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WELDING IN AIRCRAFT STRUCTURES

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SUMMARY

The welding processes relevant to the welding of aircraft materials are briefly reviewed, together with those materials of present or future interest for aircraft structures. The problems of design for welding are also considered. It is concluded that the prospects for welding are more promising in materials other than light alloys, which will be used for high speed aircraft. In addition, further development of automatic welding machines and large heat treatment facilities is needed.

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INTRODUCTION

Although fabrication by welding has become an essential partof aero-engine production, this method of joining has not achieved the same pre-eminence in the structural field. To a large extent this can be attributed to the type of alloys used in the respective components. In structures, aluminium based alloys of compositions generally unsuitable for welding have been used. Alternative methods of jointing have therefore been employed and a considerable volume of design data has been accumulated. This has led to a degree of confidence in the use of, for example, riveting and bolting that is lacking when welded joints are considered. Since welding has not been widely used in aircraft structures insufficient data have been collected and this in turn has perpetuated a reluctance to use welding for primary load bearing structures. Early attempts at welding aluminium alloys were not particularly successful and the incidence of defects was common. Whilst the presence of these was not necessarily detrimental, so little was known about their effects on the behaviour of the joint under various types of loading that designers, in the interests of safety, specified welds completely free from defects. This, in fact, was difficult to achieve with the processes then available.

Welding technology has made considerable progress over the last two decades and in industries outside the aircraft field welded joints are being used with complete confidence under severe loading conditions. It is the intention of the authors in this report to consider how far the experience of these industries can be applied to the fabrication of aircraft structures. No attempt will be made to review existing welding practice in the aircraft industry and reference to specific examples will only be made where it serves to illustrate a particular point or represents a departure from established procedures.

SUITABLE PROCESSES

A large variety of processes are now available and it is necessary to classify them if a rational treatment of the subject is to be achieved. For the purposes of this report it is convenient to consider three major groups distinguished by the incidence and location of fusion (Table I). It will be observed that the metallurgical effects of each group are significantly different and this can play an important part in the selection of the most suitable process for a given application.

Fusion welding. With those processes in which fusion of the base plate or workpiece occurs, four major groups are observed: these relate to the four types of heat source available; i.e. arc, electric resistance, high energy beam and oxy-acetylene flame.

The common arc welding processes which utilise a slag shield are mainly used for mild and low alloy steels. Complete elimination of defects is virtually impossible, particularly in the manual processes, and these processes are of little interest in the aircraft structural field except for occasions where assemblies are made in low alloy steels.

By far the most important arc processes for aircraft construction are those where the arc and weld pool are shielded by an inert gas, e.g. argon. Two variants are found. In the first the electrode is tungsten and is substantially non-consumable (TIG). The arc is used as a simple heat source and any additional metal required for the purposes of alloying or to correct the weld profile, is added to the weld pool in the form of a filler wire. The process offers a high degree of versatility and is applicable to a wide range of materials. It should be stressed however, that a highly skilled operator or automatic control must be employed if a consistent standard is to be achieved (Refs. 1 and 2). TIG welding is well established in the industry and numerous examples of typical applications can be quoted. In the main however, there would appear to be a greater use of the process on tubular structures than on sheet. Tubes range from the relatively small diameters used in helicopter structures to tubular sections for undercarriage units. An interesting instance of the latter is the undercarriage of the Vickers' VC10 where a circumferential weld is made in $1\frac{1}{4}$ in. thick Firth Vickers FV520 precipitation hardening steel (Ref. 3). Automatic TIG welding is particularly suited to the welding of butt seams in sheet and it is felt that wider use of this aspect could be made. Perhaps the biggest problem that exists is control of the distortion that can accompany welds, especially in thin sheet. Elimination or minimisation of distortion requires careful attention to jigging and preparation of the material before welding. Considerable success has been achieved in this respect by the electronics industry in the TIG welding, without filler, of 0.005 in. to 0.030 in. thick sheet for subsequent forming into bellows units. Special jigs have been produced for this work and standardised guillotining procedures have been developed to ensure uniformity of fit-up. Similar techniques were successfully employed in the construction of drop tanks for the Hawker Hunter.

An interesting variant on TIG welding is the Tungsten Arc Spotwelding process, also known as Puddle Welding (Refs. 3 and 4). By use of a stationary controlled TIG arc it is possible to produce a fused slug through two or three thicknesses of sheet thus providing localised jointing. Although not yet widely used this method of welding offers considerable potential. It is of particular interest because it is only necessary to have access to one side of the sheet. This is a particular advantage in sandwich panel structures and the process was used to fabricate the skin panels of the Bristol T188. On ferrous and nickel-based alloys, weld profile can be controlled by reducing the current gradually at the end of the weld cycle and a weld slug can be produced having a surface that is raised above that of the sheet. It is then possible to grind the weld flush and to achieve a polished surface free from flaws. With materials of high thermal conductivity, e.g. aluminium, it is necessary to add a small amount of filler metal to the slug to prevent the formation of a deep crater (Ref. 5). This leads to more complex equipment and this aspect of TIG spotwelding is still very much in the development stage. The process is well suited to close control as is illustrated by the tape controlled fully automatic spotwelding unit designed by Linde in the U.S.A. for the fabrication of fins for rockets.

The logical extension of TIG welding is the replacement of the tungsten electrode by a consumable electrode of a composition similar to that of the material being welded (MIG welding). Although used on a variety of metals, MIG welding is mainly employed for aluminium (with argon shielding) and mild steel (with carbon dioxide shielding). Until recent years the process has been confined to thick material, rarely less than $\frac{1}{4}$ in. thick. This limitation was imposed by an inherent feature of the arc by which an unsatisfactory mode of transfer of metal from the electrode to the weld pool occurs at lower currents. Two new developments have now extended the range to sheet material. In both these techniques the mode of metal transfer has been changed at low currents and welding is thus possible at the low heat inputs required for the joining of sheets. The first of these, dip-transfer (Ref. 6) utilised a controlled short circuiting arc and can only be used on materials having a high electrical resistivity and is not, therefore, applicable to aluminium and its alloys. In the second technique, Pulse-arc welding (Refs. 7 and 8), a reduced heat input is achieved by superimposing timed, high current pulses onto a low level background current. Welds of a very high quality can be produced in aluminium sheets from 0.065 in. thick and from 0.036 in. in steel. A noteworthy feature of Pulse-arc welding is the degree of control that can be exercised over the process; reproducible electrical characteristics can be readily obtained and uniform weld quality should result, given suitable control of other fabrication variables. Offering faster welding and less distortion than TIG, and better weld profiles than Dip-transfer, it is anticipated that Pulse-arc welding will be widely used in sheet fabrication.

