Metal Joining

Developments in Metal Joining Techniques

Perhaps because joining or welding is considered a construction technique of long standing, it is viewed by many as a primitive science, if not a black art. Nothing could be further from the truth. In the last 20 years, welding has evolved as an interdisciplinary activity requiring synthesis of knowledge from various basic and applied sciences. Diverse disciplines such as arc and plasma physics, materials science, thermodynamics, high temperature chemistry, transport phenomena, mathematical modelling etc. are currently making new contributions.

Of course, joining nowadays encompasses more than just welding. A joint, is defined as "a junction of two or more parts or objects". In the construction sense these may be metallic or non metallic parts or objects and in an assembly the designer or engineer immediately becomes concerned with the strength or toughness of the joint produced and its stability, in terms of maintaining these characteristics.

The basic manufacturing, joining processes have moved on from the old blacksmiths' techniques which utilised early forms of diffusion bonding, and brazing. Currently the older thermal processes, for example, arc welding, brazing, diffusion bonding and soldering are being supplemented by non-thermal processes such as friction welding, adhesive bonding, utilisation of explosive energy, and even intensive magnetic fields or riveting for example.

One of the main tasks of a modern materials scientist is the development of reliable and efficient processes to make suitable joints in a range of materials and material combinations. This involves joining a variety of similar and dissimilar structural metallic and non-metallic materials and proving that the joints developed are reproducible and have the strength, integrity and stability to meet the requirements of the application, for the required time in the appropriate environment. This is equally true whether the joints, in an aircraft for example, have to survive many take-off and landing sequences with thousands of miles of transatlantic flight in between or the many and varied scenarios to which assemblies of interest to AWE are, or are likely to be, subjected. In the latter case, the work is carried out by a small team known as the Joining Development Section in the Materials Science Research Division and this article describes some of the joining techniques which are used and are being further developed.

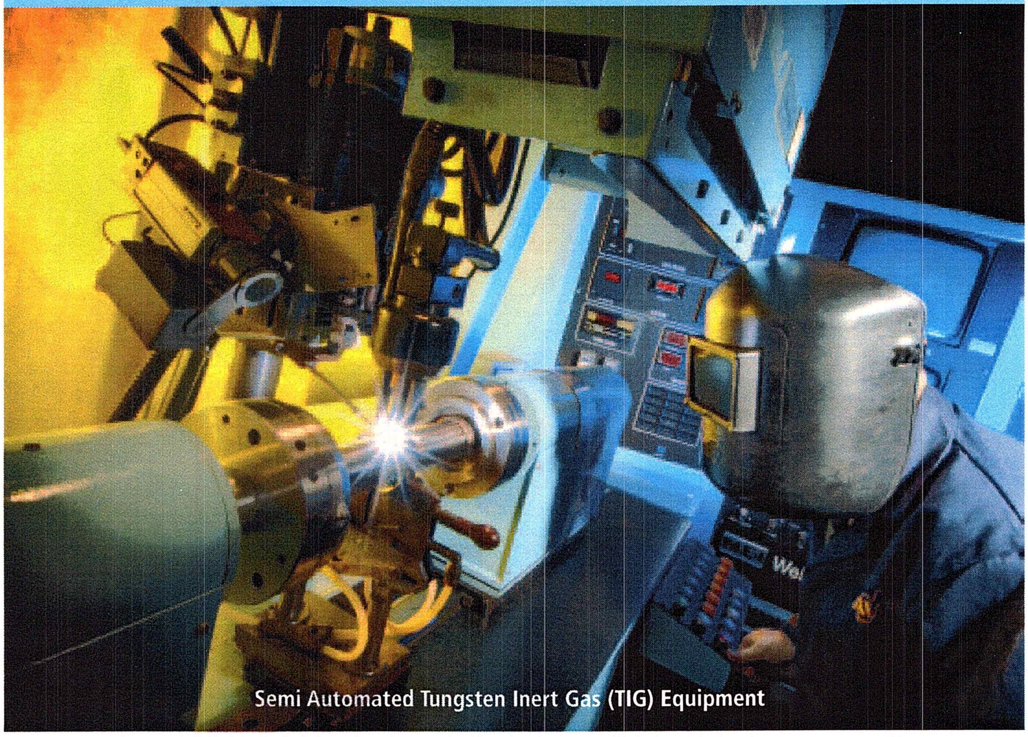
The fundamental development and understanding of joining processes generally arises from the desire to use a new material or combination of materials in a particular application or to overcome problems arising during the use of a particular process. Joining development at AWE is no exception, being driven by the material or material combinations, the application requirements, or the process chosen to fulfill the engineering and assembly requirements. For example, variable depth of penetration during the tungsten inert gas (TIG) welding (see Figure 1), of different batches of a commercial material with composition within a given prescribed range has caused many problems in the past and has received considerable attention. Work has shown that knowledge of the interfacial phenomena in welding is the key to understanding and controlling weld penetration. This leads to a need to understand the many factors determining the integrity of the resultant joint with a view to improving joint life and characteristics.

