

HANDBOOK ON SOLDERING AND OTHER JOINING TECHNIQUES

IN GOLD JEWELLERY MANUFACTURE



WORLD GOLD COUNCIL

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PREFACE

This Handbook is the sixth in the range of technical publications published by World Gold Council. These are designed to assist the manufacturing jeweller and goldsmith to use the optimum technology and best practice in the production of jewellery, thereby improving quality of the product, reducing defects and process time which, in turn, results in lower costs of manufacture. We believe that it is important for the practising jeweller to understand the technology underpinning his or her materials and processes if he or she is to achieve consistent good quality. That is one aim of these Manuals and Handbooks - not only to provide good basic guidelines and procedures but to explain, in simple terms, why they are important and how they impact quality. Armed with such knowledge, a jeweller should be better able to solve problems that will inevitably arise from time to time.

Soldering is a joining process that features in virtually all jewellery manufacture, whether it be performed by skilled goldsmiths at the workbench or in a mass production factory. In the many technical seminars that we give around the world, soldering always features high on the agenda and results in many questions. Yet it is a process that we tend to take for granted. In my experience, much wasted time and effort results from poor soldering practice. How often do I find jewellers gold plating their jewellery to hide a colour mismatch of the solder and jewellery components that it joins? Or using lower carat solders in order to get a suitable melting range? And I have not even mentioned the use of cadmium-containing solders, which are still widespread in some countries! With today's knowledge, a good colour match in solders of the same caratage and cadmium-free is possible up to and including 22 carat. In addition, the modern welding techniques allow joining of even 24 carat gold jewellery, with no colour match and hallmarking problems.

Soldering in jewellery manufacture tends to be seen as a way of just 'sticking' parts together, rather than as something that has engineering requirements. Design and positioning of joints for maximum strength and performance of the jewellery is rarely contemplated. Yet there are instances, such as soldering of posts in earrings, where optimising the engineering strength of the joint is important. Hopefully, this Handbook will allow readers to consider this aspect more deeply.

Increasingly, we are seeing other joining techniques in jewellery manufacture, of which *in situ* laser welding of machine-made chain is a good example. Recognising this, this Handbook includes a chapter on other joining techniques.

It has given me great pleasure to work with Mark Grimwade in the production of this Handbook. Mark is well known to many of you as an expert in jewellery technology, having contributed several articles on 'Basic metallurgy for goldsmiths' to *Aurum* and *Gold Technology* magazines over the years and, as a technical consultant to World Gold Council, presenting many technical seminars in countries around the world. He is, of course, author of the book, 'An Introduction to Precious Metals', unfortunately now out of print. He has a gift in presenting technical information in an easily readable and understandable way that comes from his many years as a lecturer in metallurgy. I know that this Handbook will become a classic in the jewellery field and meets a hitherto unfulfilled demand for a good comprehensive and authoritative book on the subject. I know you will find it useful and enjoyable.

Christopher W. Corti, London, November 2001

GLOSSARY

Adhesive: A natural or synthetic polymer used to form strong chemical bonding between surfaces.

Alloy: A combination of two or more metals usually prepared by melting them together. They are designed to have certain desired properties, eg strength, hardness, ductility, colour, etc.

Annealing: Restoration of softness and ductility to metals and alloys after cold working by heating to a temperature that promotes recrystallisation.

Arc-eye: A painful gritty sensation round the eyeball overexposed to intensive radiation from an arc or high temperature flame. Prevent by wearing the recommended goggles.

Assay: The analysis of items to determine their precious metal content.

Base metal: A metal other than gold, silver and the platinum group metals (the precious metals). Usually present in carat golds as an alloying constituent(s).

Binder: An organic carrying medium, stable at ambient temperatures, which holds the solder powder in suspension in a solder paste until heated to the soldering temperature. It does not chemically react with the solder powder.

Brazing: An engineering term for hard soldering at temperatures above 450°C. Strictly, it is the process by which carat gold alloys are joined with an appropriate filler metal at elevated temperature but the jewellery industry tends to still refer to this as soldering.

Capillary attraction (flow): The means by which molten solder is drawn into the joint gap.

Carat, caratage: A measure of the fineness of gold. Pure gold is 24 carat or 100% pure (1000 parts fine). 18 carat gold means that $18/24 = 75\%$ or 750 fineness of gold content, 14 carat is $14/24 = 58.33\%$ gold, 9 carat is $9/24 = 37.5\%$ gold, etc.