Resistance welding requires little introduction as it is well established in the airframe industry. Perhaps the most outstanding example of its use is to be found in the Handley Page Victor bomber (Ref. 3) where resistance spot welding was used extensively in the fabrication of the sandwich panels. All the variants (spot, seam and projection) utilise the heating effect of a high current (4,000 to more than 60,000 amps) passing through the interface between two sheets. Weld times are short, of the order of one-quarter of a second, and, provided a sufficiently high current can be achieved, it is possible to reduce metallurgical reactions in the region around the weld to a minimum. Hardened material may thus be welded without seriously impairing the mechanical properties and spot welded lap joints compare well with rivetted lap joints.

In comparing resistance welding with other processes it should be remembered that all joints must be some form of lap and a weight penalty is therefore imposed. Perhaps the biggest problem in the use of resistance welding is that of quality control. Except for aluminium alloys containing copper, radiography will only show the presence of cavities, cracks or non-metallic inclusions but will give no indication of area of fusion. One school of thought suggests that the existence of a defect implies fusion but the use of such a philosophy in testing has obvious dangers. Attention has been devoted recently to the control of the welding parameters to ensure a reproducible weld cycle and various devices have been developed to monitor the welding variables (Ref. 9). The logical extension of such devices is to introduce feed-back loops which will correct any deviations from the optimum condition. It is expected that within the next decade such systems will become widely available and this should lead to increased confidence in the resistance welding processes.

Considerable interest has been aroused in the welding field in the last few years by the introduction of joining processes using a high energy beam to produce fusion. Chronologically the first of these was Electron Beam welding

(Refs. 10 and 11). A conventional electron gun is used to generate a substantially parallel, narrow beam of electrons which release their kinetic energy on collision with the workpiece. The energy thus released is directly converted to heat which rapidly raises the metal to its melting point. The resultant weld has a high depth to width ratio, which can be as great as 20:1, which is a distinguishing feature of electron beam welding and is an important factor in the achievement of low levels of distortion. Conventionally the beam must be used in a vacuum chamber and this can be a serious limitation to the process. On the other hand, large chambers (e.g. 16 ft. long x 10 ft. diameter) have been produced in the U.S.A. and techniques have been developed in the fabrication of space vehicles in which the component to be welded forms one side of the chamber. A recent innovation uses a very high energy beam which is allowed to emerge from the chamber through a port (Refs. 12 and 13). Provided the distance between the port and the joint to be welded is about 1 cm. fusion can be produced, and satisfactory welding achieved. The profile of the resultant weld approaches that produced by arc welding.

The advantages of electron beam welding, in a vacuum, are its ability to weld both conventional and "difficult" metals, the low levels of distortion produced, the high purity of the weld metal (resulting from vacuum refinement) and the ability to weld in difficult locations. Although basically a mechanised process it is critically dependent, nevertheless, on operator skill since small variations in the beam power will produce non-uniform welds. Considerable thought must be given to the design of jigs and manipulating devices as these must operate under vacuum. Alignment and fit-up of the workpieces must be good since, due to the narrowness of the beam, it is possible for it to pass through a gap without producing fusion.

Two main types of equipment are currently available, operating at anode voltages of 30 k.v. or 120 k.v, with a movable or stationary gun. In the absence of a systematic, unbiased investigation it is difficult to comment on the choice of equipment, but it has been suggested (Ref. 19) that with the continued development of the electron beam process, voltage levels are becoming less important. To some extent this is linked with the introduction of the "cold cathode" gun which is appreciably smaller and more versatile than the conventional heated filament gun.

Potentially electron beam welding offers considerable scope, especially for such structures as spars, and sandwich panels. It has a high capital cost e.g. £25,000 for a basic equipment and many authorities feel that it can only be justified economically in mass production or high output environments.

An alternative method of generating a high energy beam is to employ a constricted, gas-shielded electric arc to produce a narrow stream of gas travelling at high velocities and having a temperature exceeding 15,000°K at the centre. This process has been called "Plasma" welding and has only recently been available commercially (Refs. 15 and 16). It has the advantage over electron beam welding that it does not require a vacuum chamber, but the thickness of the material to be welded appears to be limited to ¼ or 3/8 in. according to composition. Little operating experience has been gained in this country, and in the U.S.A. most of the information available has originated from the manufacturers of the equipment. The process offers considerable promise for sheet work, however, since penetration does not appear to be critically dependent on the distance from the torch to the workpiece and small variations in the flatness of the sheet can be tolerated. The profile of the penetration bead appears to be superior to that achieved with TIG or MIG welding, but the high speeds of welding which must be used with this process may constitute a drawback.

The imagination of most scientists has been captured recently by the potential cope of Laser equipment. The high energy light beam shows such marked resemblance to the electron beam and plasma stream discussed in the preceding paragraphs that research workers have looked hopefully to Laser beams as possible heat sources for welding. The major problem lies in the inherent inefficiency of Laser generators and it is difficult to transfer sufficient power to satisfy fusion welding requirements. In the absence of any outstanding technological advances in the next few years it is difficult to envisage Laser welding of seams in the materials used in airframe construction.