Applications/Material Drivers

The joining development team at AWE supports engineers in the design and build of trial devices. This requires an expertise and capability over a broad range of joining techniques. Given appropriate equipment, the joining challenges arise from the requirements of the physicists, interpreted by design engineers, predicated on the use of materials which are generally difficult to join. This is exacerbated by the need to maintain tight tolerances on often small, high precision and high integrity components.

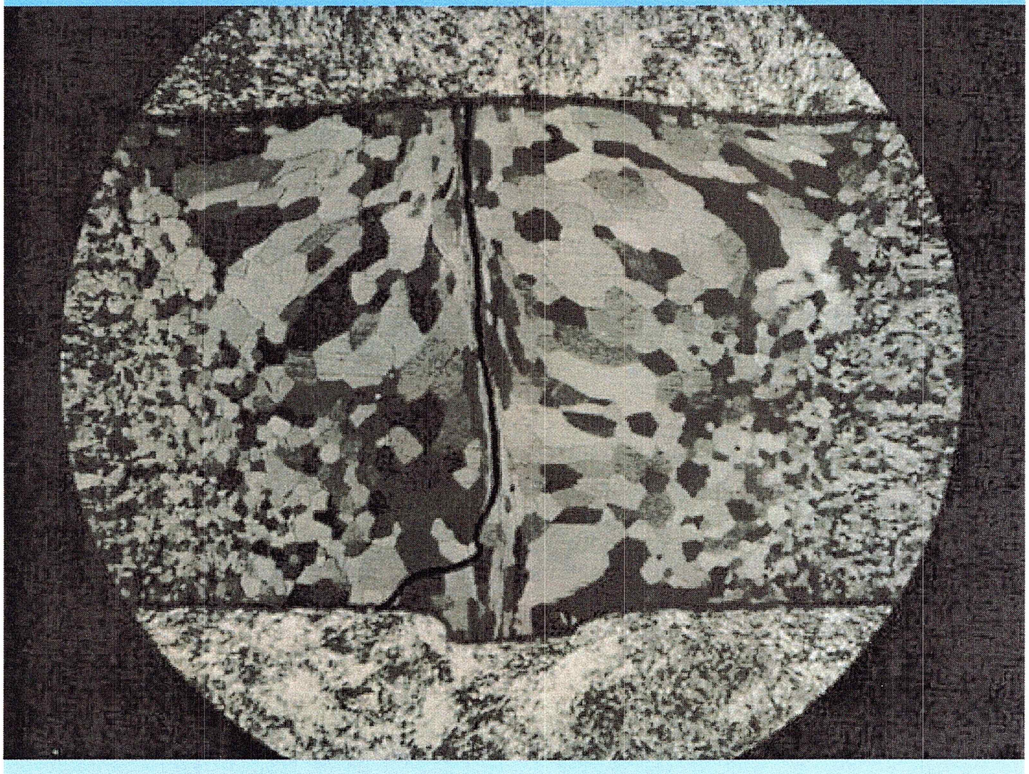
Our interest covers materials such as beryllium and uranium, refractory/high temperature metals and more conventional materials such as stainless steel and titanium. The Joining Development Section must have the capability and expertise to join all these materials. However, the combination of metallurgical and physical characteristics of beryllium makes this material a particular challenge, when joining either to itself or other metals is required. It seems appropriate therefore

Figure 1



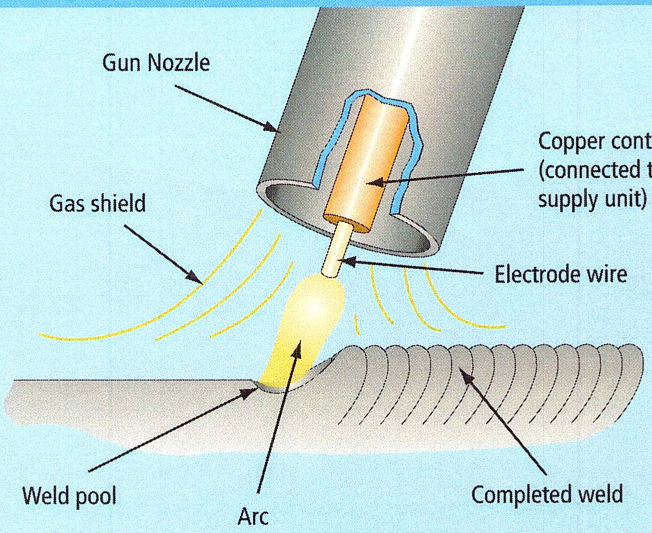
Semi Automated Tungsten Inert Gas (TIG) Equipment

Figure 2



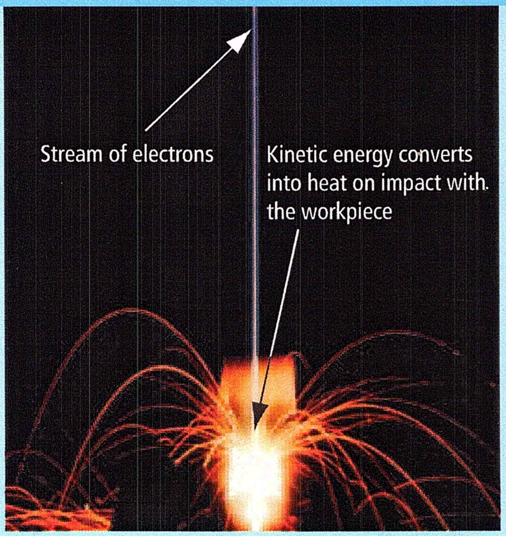
Photomicrograph of Typical Grain Boundary Fracture Path in Be. Magnification 25X[1]