Chainmaking: Chain is made by hand or produced by machine from spools of wire. Usually the links have to be joined either by soldering or welding to provide strong chain.

Colour: Carat gold alloys may be referred to by their colour as well as caratage, eg 18 carat yellow, pink, red or white. The colour can be assessed using the international standard ISO 8654 or by quantitatively measuring the colour co-ordinates using the CIELAB System.

Diffusion bonding (soldering): A bond formed by the migration (diffusion) of atoms across the interface between two surfaces. If a filler metal in the form of a foil is placed between the surfaces and transient melting occurs, the term diffusion soldering may be applied.

Dry (cold) joint: An imperfect joint caused by lack of penetration of or wetting by solder.

Electrolyte: A chemical solution capable of transmitting an electric current between two electrodes, an anode and a cathode. The solution consists of metal and non-metal or complex ions. In electroplating and electroforming the metal ions are deposited on the article that is made the cathode.

Fillet: A narrow band of filler metal around the outside of joints made between parts at an angle to each other.

Findings: Commercially made components for jewellery assembly, eg catches, clasps, ear posts, hooks, pins, etc.

Fineness: Precious metal content expressed in parts per thousand by weight, eg 22 carat is 917 fineness.

Flow point: The temperature at which molten solder will flow into a joint. It may be a few degrees above the liquidus temperature for the alloy.

Fluidity: The ability of a molten alloy to flow into a joint gap and form smooth rounded fillets at the edges.

Flux: A chemical substance that melts at a lower temperature than a solder alloy and which cleans the joint surfaces and protects them against further oxidation, thereby assisting with wetting by the solder.

Fuel gas:oxygen ratio: The ratio that determines whether a torch flame or furnace atmosphere is reducing, neutral or oxidising. For example, for the reaction $2\text{H}_2 + \text{O}_2 = 2\text{H}_2\text{O}$ where hydrogen (H_2) is the fuel gas, a ratio of hydrogen:oxygen of 2 gives complete combustion and the flame or atmosphere is neutral; a lower ratio gives an oxidising flame; a higher ratio gives a reducing flame.

Grain size: The average size of grains or crystals that make up the polycrystalline structure of metals and alloys. Grain size influences the mechanical properties.

Grain refinement: Small additions of a nucleating agent to promote a small grain size and inhibit grain growth.

Granulation: The decoration of a surface of jewellery by attaching small rounded granules by fusion. This may be achieved by diffusion bonding, laser beam welding or soldering.

Hallmarking: The stamping of precious metal articles by an independent assay office to show the fineness of that article.

Heat treatment: A treatment given to metals and alloys, involving a combination of temperature, time, heating and cooling, to effect a change in microstructure and mechanical properties.

Jeweller's rouge: A polishing medium based on ferric oxide, sometimes used as a stop-off compound to prevent the spread of molten solder.

Jigging, fixturing: A means for holding an assembly of parts in position while they are being joined.

Joint gap: The distance between surfaces that are to be joined. An important design parameter.

Laser beam: A high energy beam of coherent monochromatic light that can be focused to provide a high heat input onto a localised area.

Liquidus: The temperature above which an alloy will be completely molten.

Mechanical properties: The properties of a metal or alloy that specify strength, ductility, hardness, toughness, etc. The tensile strength is defined as the maximum stress in tension that can be withstood prior to fracture; yield strength is the stress in tension above which the metal or alloy will be permanently deformed; shear strength is the resistance to a shear stress. Ductility is a measure of the ability of a metal or alloy to plastically deform without fracture and it is usually expressed as the elongation % to failure. Hardness is the resistance to penetration by an indenter. These properties may be measured on standard test pieces using standardised procedures and equipment.

Melting range: The range of temperature between the solidus and liquidus temperatures for the alloy.

Nickel release test: A test described in EN1811:1998 that measures the rate of release of nickel from items of jewellery that contain nickel in the jewellery alloy. This must be below 0.5 micrograms per square centimetre per week. The European Union Directive 94/27/EC prohibits the sale of jewellery within the Union unless it passes the test.

Nozzle/tip for torches: Describes the type and the size of the gas/air or oxygen exit controlling the flame diameter.

Pailons: Small pieces or coupons cut from solder foil, strip or sheet placed on top of or within the joint gap. They melt and progressively flow with the on-coming flame. They are often fixed in position using a spot of flux.

