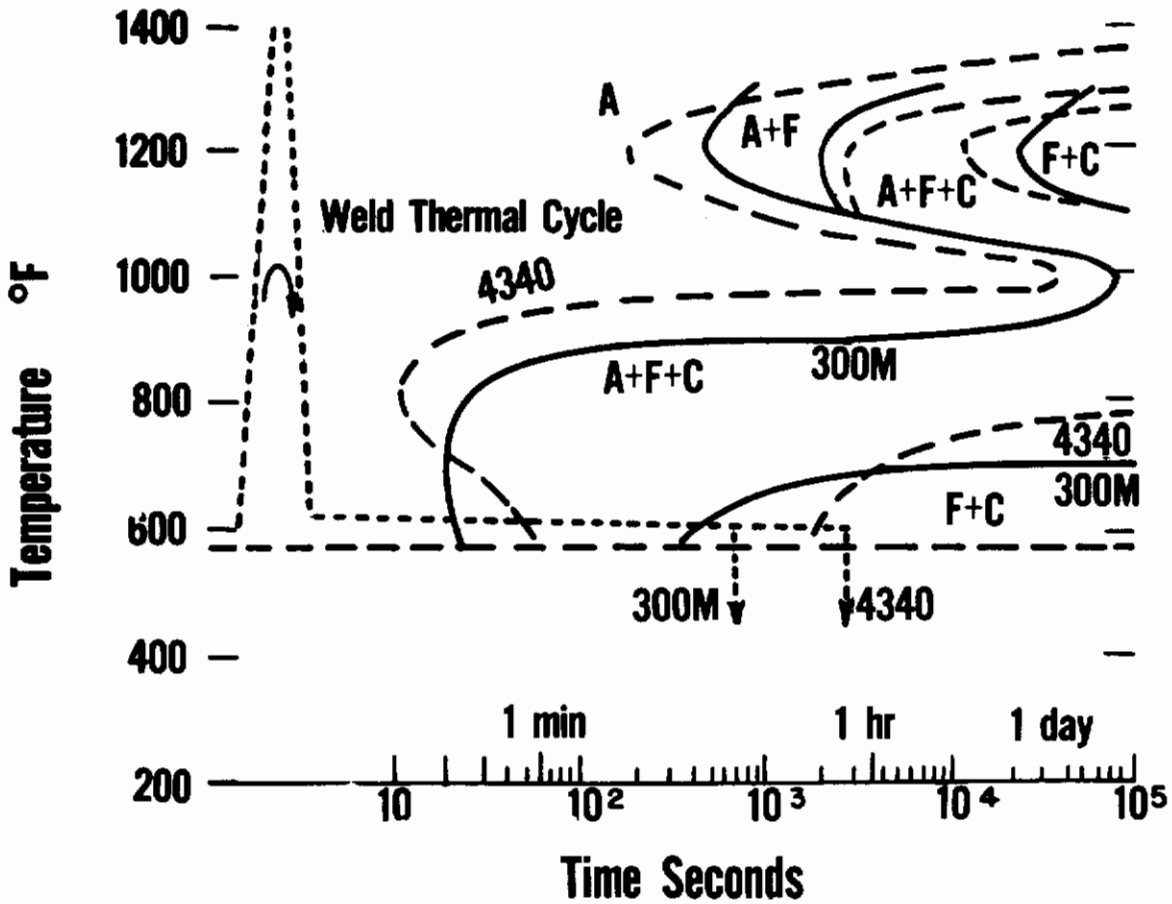
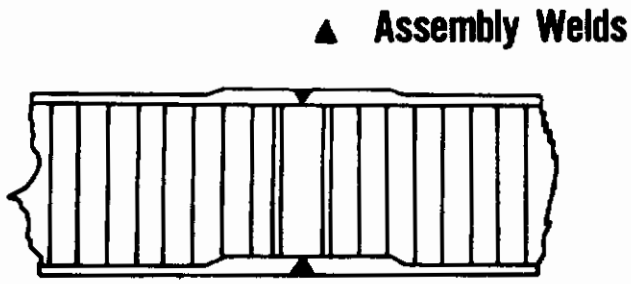


Figure 2.

ASSEMBLY of BRAZED PANELS by WELDING

Access On Both Sides



Access On One Side

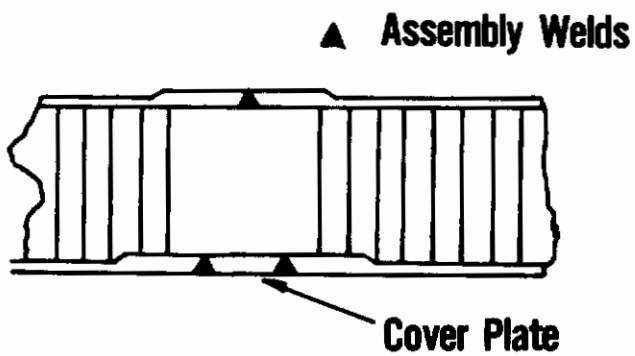
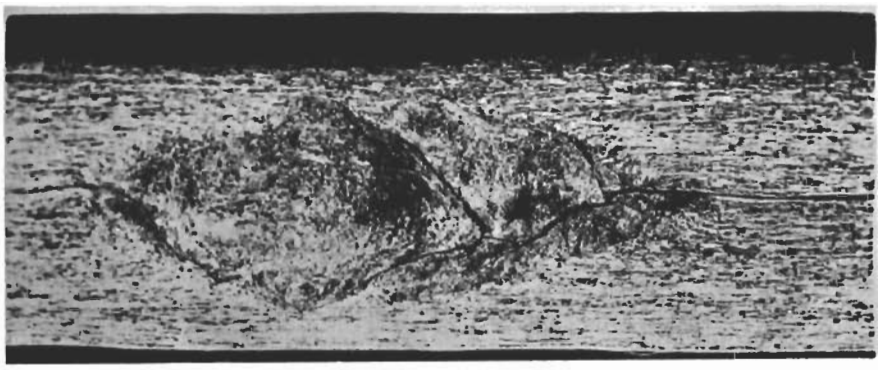


Figure 3.

CRACKS IN ULTRASONIC WELDS



0.015 in.

Mo-0.5% Ti

0.015 in.

Mo-0.5% Ti

Figure 4.