Figure 3

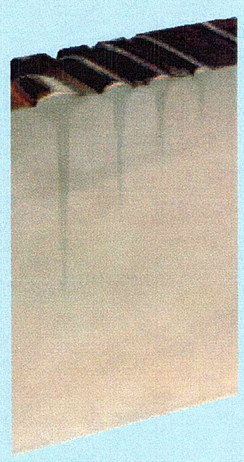


Schematic Metal Inert Gas (MIG) Torch and Weld Bead

Figure 4



Typicle EB Weld Profiles



AWE Equipment:	2 x Leybold/PTR Welders	
	Power	-150 KV/50 mA
	Vacuum Chamber Size	-1 m^3
	Control	-PLC/CNC
Applicable to:	Wide range of metals and alloys	
Advantages:	Deep, narrow single pass welds	
	Low heat input minimising stress and distortion	
	Wide penetration range	
	Good reproducibility	

Electron Beam Welding: Welding by a high energy beam of electrons generated under vacuum conditions from a tungsten filament and focussed onto the workpiece within a vacuum chamber.

Electron Beam, Material Interaction

to base this review of joining advances around the problems associated with joining beryllium and the developments undertaken to address these challenges.

Beryllium

Beryllium has been used mainly in the nuclear and aerospace industries where a unique combination of physical and mechanical properties makes it an attractive metal for a variety of applications. It has a high elastic modulus, low density and a high strength-to-weight ratio. For example, it has a density similar to magnesium and approximately 70% that of aluminium, with a modulus of elasticity approximately four times greater than either. It also has a high melting point (1278 °C), high thermal conductivity and low thermal expansion giving good dimensional stability.

Beryllium can, therefore, provide a lightweight, stiff, structure, very useful, for example in aerospace structures or instrument platforms. Its low density makes it suitable for X-ray windows. It also exhibits low thermal neutron and X ray absorption plus excellent neutron reflection properties which make beryllium particularly attractive for nuclear applications.

The crystal structure of beryllium, however, results in an inherently low ductility. The hexagonal close packed structure provides a very limited number of active slip systems along which the metal atoms can easily move to accommodate plastic deformation. In a polycrystalline material, if a grain is to remain joined to its neighbours it must be able to change its shape arbitrarily, which leads to a condition that for polycrystalline plasticity, grains must possess at least 5 independent slip systems. In hexagonal closed packed crystals this causes real difficulty because the number of independent glide systems with low critical resolved shear stresses is usually too small to satisfy this condition.

The use of beryllium has been restricted by significant disadvantages such as toxicity, low ductility and crack susceptibility. High cost and joining difficulties have further limited commercial utilisation of the metal.

Beryllium Joining

A major problem in the welding of beryllium is the low ductility and inherent high modulus of the material and, with very few metals having significant solid solubility in beryllium, alloying to enable modification of these properties is very limited. The brittleness of the basic material is exacerbated by high thermal conductivity, which allows steep thermal gradients to form within the fusion zone of any weld and tends to cause growth of large directional grains. These can provide "planes of weakness" within the joint as is shown by the grain boundary cracking illustrated in Figure 2[1]. These steep thermal gradients, combined with the high modulus of the material, result in potentially high levels of residual stress around the joint, all of which tend to promote a tendency for cracking in and around the joint.

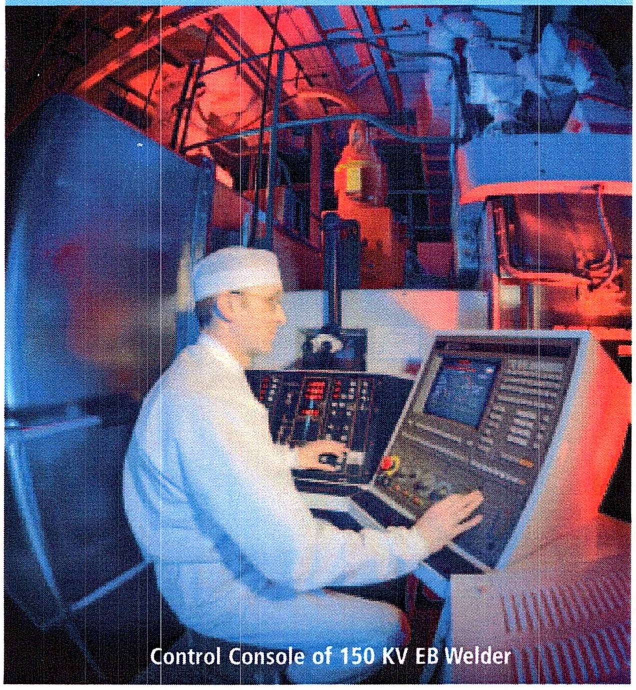
The presence of impurity elements can further increase the tendency for cracking and poor weldability and the low ductility means that very little energy is required to propagate a crack, once formed. However, careful choice of the welding process and variables can reduce or eliminate cracking, if the physical and metallurgical characteristics of the beryllium being joined have been optimised.