Phase diagram (equilibrium diagram): A diagram that describes the alloying behaviour, under equilibrium conditions, of two or more metals in terms of temperature and alloy composition.

Pickling: The process of dissolving away surface oxides and flux by immersion in a suitable dilute acid bath. May be part of both the initial surface preparation and post-soldering or welding operations.

Protective atmosphere: A gas atmosphere used in a furnace to prevent oxidation of the parts during soldering and heat treatment.

Quenching: The immersion of a metal item into a fluid to cool it rapidly from a high temperature, say after soldering or annealing or any other heat treatment. The quenchant is usually water for carat gold alloys.

Residual stress (internal stress): A stress remaining locked in an article that has been either cold worked or rapidly quenched. Can cause stress corrosion cracking in low carat gold alloys.

Scrap: Rejects or excess process material that may be recycled in-house or sent for refining to reclaim the precious metal content.

Soldering: Joining metal or alloy parts by fusing them together with a lower melting range alloy known as the solder. Soft soldering is defined as soldering at less than 450°C; hard soldering is done at greater than 450°C.

Solder paste: A paste made by mixing pre-alloyed solder powder with an organic binder, with or without a flux additive. Supplied in syringes or pots for easy dispensing.

Solidus: The temperature below which an alloy is completely solid. N.B. The solidus and liquidus for a pure metal are the same temperature because pure metals melt and solidify at one characteristic fixed temperature rather than over a range.

Stress relief: A relatively low temperature heat treatment, typically 30 minutes at 250°C, that reduces the level of residual stresses. It has little effect on other mechanical properties but will reduce the risk of stress corrosion cracking.

Tarnish: The surface discoloration due to the formation of sulphide films on low carat golds and silver. Caused by many factors including exposure to atmospheric pollution, certain cosmetics, domestic cleaning fluids and an individual's body chemistry (perspiration).

Thermal expansion (contraction): The increase (or decrease) in linear and volume dimensions of an article on heating (or cooling). It must be considered when holding an assembly by jiggging or using a fixture board for a heating operation.

Thermal diffusivity: A measure of chilling or insulating power. It is defined as the ratio of the thermal conductivity to heat capacity. Silver has the highest thermal diffusivity of the precious metals closely followed by gold and the high carat alloys but platinum has a low thermal diffusivity.

Toxic: Poisonous, hazardous to health.

Welding: A process in which parts are joined by mutual fusion at the interface but no solder is used. Resistance welding is achieved by localised heating caused by resistance to a pulse of electric current across the interface, eg spot, tack and seam welding. Plasma arc welding is due to intense heating by a gas ionised by an electrical discharge. Laser beam welding is achieved by focusing a laser beam with a high heat input onto a localised area.

Wettability: A measure of the ease of wetting between a molten solder (or adhesive) and a solid surface. The contact angle between the liquid and the solid must be less than 90°.



Courtesy Quimijoy s.a., Spain

1 INTRODUCTION

It is commonly found that an article has to be made that is so complex in shape that it is either impossible or too costly to fabricate it directly as one piece. However, it may be feasible to produce the article from an assembly of relatively cheaply produced parts of simpler design by joining them together with a suitable process. This applies not only to engineering components and structures, but also to small intricate items of jewellery, *eg* filigree pieces, chain links, attachment of jewellers findings, joining ring shanks to gemstone settings, etc. It is true that the lost wax investment casting process has enabled manufacturers to fabricate single or near-net shape items, which formerly were constructed from simpler shapes by joining processes. This was mainly by soldering and it involved a high degree of craft skill. A prime example of this was in the construction of gemstone settings. Nowadays, these are usually cast as one-piece items and incorporate other parts such as a ring shank, earring, brooch or pendant. Nevertheless, there are many items that cannot be cast because either the shape is too complex or the section is too thin.

Apart from jewellery manufacture, there are other areas where joining processes are widely used. First, there is the repair of items in everyday use, which suffer fair wear and tear and other types of damage. This may include resizing or refitting ring shanks; replacing or re-tipping claws (prongs) and replacement of catches and findings. Secondly, joining processes are necessary for the restoration and reconstruction of antique pieces. Thirdly, although not joining in its strictest sense, the same techniques, materials and equipment are used for the repair of defects that may arise in casting. Notably, this is usually large casting porosity that appears on the surface of items and which may be filled in by the application of localised heating and a suitable solder or weld.