Joining without fusion of the workpiece, and without a filler, historically was the first method of welding. In recent years revived interest in solid-phase bonding has lead to many significant developments. The simplest method is that known as small tool welding in which bonding over a limited area is produced by forcing the surfaces together. This involves a large amount of deformation (e.g. 40% reduction of sheet thickness with aluminium) and is not likely to be of interest where fatigue loading is experienced. The level of deformation can be reduced to as little as 5% if relative movement can be induced between the surfaces to be joined. This has lead to the development of ultrasonic welding where one member of the joint is made to oscillate at a frequency of 20 kc/s. Ultrasonic welding has proved to be very successful on thin sheet (Ref. 17), but on 20 s.w.g. and thicker material it offers no operational advantages over resistance welding. It is possible, however, that slightly better fatigue performance may be achieved due to the smaller surface indentations produced by ultrasonic welding.

A particularly interesting development is explosive welding. Little is known about this process at present, but work on aluminium by Aluminium Laboratories Ltd. (Ref. 18) in this country has suggested that with the high rates of deformation achieved, very good solid phase bonding occurs between components. It is feasible that explosive forming and explosive welding could be combined to provide a useful method of producing complex sheet components.

MATERIALS PROBLEMS

The most significant factor in any fusion welding process is the weld thermal cycle that is undergone by the components being joined. At the joint interface metal is melted and re-solidified, and the heat necessary for fusion is then dispersed mainly by conduction through the parent material. Thus a fusion welded joint will consist of three regions: (Fig. 1):

(i) the weld metal, A
(ii) the weld heat affected zone, B
(iii) the unaffected parent material, C.

It is the effect of the first two regions on the properties of the unwelded parent material that is of concern to the aircraft designer, constructor and operator.

Welding is often described as "casting in miniature" indicating that weld metal has the structure and properties of a casting and most weld metals have properties nearer to those of a casting than to wrought material. However, the high cooling rate experienced in most welds together with the stress arising from restraint, does give some improvement over cast metal. In the case of mild and low alloy steels, this effect is such that weld metal has a higher tensile and proof stress than hot-wrought material of the same composition.

In the heat-affected zone, the parent material will have undergone a thermal cycle depending upon its proximity to the weld metal, the heat input and the size and physical properties of the parent material. The effect of these thermal cycles on the parent metal structure and properties will obviously depend upon the parent material and its condition. Thus an annealed pure metal or single phase alloy will suffer only a little grain growth with no effect on properties whereas the same material in the work hardened condition will soften and the properties will be reduced to those of the annealed material. With materials that undergo a transformation in the solid state such as most ferritic steels, the weld thermal cycle may effect this transformation giving a heat affected zone structure considerably different from that of the parent material.

Finally, it is necessary to consider the effect of the thermal cycle on materials whose properties are obtained by a careful heat treatment, such as precipitation-hardened light alloys, nickel alloys and steels, and the quenched and tempered steels. It is unrealistic to imagine that the weld cycle will have no effect upon the metallurgical nature of the material and in most cases this will cause a drastic fall in properties.

These problems of fusion and the weld thermal cycle focus attention upon the attractions of solid phase bonding. With these processes fusion does not occur and in some cases even heat is unnecessary. Thus these processes are the only ones which offer prospects of a joint without fused metal or a heat affected zone.

Materials used in Aircraft Structures

The metals and alloys used in aircraft structures range from the light alloys of conventional aircraft through titanium to the high-strength steels. The light alloys will continue to be used almost exclusively for subsonic aircraft but the elevated temperatures that will be encountered by supersonic aircraft demand alloys that maintain their strength above ambient temperature. The strength to weight ratios of various representative alloys and the variation with temperature is shown in Fig. 2.

In this section it is intended to review each class of alloy, considering the strength at various temperatures together with the response to fusion welding.

The wrought aluminium alloys can be divided into two groups:

(1) solid solution hardening alloys which are basically single phase and not heat treatable, so that strengths can only be increased by cold working;

(2) heat treatable alloys, strengths of which can be markedly increased by natural or artificial ageing treatments.

The non-heat-treatable aluminium alloys (e.g. with 3 per cent magnesium and 1 per cent manganese) in the annealed condition tensile strengths of 12 - 16 ton/in^2 which can be increased to 15 - 19 ton/in^2 by cold working. Strengths are maintained to about 100°C after which they fall rapidly. These alloys are readily weldable by the inert gas processes: joint strengths tend to be slightly below those of the annealed parent material, i.e. up to 15 ton/in^2 and the corrosion resistance of the joint is generally slightly inferior to that of the parent material. Resistance welding of these alloys is also readily feasible and alloys welded in the work hardened condition give fatigue strengths comparable with those obtained with rivetted joints (Ref. 3).

The welding of the heat treatable alloys, which offer tensile strengths up to 36 ton/in^2, presents two main difficulties:

(a) most of these alloys are susceptible to hot cracking in the weld metal (Ref. 19)

(b) the weld heat affected zone contains an overaged region whose properties can only be recovered by a full solution and ageing heat treatment.

The cracking problem has generally led to a non-ageing aluminium-silicon weld deposit being used for welding, with a tensile strength of 10 t.s.i., so that for most purposes the heat treatable alloys must be considered unsuitable for welding if high joint efficiencies are required.

Over the last few years a group of medium strength heat treatable alloys have been developed which appear to weldable by the TIG and MIG processes: these are the alloys containing 3.0 - 5.0% zinc and 1.0 - 2.5% magnesium. These alloys are less susceptible to weld metal cracking than other heat treatable alloys and hardenable filler wires have been developed. Equally significant no fully overaged region occurs in the heat affected zone so that considerable recovery of properties is attainable by natural or artificial ageing. Considerable experimental work on the welding response of these alloys has been carried out in this country (Refs. 20-23) but the most comprehensive paper on the subject (Ref. 24) was presented in Milan in May 1965. This work indicated that joint strengths of up to 24 ton/in^2 can be achieved by natural ageing after welding, 28 ton/in^2 by ageing for 24 hours at 100°C plus 24 hours at 120°C and as high as 32 ton/in^2 by a complete solution and ageing treatment (Table II). The main doubt about these alloys is a tendency to exfoliation corrosion in part of the heat affected zone, but this problem has still to be completely defined.