Beryllium Joining Options

Brazing and braze welding, using Metal Inert Gas (MIG), shown schematically in Figure 3, are probably the most common techniques for joining beryllium, as the use of a ductile filler metal can produce joints with some ductility, when compared to the base material. However, the choice of filler metal is limited to avoid the formation of brittle intermetallic compounds. In addition the stable surface oxide on beryllium means joining operations must be performed in a vacuum or inert environment.

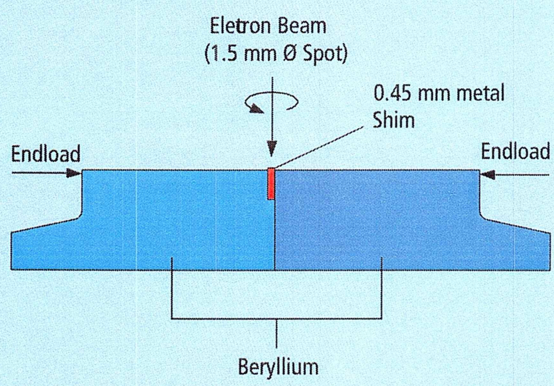
"One of the main tasks of a modern materials scientist is the development of reliable and efficient processes to make suitable joints in a range of materials and material combinations."

Figure 5



Control Console of 150 KV EB Welder

Figure 6



Joint design for an EB shim weld which is used on thinner section beryllium to improve build quality and reduce distortion.

For beryllium, MIG braze welding using a filler wire has been the main joining technique used over the past 30 years. However, the residual stresses arising during the application of this technique result in some distortion. Furthermore, low melting point eutectic alloy formed in the joint makes this an unsuitable route for manufacture of any units requiring a high temperature capability.

EB Shim

An electron beam technique, currently used for joining beryllium, is EB braze welding, (referred to as EB shim welding). This is illustrated in Figures 4 and 5. This process currently uses a shim interlayer preplaced in the joint shown schematically in Figure 6, which is melted, using an electron beam to alloy with the beryllium. As shown in Figure 7 a relatively narrow joint is produced with low heat input and consequently relatively low thermal stresses and distortion. With care, joints can be produced which are relatively ductile and with suitable joint design, strengths can be obtained which are similar to that of the parent metal.

During welding the shim material remains fluid long enough to backfill any microcracks. EB shim welding with filler metal has been succesfully employed on units which required relatively shallow joints. The metal content in the fusion zone directly affects the weld microstructure and crack susceptibility. The variation in composition of the fusion zone, with joint depth and the effect on joint microstructure and strength/cracking are areas for future study.

"The joining development team at AWE supports engineers in the design and build of trial devices. This requires an expertise and capability over a broad range of joining techniques."

The addition of much smaller quantities of metal in the joint, together with lower distortion, when compared to MIG braze welding, makes EB shim attractive but the eutectic temperature (645 °C) is prohibitive when high temperature applications are required. Improvements to the technique are currently being investigated, to reduce further any distortion arising during welding. Modification of the welding process, to distribute the heat of welding more evenly, is being evaluated to determine the effect on final distortion of the welded assembly. Although the length of weld cycle and thus total heat input to the assembly is increased, it is anticipated that the temporary temperature rise in adjoining materials will be acceptable.

Autogenous Welding

The capability to weld beryllium autogenously, i.e. without using a filler material, is particularly desirable. It would enable joined assemblies to meet higher temperature requirements.

The metallurgical problems associated with autogenously joining beryllium are primarily due to cracking caused by thermal stressing of the inherently low ductility beryllium and the effect of impurities in the metal. The potential for success with autogenous welding of beryllium was originally demonstrated by TIG welding. A limited programme of work was conducted at AWE during the 1980s to investigate the crack susceptibility of different grades of beryllium based on some earlier US work.

Various grades of beryllium were exposed to a thermal shock caused by applying a central TIG spot-weld to 6 mm thick x 50 mm diameter disc samples of beryllium. By examining the severity of cracking and monitoring acoustic emission, the weldability of the pressed powder beryllium could be assessed. This is a severe test with a high degree of constraint and with no preheat. Higher purity beryllium, derived from electrolytic flake, was least susceptible to cracking, generally showing no visible cracks, although hairline cracks were found in test pieces welded under maximum restraint. Acoustic emission recorded on all the tests indicated the majority of cracks occurred within a few seconds of completion of welding, although crack propagation could continue for up to a a factor of ten longer after welding had ceased. Recently, investigation into autogenous welding of beryllium has concentrated on power beam welding techniques.