This Handbook is designed to assist craft jewellers and manufacturers by providing information on best practice. Hopefully, it will promote an understanding of the principles and practice of joining technology and help them to improve the quality of their gold jewellery.

1.1 TYPES OF JOINING PROCESSES

Joining processes can be classified into a number of types as follows:-

- Non-permanent – *eg* screw assembly
- Mechanical fastening – *eg* riveting, shrink fitting
- Solid state – *eg* diffusion bonding, pressure welding, friction welding
- Fusion welding – *eg* resistance spot and seam welding, laser beam welding, plasma arc welding
- Liquid/solid joining – *eg* soldering, brazing, adhesive joining.

All of these processes have been used in the fabrication of jewellery but it is true to say that the soldering (brazing) processes have been the most widely used from earliest times. Records show that gold soldering was practised in the Middle East at least 5500 years ago. The famous Leyden Papyrus, found in Egypt and written in Greek about 350 AD, outlines procedures for making solder alloys. Consequently, the major part of this handbook will be concerned with soldering, although one section will be devoted entirely to other joining techniques. In particular, the relatively recent

introduction of laser beam welding technology into the industry has offered many advantages. Non-permanent and mechanical methods should only be considered when other processes are not possible for reasons of damage due to overheating, distortion, residual stresses, lack of joint strength, etc. Fortunately, this is a rare occurrence and, hence, these methods will not be discussed further.

1.2 DEFINITION OF SOLDERING

It is important to draw the distinction between the terms **soft soldering**, **hard soldering** and **brazing**. By convention, 'soft soldering' refers to joining by soldering at temperatures below 450°C (842°F), whereas 'hard soldering' is soldering at temperatures above 450°C. The dividing line is somewhat arbitrary and it arises from the fact that soft solder alloys have relatively low melting points and ranges and hard solders had much higher melting temperatures. The best-known soft solders are based on the lead (Pb)-tin (Sn) alloy system. It must be emphasised strongly that Pb-Sn solders should not be used, except in very rare circumstances, as lead contamination will cause embrittlement and catastrophic breakages in gold jewellery. It can cause severe problems if it gets into recycled scrap.

Hard soldering at higher temperatures is known also as 'brazing', particularly in the engineering industry, and hard solder alloys are referred to as 'brazing alloys' because the original alloys were based on copper-zinc, i.e. brass. This is the temperature range commonly used by jewellers when assembling pieces with solder. The principles of soldering and brazing are the same and because jewellers have traditionally used the term 'soldering' instead of 'hard soldering' or 'brazing', this will be followed throughout this Handbook where applicable.

1.3 FACTORS TO BE CONSIDERED

In addition to understanding the mechanisms by which joints are formed, whether it be by soldering or one of the other processes, there are other factors that need to be considered and which will be discussed in this Handbook. The design of the joint has an important bearing on its strength and quality. There is an added constraint in fabricating jewellery, namely, that the item has to look aesthetically pleasing. Nevertheless, designers do need to think about how the joint can be made so that it has sufficient strength and yet remain relatively unobtrusive. Some regard should also be given to the assessment of joint quality. As with all manufacturing processes, the quality of the final product is dependent on controlling quality at every stage of the process. For this reason, the various stages of the soldering process and other joining processes are looked at in some detail.

Soldering of carat gold jewellery imposes additional restrictions that are not met in other situations involving soldering. There may be a legal restriction on assaying and hallmarking that limits the caratage of the solder alloy to that of the carat gold alloy being joined, although certain exemptions do exist and the legislation may vary from one country to another. In order that the solder joints should be as unobtrusive as possible, it is desirable that the colour of the solder alloy should match that of the carat gold being soldered. The caratage and colour of gold solder alloys is a function of alloy composition and a section of the Handbook will be concerned with these aspects and will include typical gold solder compositions.

1.4 HEALTH AND SAFETY

There are health and safety issues that need to be addressed. It is vital that the interests of the workforce are protected if good quality and productivity are to be ensured. Some of the materials used in the preparation of joint surfaces may be hazardous or toxic. The use of cadmium as an addition to solder alloys is strongly discouraged and its use is banned in some countries. It may not be enough to provide adequate fume exhaust and ventilation systems as environmental pollution may result. The emergence of laser beam welding in recent years has imposed certain safety precautions, particularly with regard to eye-protection.