Resistance welding of the fully hardened heat treatable alloys is quite possible and gives very little loss in strength. Cracking is not a great problem provided attention is paid to the welding conditions; copper and zinc bearing alloys are the most susceptible. Copper bearing alloys may exhibit preferential corrosion in the heat affected zones of spot welds.

Pure annealed aluminium and several of the non-heat treatable alloys are readily pressure welded. Pressure welding of age hardened alloys has not been reported but may well prove possible.

Magnesium base alloys have been far less utilized in aircraft structures than aluminium base alloys, due to a greater susceptibility to corrosion. The alloys have annealed tensile strengths up to 23 ton/in^2 and some magnesium-base alloys retain reasonable strength up to 350°C. TIG and MIG welding of the alloys give joint efficiencies of 90% while resistance spot and seam welding are also feasible. Cold pressure welding requires high deformations.

Several years have passed since titanium was viewed as a possible low density, high temperature, material, but many of its alloys retain useful properties at intermediate temperatures (up to 500°C). The main welding problem of all the alloys is their high affinity for oxygen. With the exception of resistance spot or seam welding, an inert gas shield or vacuum is essential during fusion welding if the welds are not to be severely embrittled. Arc welding (Ref. 25) is best carried out in argon shielded welding chambers although open air TIG welding is reported possible (Refs. 26 and 27), provided considerable care is taken.

Inert gas shielded welding produces good weld quality in the single phase non-hardenable alloys, 100% joint efficiencies being attainable even in the high strength (67 t.s.i. UTS) alloys (Ref. 28). Many of the precipitation hardening alloys are not suitable for welding whilst the others need complex post-weld heat treatment if good joint strengths are required (Refs. 29 and 30).

The use of titanium alloys in aircraft structures tended to remain static for many years but more of these alloys seem to be finding uses in the American aircraft industry. In 1964, airframes replaced missile and space applications as the major customer for titanium alloys and over 1,000,000 lbs. of titanium were used for civil aircraft out of a total of 15,000,000 lb. for all applications (Ref. 32). The specific applications of the alloys and the extent to which welding was used during fabrication has not been reported.

Because of their comparatively high density, iron-base materials can only be of use when they attain very high strength levels (above 70 t.s.i.) or can maintain moderately high strengths at temperatures above 350°C. The traditional, and cheapest, method of obtaining high strengths is to increase the carbon content, but this increases the problems of welding and also notch sensitivity in all but sheet material. Alloy steels with carbon contents up to 0.5%C have been used in aircraft, mainly for undercarriage components, but these have generally be forged from single billets. The introduction of low carbon alloy steels and of new forming techniques has greatly increased the number of ductile steels with tensile strengths above 70 ton/in^2, and even 100 ton/in^2 and many of these materials are readily weldable. However, where these steels rely upon heat treatment or on elevated temperature forming treatment for their strength, some fall in properties must be expected in the heat affected zone.
Fortunately a low temperature ageing treatment will often

lead to almost complete recovery of properties. Steelmaking practice and impurity levels greatly influence the properties and weldability of steels. Vacuum melted material is preferable, particularly high strength steels.

The medium carbon low alloy steels mentioned above are only marginally weldable. There is a considerable danger of bittle martensite being formed in the heat affected zone, impairing properties and leading, in some cases, to cold cracking. The welding of these steels is not recommended but when it is unavoidable high preheat temperatures are used together with a post-weld heat treatment, which are impracticable in many cases.

Steels of similar carbon content have been extensively used in sheet form for rocket motor casings. In the hardened and tempered conditions these materials give strengths in excess of 80 ton/in^2 and, therefore, are of some interest in aircraft structures. In thicknesses below 1/8 in. conditions of cooling rate and restraint are insufficient to cause cold cracking and large quantities of these materials have been welded satisfactorily by the TIG process (Ref. 33).

A very successful development in both the U.S.A. and U.K. has been the controlled transformation stainless steels (Ref. 34) in which the steel is formed in the austenitic condition, transformed to a comparatively soft low carbon martensite and then further strengthened by a precipitation heat treatment. These steels in both bar and sheet form in the hardened condition give tensile strengths in the range 70 - 110 ton/in^2. Welding is generally carried out on material in the martensitic condition and the complete structure is age hardened at 450°C after welding which may limit certain applications. Joint strengths may be a little lower than parent metal strengths due to the presence of retained austenite in the heat affected zone; typical figures are given in Table III (Ref. 35). Maximum service temperature is about 500°C. A steel of this type was chosen for the Avro 730 supersonic bomber (a project which was cancelled in 1957) and has since been used in the wing and fuselage structures of Blue Steel. In the U.S.A. similar steels have been used for the Valkerie B-70 aircraft. Resistance spot, TIG spot and TIG butt welding have been used for Blue Steel and TIG butt welding for the B-70 (Ref. 36).

The 12 - 16% Cr martensitic stainless steels offer attractions of high strength but also have several disadvantages, including that of being virtually unweldable. Development of this type has led to a reduction in carbon content (to less than 0.1%) and the use of an age hardening treatment to increase the strength of the low carbon martensite (Ref. 37). In the fully hardened condition these steels offer tensile strengths greater than 60 t.s.i. (up to 120 t.s.i.) and can be used up to 400 - 500°C. These steels are weldable (Ref. 35) by the normal arc processes in the martensitic or overaged condition, so that post heat treatment at 550°C is needed to develop joint strength: joint strengths may range between 75% and 95% of parent metal strengths.