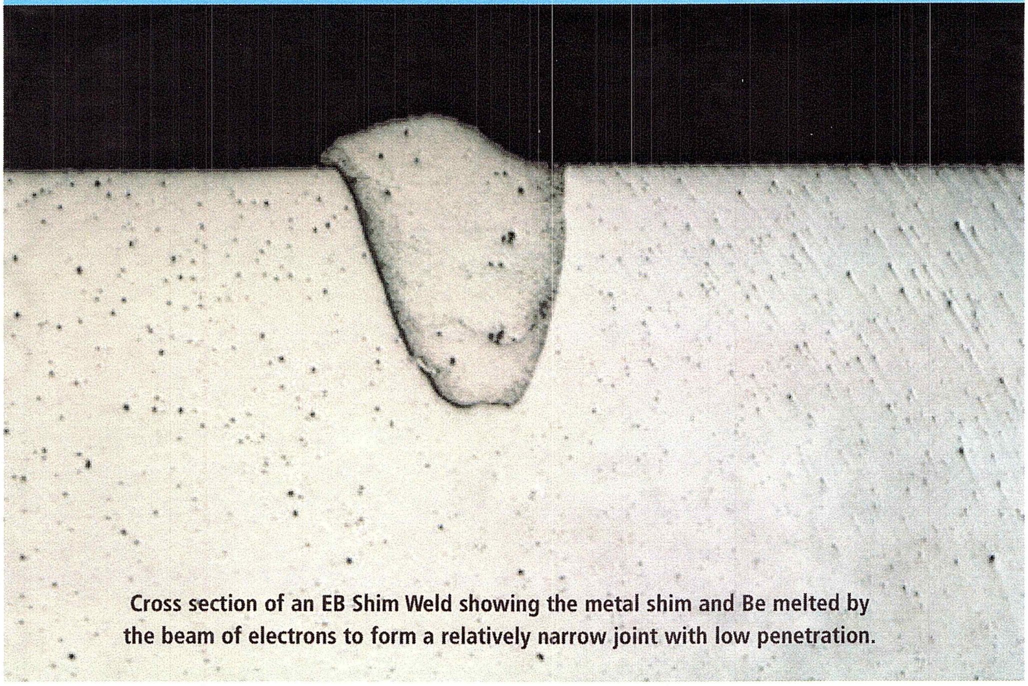
Power Beam Welding

Power beam welding techniques using lasers and electron beams, are potentially the most suitable for autogenously welding beryllium as both can produce narrow fusion zones, minimising heat input to the joint and thus minimising thermal stresses. A low heat input joining process may also be necessary if there are heat sensitive materials adjacent to the weld area in a multi-component assembly. Laser welding has the advantage of producing a lower and more controlled heat input by energy pulsing and successful autogenous welding of commercial grades of beryllium by laser is reported by Hanafee and Ramos[2]. However, early work on autogenous welding was conducted using EB welding because, at that time, this technique had a number of advantages when compared to the laser. For example, EB welds had a much higher depth to width ratio and narrow fusion and heat affected zones (HAZ), as a result of low heat input, thus reducing stress and distortion.

Development of laser welding techniques since then, has brought laser welding on a par with EB in these aspects. The available power with both EB and laser welding is such that a single pass weld is feasible. However, EB welding is, of necessity, conducted in a vacuum, preventing oxide formation in the weld and providing containment of the beryllium thereby reducing the toxicity hazard.

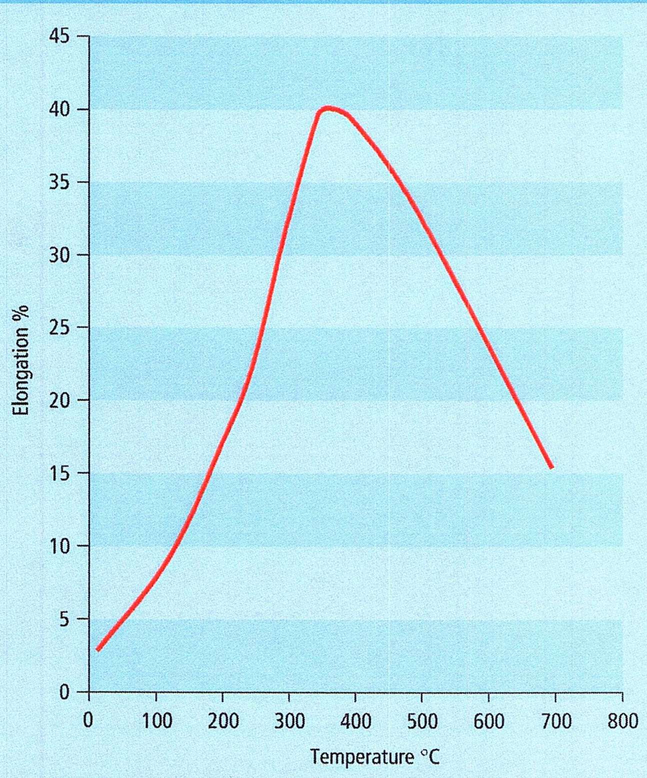
Investigations into autogenously joining beryllium by EB welding, have focused on two main areas, the properties and composition of the parent material and the welding process variables.

Figure 7



Cross section of an EB Shim Weld showing the metal shim and Be melted by the beam of electrons to form a relatively narrow joint with low penetration.