1.5 FURTHER INFORMATION

Finally, at the end of the Handbook, there is a bibliography and list of references for those who wish to read further into the subject. A list of manufacturers of solders and equipment is also given. This is just a representative list as it is almost impossible to provide a comprehensive one.

2 THE PRINCIPLES UNDERLYING THE SOLDERING PROCESS

Soldering is the operation whereby a molten filler metal or alloy will wet and flow across the surfaces of the joint to form a strong metallurgical bond between the filler (solder) and the pieces being joined. There are a number of requirements if successful joints are to be produced.

- a) The solder alloy must have a lower melting range than that of the parent metals being joined. This means that for jewellery, the liquidus temperature of the gold solder is below the solidus temperature of the carat gold alloy used to make pieces being joined. The solidus temperature is the temperature below which the alloy is completely solid. In practice, ideally there should be a difference of at least 50°C between the temperature at which the solder is completely molten, and will flow, and the solidus temperature of the parent metal in order to avoid incipient melting of the component pieces.
- b) Although there is no melting of the parent metal surfaces during soldering, some diffusion of atoms will occur across the liquid/solid interface to produce a strong bond. The solder alloy must be chemically and metallurgically compatible with the parent metal. For example, the formation of brittle intermetallic compounds at the interface is undesirable, as the joint is likely to fail. Fortunately, this problem does not occur generally when soldering carat golds and bonding is achieved by a degree of mutual solubility and alloying.
- c) In order for the molten solder to flow through the gap between the joint surfaces, *ie* the **joint gap**, it must 'wet' the surfaces in the same way that water will completely wet a clean, grease-free surface of metal or glass. According to the classical theory of wetting*, a liquid will spread over a surface to give a contact angle ϕ as shown in Figure 2.1. The contact angle ϕ is a measure of the degree of wetting. A non-wetting situation occurs when the liquid completely balls up to form individual droplets having $\phi = 180^\circ$. We see this readily when water is put onto a greasy surface. If $90^\circ < \phi < 180^\circ$, some wetting will occur but the liquid will not spread across the surface. If $\phi < 90^\circ$, then wetting occurs and the liquid will spread over the surface. The extent of spreading is dependent on the contact angle, such that the area of spreading increases with decreasing ϕ . To obtain wetting conditions, it is essential that the joint surfaces are clean and free from grease, dirt and oxide films. This necessitates the use of a flux to clean surfaces or furnaces with protective atmospheres to prevent oxidation (see Section 4).
- d) Ideally, the molten solder is drawn into the joint gap by the action of a **capillary force**, sometimes known as capillary attraction. This can best be illustrated by immersing the ends of glass tubes of small inner diameter in a container of liquid, Figure 2.2. You can see that the liquid has risen inside the tubes to a level that is higher than that of the liquid in the container. The smaller the tube diameter, the greater is the rise of liquid within the tube. The magnitude of the capillary force is a function of the surface tension γ_{LV} , density of the liquid, the contact angle ϕ and

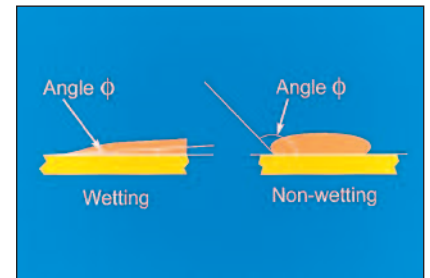


Figure 2.1 Sketch to show wetting and non-wetting. Wetting occurs when the contact angle ϕ is less than 90°

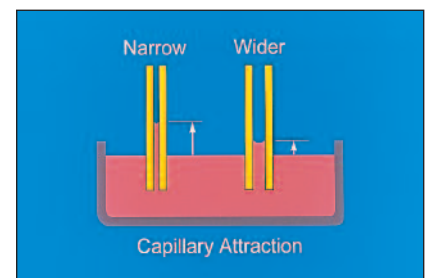


Figure 2.2 Capillary attraction

the tube diameter. It is easy to translate this to the situation of making a good solder joint in an item of jewellery, or in any jointed component. The tube diameter is analogous to the joint gap, i.e. the clearance between the joint surfaces. It is recommended that a joint gap should be between 0.01 and 0.1 mm. The joint gap and joint length are important factors in the design of joints for soldering and they will be discussed further in the next Section.