In the absence of carbon an addition of 18% nickel to iron gives an alloy which transforms from austenite to a soft ductile martensite offering an excellent base material for age hardening. Five maraging steels have been developed (Table V, Refs. 38 and 39), offering not only high tensile strengths in the hardened condition (90 - 140 t.s.i.) but excellent notch toughness, plus relatively easy forming in the unaged condition. Ageing is carried out above 450°C and these steels maintain high strengths up to 350°C. Welding does not offer any cracking problems and satisfactory results (Refs. 40 and 41) have been reported with the TIG, MIG, submerged arc, and shielded metal arc processes for a wide range of material thickness. The ageing process is sluggish so that welding does not produce an overaged region, and welding does not lead to problems of overaging. Welds may be produced in as-rolled, annealed or fully hardened steels. Some solution of precipitates does occur but properties can be restored to about 95% of the parent metals strength (Table VI) for most of the alloys by a simple ageing treatment (local or overall) (Ref. 42). The reason for this drop in strength is the formation of stable austenite which cannot be aged. The only solution is a complete heat treatment which is not always practicable. Even so, the examination of maraging steels in some aircraft applications has been reported recently (Ref. 40) although only in comparatively small amounts. Examples quoted are helicopter landing gear, an aircraft arrestor hook, rocket motor cases, and a landing gear tail wheel fork. The extent of welding in these components has not been reported.

HEAT TREATMENT

Despite the importance of heat treatment with so many aircraft alloys the amount of development work done on large furnaces suitable for the heat treatment of structures and sub-assemblies, has been very little. Present practice is to solution treat and age individual sheets and spars prior to fabrication. Ageing treatments have been carried out on larger sections after fabrication but even this has not found very much favour. The problems of preventing distortion in large thin walled structures and of maintaining the temperature of a large volume are recognised but are not considered to be insuperable. The pressure vessel industry has shown that it is possible to stress relieve (at 550 - 650°C) very large vessels up to 60 ft. diameter on site, whilst rather smaller electro-slag welded steel structures have been normalised (at 880°C - 920°C). In the aerospace industry the Altamil Corporation uses (Ref. 43) a controlled atmosphere furnace for aircraft and missile parts which has working dimensions of 8 ft. diameter x 5½ ft. high, and is controllable in two ranges up to 566°C and 1149°C.

THE DESIGNER'S PROBLEMS

Traditionally with wooden and aluminium aircraft structures the joints have been made by glueing, riveting and bolting and any change to welded joints is not just a straightforward alternative, as the welded joint requires a higher degree of design skill, if it is to work successfully. It is necessary to explain why a new philosophy is required for welded joints in contrast to the alternatives.

When a joint is designed for riveting or bolting, there is rarely any problem with the suitability of the material or materials to be joined and the connection is defined for the material by a hole drilled to a given size and tolerance in each piece to be connected and nothing more. Subsequently there must be a decision on the quality and size of rivet or bolt, tolerances on assembly and the method of fitting the rivet or bolt. The drilling of the hole may present difficulties for certain materials, but, in general, it is a simple matter for the usual aircraft structural materials.

The designer has freedom to join different materials and to choose rivets or bolts of a strength appropriate to the duty in service. There are restrictions on the location of rivets or bolts near the edge of sheeting, there is a loss of area in the sheet or plate being joined and connections must be lapped not butted with the rivet or bolt preferably in shear rather than tension or bending. Further there can be difficulties, when the designer's concept of the ideal riveted or bolted joint is not achieved due to an accumulation of manufacturing difficulties.

By strict enforcement of quality control during manufacture and inspection afterwards the riveted or bolted joint will usually meet the designers requirements with a statistically sound degree of success. The designer relies upon the rivet or bolt manufacturers to provide products of sound quality and for the workshops to ensure the highest standards in the assembly shops.

If the aircraft designer is aiming at structural perfection, defined by a maximum strength to weight ratio, the riveted or bolted joint could be excluded on at least three counts; the necessity for drilling a load bearing member giving a reduction in cross-sectional area, the associated stress concentration and the burden of extra weight due to rivet or bolt heads. The welded joint allows the designer to eliminate the three sources of difficulty which have just been mentioned, but there is now the effect of the weld thermal cycle on the material to be joined and the stress concentrations due to the weld. Immediately the weld is introduced into the fabrication, there is a significant metallurgical discontinuity, the possibility of external and internal stress concentrations and the presence of residual stresses whose magnitude can be as high as the yield stress of the weld metal depending on the restraint conditions during cooling.

Where there is a metallurgical discontinuity, the designer will be interested in the variation of material properties and this means that the fracture toughness, the stress-strain curves and other properties for the various regions of the welded joint will not be the same. The modulus of elasticity is consistent across the joint, but the yield or proof stress and the ultimate tensile stress will vary. For mild steel the yield stress of the weld metal can be fifty per cent greater than the yield stress for the parent plate and there is a reduction of ductility in the welded zone. In contrast, for aluminium alloys which are locally weakened by annealing in the heat affected zone, on loading the initial plastic straining will occur in the annealed zone. The value of the tensile test specimen from a trial welded joint is now apparent: the weakest and hence the critical cross-section of the joint is revealed.

The stress concentrations of the welded joint can be conveniently classified under two headings, external due to discontinuities at the surface and internal due to faults within the welded joint and the material adjacent to the joint.

The external stress concentrations are due to changes in surface profile at the welded joint and include the reinforcement, retained backing strips, lack of alignment either by displacement or rotation, change in thickness, weld spatter, restrike craters, undercut, overlaps, rippling on the surface of the weld metal, cracks at the surface and some post welding variables are incorrect grinding or machining and scratching or cracking or pitting in service.

Internal stress concentrations are generally caused by faults within the welded joint due to the limitations of control in the welding process and include porosity, cracking, lack of penetration, lack of fusion and inclusions. There may be a further problem with the material adjacent to the weld, where minor flaws may be magnified by the thermal effects associated with welding.

Before the further discontinuities due to residual stresses are examined, it is worth contrasting the increase in the number of variables in a welded joint in comparison with the variables in a riveted or bolted joint. It is not suggested that all or any of the variables will be significant at one time but neglect of any variable could be critical for particular loading conditions on the welded joint. There is a further complication in welding, because there is usually a higher degree of scatter for each type of significant stress concentration than would occur for a bolted or riveted joint, for example the distribution of porosity in a welded joint can occur in an infinite number of ways.