Figure 8



Elongation verses temperature curve for beryllium fabricated by Hot Isostatic Pressing Be Powder

Achieving successful autogenous welds is difficult but chances are improved by careful choice of the parent material. Reduction in beryllium oxide and minimising other impurities will reduce porosity, weld undercutting and associated cracking. Hot cracking susceptibility can be reduced by control of the Fe/Al content of the Be, and reduction of the base metal grain size will also aid weldability. Control of the welding variables may reduce the chances of weld cracking and the procedures should minimise heat input, grain growth and thermal stresses.

Preheat of the parent material prior to welding has been shown to promote weldability. Preheating both reduces the thermal gradients in the beryllium during welding and increases ductility. Figure 8 shows that maximum ductility is achieved between 300-400 °C with a typical hot pressed powder beryllium. Higher preheat temperatures result in a wider fusion zone of larger grain size, and more grain growth in the HAZ. In some cases post-weld heat treatment has improved ductility.

Welding speed, focus of the beam and beam manipulation affect energy input to the weld and have been found to influence the weld microstructure and HAZ significantly. A highly oriented columnar grain structure in the fusion zone tends to promote cracking along grain boundaries, as shown in Figure 2, and a tendency for undercutting and porosity also increases.

Centre line cracking is generally found to be the predominant failure mechanism and a means of modifying the fusion zone microstructure to promote a more random oriented fusion zone grain structure is being investigated. Smaller grains should improve joint properties and could maintain high temperature capabilities.

A reproducible and repeatable autogenous welding technique for beryllium has still to be developed and the parameters for achieving the best microstructure and mechanical properties in the weld zone have yet to be determined. A programme of work to undertake this is underway at AWE and crack free beads on plate welds on 3 mm thick plates have been achieved, as shown in Figures 9 & 10. Full evaluation of these welds is currently being carried out.

Diffusion Bonding

Diffusion bonding of beryllium to itself is possible and the development of suitable techniques has been stimulated by recent work on fusion reactor development where beryllium is considered a suitable material for the plasma-facing wall. Theoretically, it should also enable distortion free joining of metallic components, and would therefore be a very attractive technique, however, temperatures around 800 °C are required to bond beryllium to itself. To overcome this limitation, diffusion bonding using shim interlayers was investigated and more recently, silver coated beryllium surfaces have been evaluated.

Work at AWE in the early 1980s demonstrated good joint strengths, but there were reliability issues, which were attributed to difficulties with ensuring repeatable results with the silver coating applied by a field emission technique. With the availability of a superior coating facility, ion plating via a planar magnetron, the work was recently reinstated to investigate whether a lower bonding temperature could provide reliable and distortion free joints. There was also an intention to investigate the susceptibility of these joints to time-dependent failure due to the presence of residual stresses, although this was considered unlikely.

Initial results on simple test pieces were very encouraging, with parent metal strength achieved during tensile testing of simple rod specimens, i.e failure occurred away from the joint, see Figure 11. Whilst the practical problems associated with moving on to more representative test pieces have been overcome, initial results on these were disappointing and a metallographic evaluation is in hand to determine the causes.

Residual Stress

Residual stresses were identified as a major contributor to cracking in autogenous beryllium welds and to distortion in EB shim welds. However, the residual stresses arising as a direct result of heat input during welding and the expansion and subsequent contraction of relatively small volumes of metal in and around the fusion zone, can be a problem in any welded component. This is particularly true in small, tightly toleranced systems where the distortion caused by relaxation of residual stresses can completely swamp the dimensional tolerances.

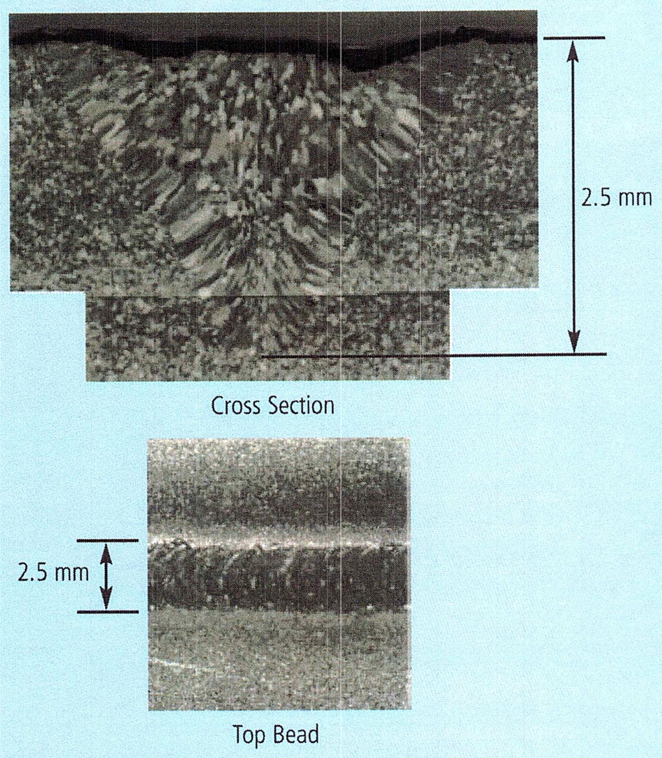
Modelling of heat input, temperature rise, expansion, contraction and constraint should enable the stresses generated to be calculated and with knowledge of the mechanical properties of the materials being modelled, it should be possible to determine the resulting distortion and residual stresses.