- e) The rate at which molten solder will flow into the joint gap is dependent on its viscosity. This is a measure of the rate at which a fluid will change its form, eg consider and compare treacle or water falling off a spoon. It has been shown that typical joint filling times are of the order of 0.1 seconds. Anyone experienced with torch soldering will recognise the rapidity with which solder will suddenly run and fill the joint gap when it is applied at the correct soldering temperature. The viscosity, surface tension and contact angle will all decrease as the temperature is raised above the liquidus temperature of the solder allowing easier flow and joint filling.
- f) It is known that surface roughness has a beneficial effect on the spread and flow of molten solder. The reasons for this are thought to be that the effective contact angle ϕ is reduced and that the network of fine channels resulting from the roughened texture enhances capillary attraction. Abrasion of the joint surfaces with silicon carbide-impregnated paper, say of 400 grit size, is likely to give a better filled joint than if they are highly polished. However, it is appreciated that this may not be easy to arrange when soldering items of jewellery.

***Footnote.** The liquid will spread and wet the surfaces until the surface tensions between the liquid and solid substrate (γ_{SL}), the liquid and the atmosphere (γ_{LV}), and the substrate and the atmosphere (γ_{SV}) are in balance, as shown in Figure 2.1. This is expressed by the wetting equation $\gamma_{SL} = \delta_{SV} - \delta_{LV} \cos \phi$. It shows that $\phi < 90^\circ$ corresponds to the condition $\gamma_{SV} > \gamma_{SL}$. This imbalance provides the driving force for wetting and the spread of liquid across the surface. In practice, the equation has to be modified due to alloying and other conditions at the interface but it is not necessary for jewellers and manufacturers to know the details

3 JOINT DESIGN

A successful soldered joint is not simply a matter of putting two surfaces in close proximity to each other and running molten solder into the joint gap. In order to ensure that the joint will have sufficient strength and integrity for its purpose, it is necessary to give consideration to a number of features. These include the width of the joint gap, the joint length and area, and joint configuration.

3.1 JOINT GAP

The importance of the joint gap and its influence on capillary attraction has been referred to in the previous section. The gap must be sufficient to allow any flux or gas to escape ahead of the flowing solder otherwise entrapment will seriously weaken the joint. For this reason, the joint design and the application of solder should be such that the solder flows into the gap only from one direction, Figure 3.1. At the same time, it is equally important that the flux, trapped air or reducing gases, if furnaces are used with protective atmospheres, can readily access the joint surfaces.

Figure 3.2 shows the variation in fracture strength of simple butt joints as the joint gap thickness is increased. The strength increases to a peak as the thickness decreases and then decreases again at very narrow gaps. This is probably because of the difficulty in adequately filling very narrow gaps. It can be seen that the peak strength is considerably higher than that of the bulk solder alloy but that as the gap increases in thickness, the joint strength drops to that of the bulk strength. In effect, at a large gap width, the capillary force is small and the molten solder is simply being cast into a mould made by the joint surfaces. As mentioned previously, a joint gap width in the range 0.01-0.1 mm is recommended.

It is appreciated that a craftsperson or a manufacturer of jewellery cannot make such a precise measurement and has to rely on skill and experience to achieve an acceptable gap. Very often, the situation arises where the individual parts simply rest on each other as the assembly is heated. The joint gap will then tend to regulate itself to an optimum gap thickness related to the surface tension of the molten solder. Similarly, an easy slip fit between parts will usually give the required clearance. The primary aim should be to ensure that just enough solder is used to completely fill the joint and to avoid defects. The presence of trapped flux, gas, cracks and porosity will seriously weaken the joint. Provided the joint is sound, the actual strength may be of secondary importance as usually the bulk strength and ductility of the solder will be sufficient for jewellery. Nevertheless, wide joint gaps can and should be avoided even in the manufacture of jewellery.

To assist the solder to flow into the joint gap and promote the formation of well-rounded fillets, it is good practice to chamfer or radius the edges at the entrance to the gap where possible, Figure 3.3.