Residual stresses are present in all materials at all times, but they are usually so small in magnitude that they can be neglected in the design process. When a weld is introduced there is local heating and uneven cooling which lead to a complex field of residual stresses in the weld metal and the surrounding parent plate. These residual stresses form a self-balancing system of tensile and compressive stresses varying in three directions and can be as high as the yield stress of the weld metal.

The advance in the techniques of measurement of residual stresses is leading to a better understanding of the distribution of residual stresses and their influence on the performance of the welded structure. During fabrication residual stresses can buckle the material which is being welded. It is now appreciated that, where the welded material does not buckle, there may be a decrease in the reserve of strength against local buckling and the designer has two alternatives, to reduce the level of residual stresses by heat treatment or modification of his welding procedure, or to thicken the sections to be joined. Generally the latter choice would be unacceptable to the aircraft designer.

Stressing the Welded Joint

If the practice of the stress analysis of welded joints carried out in the 1930's (Refs. 44 and 45) is compared with the existing practice, two points stand out. There has been little advance in the analytical methods, although there are promising signs of a breakthrough on the behaviour of fillet welds (Ref. 46) and there is some indication that fracture mechanics (Ref. 47) is making a contribution to the understanding of brittle fracture. The second point is that the vast increase in the amount of experimental evidence on the behaviour of different types of welded joint with different types of loading and in a wide range of environments is enabling the designer to predict with a greater degree of certainty the performance of the joint in service.

Briefly there are three basic types of welded joint, butt, fillet and spot welded, Fig. 3 which occur in many forms other than those which are illustrated. For static loading analysis can only be useful after the designer knows the properties of the weld metal, heat affected zones and parent plate. For butt welds if the parent plate is the weakest of the three, failure will occur there and the introduction of the welded joint can be neglected in the stressing. Where failure occurs in the weld metal or parent plate, the designer must rely on test data for the welded joint.

For fillet welds analysis for static loading is still based on the evidence of tests. Another factor which is significant in the assessment of the reliability of the fillet weld is quality control during manufacture. The development of nondestructive techniques of inspection has not reached the stage, where the quality of the fillet weld can be guaranteed especially at the root of the weld which is inaccessible. With no guarantee of full penetration and weld metal free of cracks at the root the fillet weld must be suspect as a load carrying joint for critical service conditions: process control can minimise these problems, but it will not eliminate them.

Spot welds present as many stressing problems as fillet welds, when they are used in load carrying joints. The designer has to rely largely on test data of similar welded joints, process control and inspection techniques and, although the advances in the latter two fields have been substantial in the last decade, it could well be argued that the spot welded joint is on a statistical basis less reliable than the riveted or bolted joint.

For fatigue behaviour the need for testing is common to riveted, bolted, glued and welded structures. In the design of mild and low alloy steel girder bridges (Ref. 48, there is some guidance on the order of merit of different types of riveted, bolted and welded joints and, whilst the test results are, in general, of little quantitative interest to the aircraft designer this merit table giving seven groups of joints in descending order of fatigue strength is indicative of good practice in the design of welded joints to resist fatigue loading.

Effect of Welding on Aircraft Structures

For the purpose of presenting certain arguments let it be supposed that an aircraft fuselage is to be made not by riveting or bolting but by welding alone from materials which require similar heat treatment. It is assumed that the development of welding processes has enabled a concentrated heat source such as electron beam welding to be used as a precision machine tool with welding distortion minimised.

Quality control cannot be assured during the welding process and it would be necessary, subject to experience, to inspect non-destructively for internal soundness by radiography, ultrasonic methods and to examine for surface cracking. In this respect the inspection would be more thorough than that used for riveting or bolting.

Heat treatment of the completed fabrication could be applied for the reduction of the level of residual stresses which could lead to premature local buckling and to achieve desirable metallurgical changes. The heat treatment of complex fabrications of relatively slender components, and in particular the necessary accuracy of control of furnaces, both raise many problems which have received little attention from research workers. Pressurisation during heat treatment to stretch the fabrication against a jig might be a useful technique. After heat treatment it would be necessary to repeat the inspection process for cracking.

The designer, with the fabrication and inspection of the complete component, has performance problems to resolve to consider its characteristics in respect of damping and fatigue.

There is no doubt that damping of vibrational energy will be less in an all welded structure than in a riveted structure, but it is most unlikely that this reduction in damping is of any significance in comparison with the total aerodynamic damping. There should be a marginal increase in stiffness for the welded over the riveted or bolted structure.

Fatigue cracking could arise from loading due to airfield and flying conditions or from acoustic sources. Fatigue failures for the latter are usually associated with panels cracking away from the joints, and the joining techniques therefore would not be of primary importance. The more usual forms of fatigue cracking would present the designer of the welded structure with some severe problems. The joints in riveted or bolted structures can be used as crack arresters, but the continuity of the welded structure implies large areas into which the fatigue cracks can propagate and it has to be decided whether or not the change to welding offers more chance of a catastrophic failure in an aircraft structure. On the other hand, welded joints do not present the sites for fretting damage which are an unavoidable feature of riveted and bolted assemblies.

The introduction (Refs. 49 and 50) of compressive residual stresses in critical areas by overstraining, pressing, local heating, shot and hammer peening have proved beneficial in the improvement of fatigue performance of a wide range of welded steel joints. Taking into account all types and directions of loading it might be possible to introduce compressive residual stresses in the appropriate parts of a welded aircraft structure.

FUTURE TRENDS

The last few years have seen the development of new alloys, new welding processes and, less spectacular but equally worthwhile, great improvements in control and handling (Refs. 51, 52 and 53). Further improvements will undoubtedly occur, but the immediate need is the introduction of these new materials, processes and controls to production. It is interesting to note that in 1963 the Aerospace Industries Association of America forecast (Ref. 54) that the use of welding would double between 1962 and 1972 whereas the use of mechanical fastenings would be halved. The figures given were:

1962	60% mechanical fastening;	30% welding;	10% brazing and adhesives
1972	30% mechanical fastening;	60% welding;	10% brazing and adhesives.

Unfortunately a further breakdown of the use of welding in various parts of aircraft structures was not attempted.