The Joining Development Section, in conjunction with The Welding Institute, is currently exploring the capability to model residual stresses, arising from electron beam welding, using the finite element code ABAQUS to solve problems ranging from relatively simple linear analyses, to more challenging nonlinear simulations. Of course there are a number of assumptions which have to be made, which build in uncertainties to the calculations and the model must be verified against practical results.

Initially this was carried out on stainless steel using thermocouple measurements during welding to determine temperature rise over an area adjacent to the weld for comparison with the model. Progress is also being made to develop a residual stress measurement capability at AWE, using a hole drilling technique,shown in Figure 12. This technique uses a fine, high speed steel drill to create small diameter holes in areas of interest, around which strain gauge arrays are placed to measure the relaxation of stresses.

The movement in the surrounding material can be measured incrementally with depth and used to calculate the corresponding stresses, which have been relieved by the creation of the free surface around the small diameter hole. This work is being developed on stainless steel to enable early comparison of the practical results with the model.

Figure 9

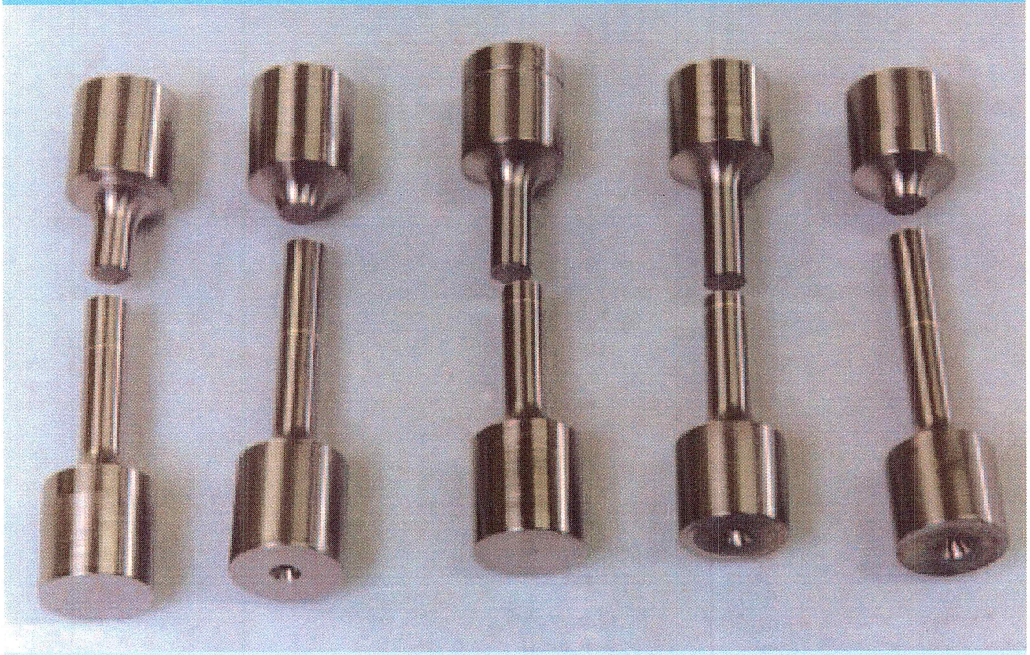


Electron Beam Autogenous Weld in Hot Pressed Beryllium

Figure 10

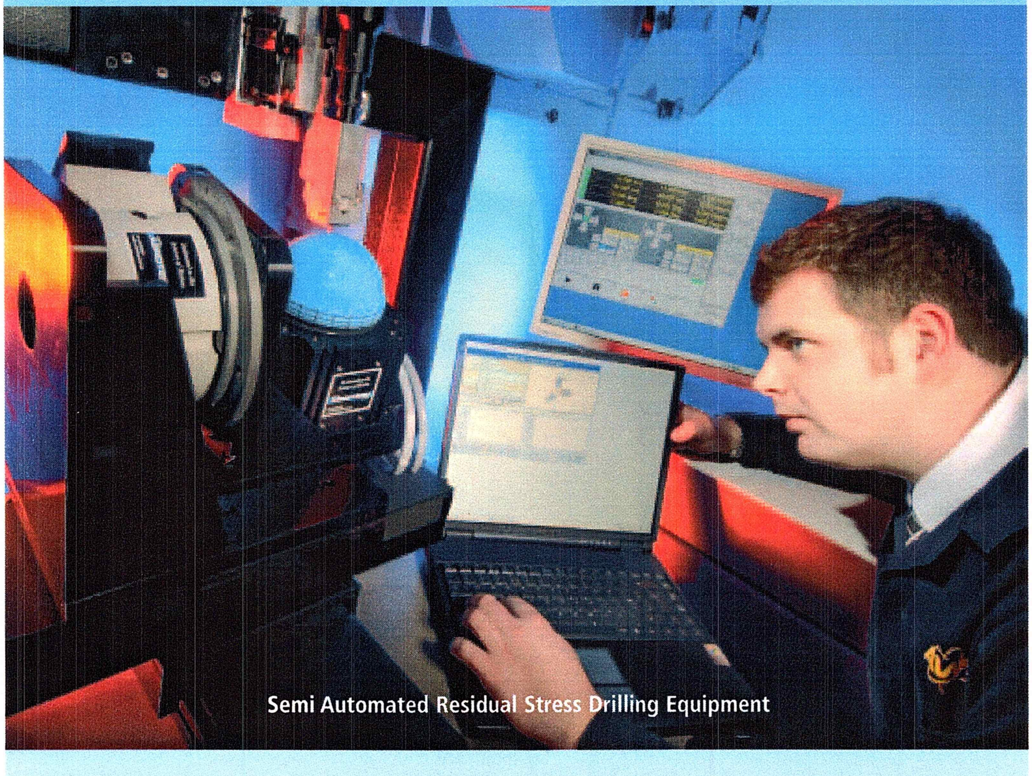
Jointed Beryllium Test Plates - Pre and Post Weld

Figure 11



Tensile Test specimens after testing to failure, showing brittle fracture through the beryllium, away from the diffusion bonded joint line.

Figure 12



Semi Automated Residual Stress Drilling Equipment

Brazing

With the exception of diffusion bonding, the techniques discussed have had the capability only for joining beryllium to beryllium. There are practical limitations on the use of diffusion bonding, for example, it may not be practical to design a system in such a way as to enable sufficient load to form a bond to be applied to the two components to be joined. Brazing can provide a more suitable technique in these circumstances and has been used successfully in the past to enable ancillary items to be joined to beryllium components. However, the very reactive nature of beryllium can result in the formation of a very stable surface oxide and brittle, intermetallic, compounds with very many metals unless precautions are taken.

A continuous oxide film will make brazing impossible and formation of a continuous brittle intermetallic compound in a brazed joint would render the joint brittle and of very low toughness.

These both make brazing of beryllium difficult, limiting the metals available to use as braze alloys and requiring precautions to be taken to assist in the breakdown and penetration of the oxide film and prevent reformation of the oxide.

These difficulties have been successfully overcome at AWE where brazing of beryllium to a nickel alloy is carried out under vacuum using a combination of materials such that the oxide layer is penetrated and reoxidation is prevented thus allowing the brazed joint to be formed.

The formation of a brittle intermetallic compound within the joint is limited to acceptable levels by minimising the time at brazing temperature. Work continues to broaden the range of alloys and braze temperatures, which can be used to repeatably produce strong brazed joints between beryllium and both itself and other metals/alloys.

The Future

Whilst much progress has been made in understanding welding processes and welded materials, several key problems and issues remain to be addressed. Modelling has provided significant insight into the dynamics of the welding processes and the properties of the welded materials.

This powerful tool has, however, been of only limited use to the engineer, because of the scarcity of relevant data and limited experimental validation. In view of the complexities of welding processes, theoretical calculations of welding variables must be tested by well designed experiments. In addition, reliable, science based correlation between the microstructure and properties of welds and models to predict such relationships are necessary for the development of the field.

Modelling of phase transformations and the resulting microstructure in weldments remains a great challenge. Another key issue is the development of residual stress and stress gradients due both to thermal effects and phase transformations encountered during joining. These can have implications for both performance and life. Integration of a fundamental understanding of the joining processes and knowledge of the evolution of microstructure and properties remain major challenges in the pursuit of intelligent process control to produce defect free, structurally sound and reliable joints.

By maintaining a broadly based Joining Development Section at AWE it has been possible to retain an awareness of advances in joining technology and develop these as appropriate for use in fabrication of components of interest to AWE. Implementation of such techniques has enabled problems to be overcome to meet required safety and security criteria and will enable us to meet future challenges. Complexity of design, the wide range of materials and tight tolerances give rise to challenges, in addition to those associated with some of the difficult to handle special materials used.

References:

1. J. E. Hanafee & T. J. Ramos, Energy and Technology Review, University of California, LLNL, (April 1995).

2. R. P. Campbell, R. D. Dixon, & A. L. Liby, Electron Beam Fusion Welding of Beryllium, RFP 2621, January, (1978).

Author Profile

Duncan can be contacted on e-mail: Duncan.Irvine@awe.co.uk

Duncan Irvine

Duncan was educated at Hulme Grammar School in Oldham, Lancashire. He moved south in 1971 to Surrey University where he gained a BSc(Hons) in Metallurgy and Materials Science in 1975 and followed this with a PhD in the Metallurgy of Brazed Joint Formation. He joined AWE in 1980, direct from Surrey University , initially in the General Metallurgy Section working on uranium. Within a couple of years Duncan transferred to the Joining Section where he worked on brazing techniques in support of Trident and underground nuclear tests. He has since worked on a range of joining techniques and is currently Team Leader of Joining Development. Whilst retaining this team leader role he has also had project responsibilities, managing the development of non-destructive evaluation techniques.