The new alloys that have recently been developed show a much better response to welding than the older heat treatable light alloys: this is partly due to an increased recognition of the importance of welding influencing alloy development. However, most of the new high strength alloys still depend on precipitation hardening although the response to thermal cycling may be less critical, and resistance to hot cracking may be very good. Thus the necessity for heat treatment after welding will remain.

The newer welding processes offer exciting possibilities but further work is needed on the properties of the joints produced. Electron beam welding is obviously a favourite with the American aerospace industry (Ref. 55) but the authors feel that the possibility of explosive forming and welding in one operation would repay investigation. The inert gas chielded processes are already important in the industry and pulse-arc welding offers improved control. In fact the question of close control of the welding variables and of jigging is perhaps the most important that faces the welding industry. At present automatic welding equipment is regarded as a novelty: in the future it must be commonplace. The fully automated welding machine is a machine tool: it costs as much as other machine tools and must be just as accurate.

Further development in non-destructive testing techniques and quality control is also needed. The position is reasonably satisfactory for butt welds but much less so for fillet welds and resistance welds.

CONCLUSIONS

In the field of aircraft constructed largely from light alloys, the authors feel that any great extension of welding is unlikely. The weldability of the high strength alloys is poor and although riveted structures are not perfect, considerable information is available on their service performance. A greater use of welding would be possible if the medium strength of the weldable aluminium-zinc-magnesium alloys could be accepted. Even in subsonic aircraft, however, the use of maraging, or controlled transformation, steels for undercarriages would be attractive and welding could further increase the weight advantage.

With high speed aircraft, where titanium alloys and steels replace aluminium alloys, the future for welding is more promising. Welding is feasible and reliable for most alloys, giving joint efficiencies between 85% and 100%. To obtain the best fatigue performance careful dressing of welds will be necessary but this should present no great problem.

The need to maintain a high uniformity of weld performance will lead to fully automatic equipment in which the skill of operators will play no part. A few fully automatic machines are already in operation but much wider use will be necessary.

Heat treatment after welding to obtain optimum properties cannot be avoided and the development of techniques for the heat treatment of large components is essential. The main problem will be uniformity of temperature within the heat treatment furnace and the prevention of distortion.

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TABLE 1

Major divisions of Welding Processes

GROUP	CHARACTERISTICS	COMMENTS
1	Fusion of both workpieces	Heat source must create highly localised, high temperature region. High rate of heat input therefore required if fusion is to occur over a limited area.
2	Fusion of filler between solid workpieces	Heating required over a wide area; rate of heating not so important.
3	No fusion	Workpieces solid, no filler required. Bonding may occur at any temperature up to the solidus of the parent metal.

TABLE II: JOINT PROPERTIES OF TIG WELDED BUTT JOINTS IN AL-ZN-MG ALLOYS

Alloy Composition		Joint Properties		
% Zn	% Mg	As welded and aged for 20 days at 20°C.		
		Elastic Limit tons/in.^{2}	Maximum Stress tons/in.^{2}	Elongation %
3.5	2	12	18	12
3.5	3	13	20	10
3.5	4	14	21	9
4	2	13	20	11
4	3	14	21	9
4	4	15	23	9
5	2	15	22	9
5	3	15	23	8
5	4	16	24	6

TABLE II: JOINT PROPERTIES OF TIG WELDED BUTT JOINTS IN AL-ZN-MG

Alloy Composition		Joint Properties		
		As welded, aged for 24 hrs at 100°C + 24 hrs at 120°C		
% Zn	% Mg	Elastic Limit tons/in.^{2}	Maximum stress tons/in.^{2}	Elongation %
3.5	2	18	22	7
3.5	3	19	23	6
3.5	4	19	24	6
4	2	19	23	6
4	3	20	25	5
4	4	22	26	4
5	2	22	26	6
5	3	21	26	5
5	4	22	28	5

TABLE II: JOINT PROPERTIES OF TIG WELDED BUTT JOINTS IN AL-ZN-MG

Alloy Composition		Joint Properties		
% Zn	% Mg	As welded, solution treated 1 hr. at 465°C, water quenched, aged 24 hrs at 100°C + 24 hrs at 120°C		
		Elastic Limit tons/in.^{2}	Maximum Stress tons/in.^{2}	Elongation %
3.5	2	19	23	8
3.5	3	21	25	8
3.5	4	22	28	7
4	2	21	25	7
4	3	25	29	7
4	4	26	32	5
5	2	26	29	4
5	3	28	31	2
5	4	29	31	1

TABLE III : TYPICAL JOINT PROPERTIES FOR TIG BUTT WELDS IN A CONTROLLED TRANSFORMATION STAINLESS STEEL (FV520S)

Sheet Thickness ins.	Treatment	0.2% Proof Stress ton/in.^{2}	Maximum Stress ton/in.^{2}	Elongation %	Vickers Hardness No.
0.067	1050°C, Air Cool; 2 hrs at 750°C, Air Cool; ½ hr. at 550°C, Air Cool.	66.2	68.5	12	366
	1050°C, Air Cool, 2 hrs at 750°C, Air Cool; Weld; 2 hrs at 750°C, Air Cool; ½ hr at 550°C, Air Cool.	66.4	68.8	9	366
0.037	Unwelded, as above	61.7	65.6	11	362
	Welded as above	63.0	65.9	8	360

TABLE IV THE MARAGING STEELS

Alloy	18% Ni-Co-Mo			
	90 ton/in.^{2} P.S.	110 ton/in.^{2} P.S.		125 ton/in.^{2} P.S.
% Ni	17 - 19	17 - 19		18 - 19
% Co	8 - 9	7 - 8.5		8.5 - 9.5
% Mo	3.0 - 3.5	4.6 - 5.1		4.7 - 5.2
% Ti	0.15 - 0.25	0.3 - 0.5		0.5 - 0.7
% Al	0.05 - 0.15	0.05 - 0.15		0.05 - 0.15
% Nb	-	-		-
Production Method	Air Melted	Air Melted	Vacuum Melted	Vacuum Melted
0.2% Proof Stress ton/in.^{2}	85 - 94	104 - 118	104 - 118	132 - 136
Maximum Stress ton/in.^{2}	89 - 98	107 - 122	107 - 122	134 - 138
Elongation, %	14 - 16	10 - 12	10 - 12	12
Reduction of Area, %	65 - 70	45 - 60	50 - 60	60

TABLE V TYPICAL JOINT PROPERTIES FOR WELDS IN ½ INCH THICK 18% NICKEL (110 ton/in.^{2} P.S.) MARAGING STEEL IN THE FULLY AGED CONDITION

	As Welded	As Welded Aged 3 hrs at 480°C
0.2% Proof Stress, ton/in.^{2}	60	98
Maximum Stress, ton/in.^{2}	69	105
Elongation,	5	7
Reducation of Area, %	40	30

FIG.1 REGIONS IN A BUT WELDED JOINT
(a) ARC BUTT WELD
(b) RESISTANCE SPOT WELD

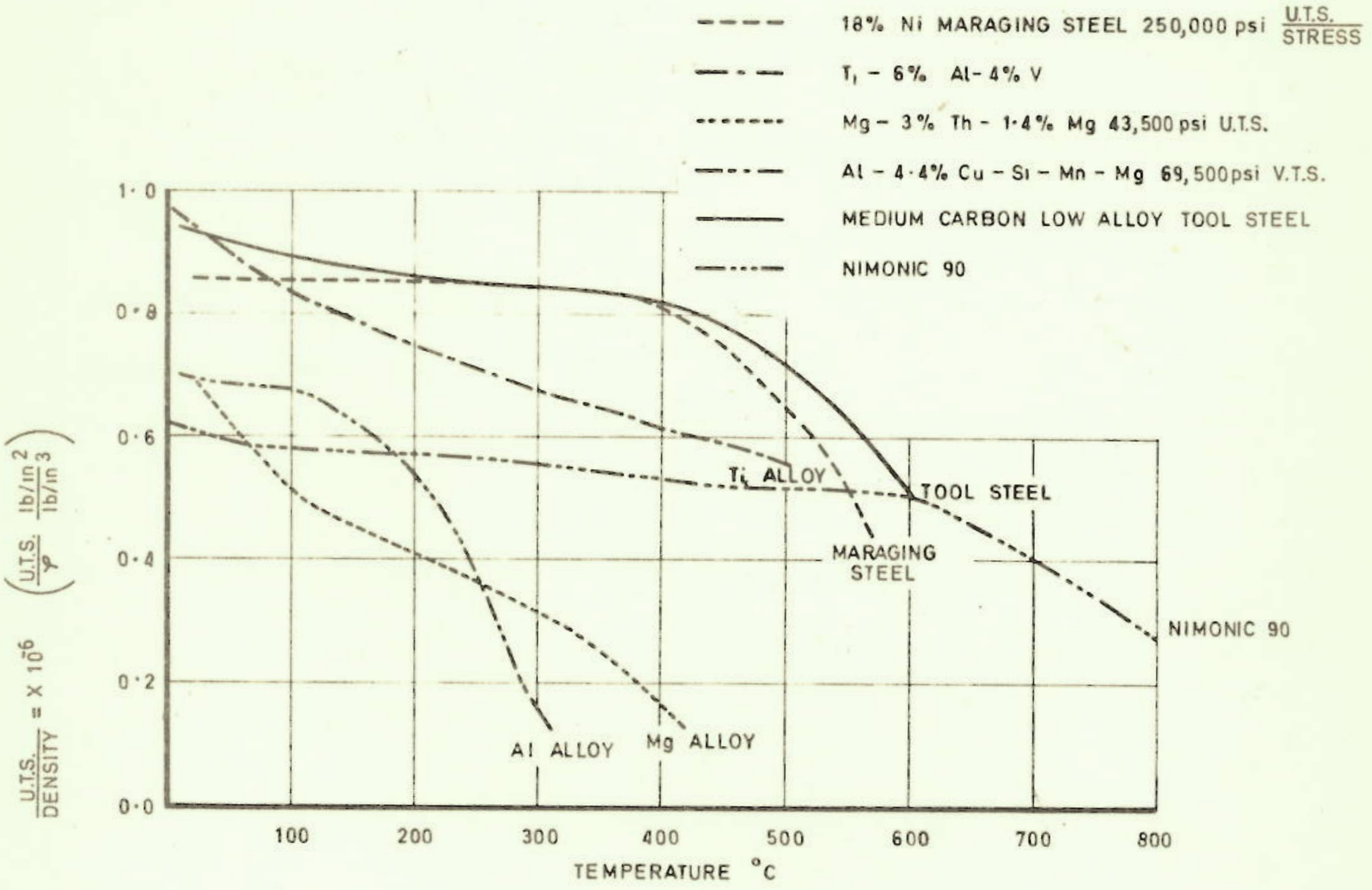
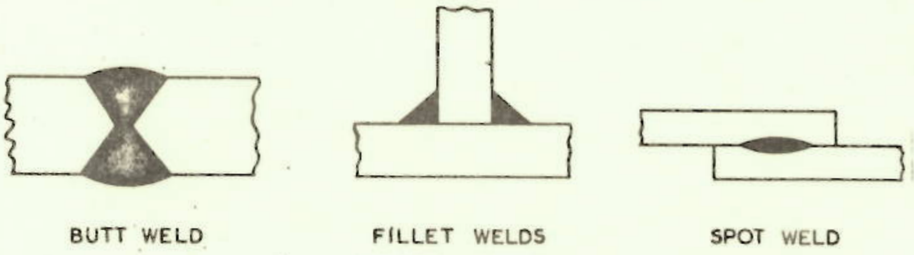


FIG. 2. VARIATION OF STRENGTH TO WEIGHT RATIO WITH TEMPERATURE



BUTT WELD

FILLET WELDS

SPOT WELD

FIG. 3. TYPICAL WELDED CONNECTIONS