3.2 JOINT LENGTH AND AREA

It might be thought that increasing the joint length or area would give an increased joint strength. This is true only up to a certain limit above which the strength does not continue to increase in proportion. For example, increasing the length of a lap joint beyond the limiting value can lead to a decrease in shear strength since the

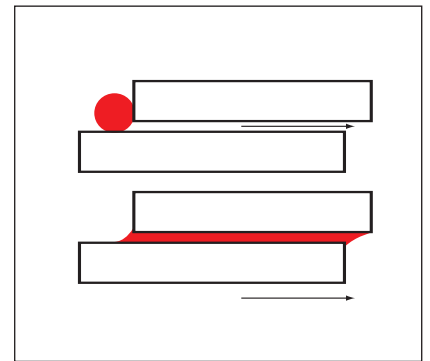


Figure 3.1 Sketch to show the uni-directional flow into and through the joint gap

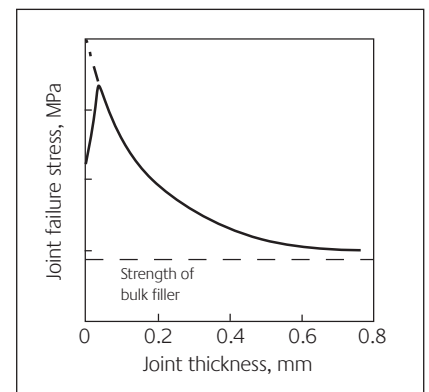


Figure 3.2 Variation in fracture strength of butt joints with joint gap thickness

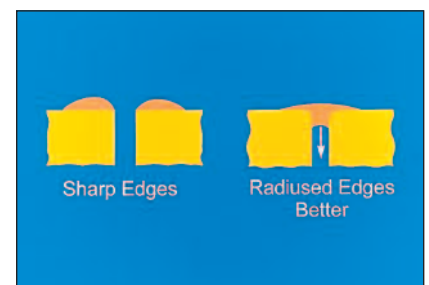


Figure 3.3 Sketch of chamfered or radiused edges to assist flow of solder into the joint gap

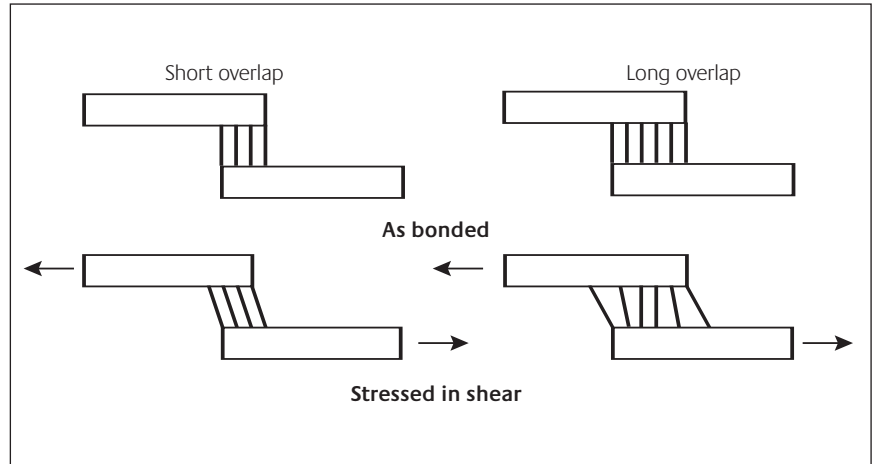


Figure 3.4 Stress distribution in a lap joint

stress is concentrated at the ends of the joint and the central portion has little or no stress imposed on it, Figure 3.4.

Increasing the joint area above a certain value will increase the tendency for the joint to contain trapped gas or porosity. Some of this porosity will be shrinkage porosity arising from the solidification of the solder in the joint.

Fortunately, these effects are much more likely to be a problem with engineering components where strength has a greater importance and where joint lengths and areas may be large in comparison to the joints found in jewellery.

3.3 JOINT CONFIGURATION

In terms of joint design and configuration, the weakest joint is the simple butt joint with two pieces joined end-on or at right angles to each other. However, there are a number of techniques to increase joint strength that may be considered when designing joints. Basically, these involve increasing the joint area and reducing the stress concentration by redistributing any load applied in service. Figure 3.5 shows typical joint configurations. The scarf and step joints have the advantage that they are stronger than butt joints whilst retaining the same thickness and external shape. The lap, double lap, strap and double strap joints are much stronger but have the disadvantage, at least for jewellery items, that the joint thickness, shape and weight are all increased. A balance may have to be struck between having joints of sufficient strength for the intended purpose and retaining the aesthetic appeal of jewellery.

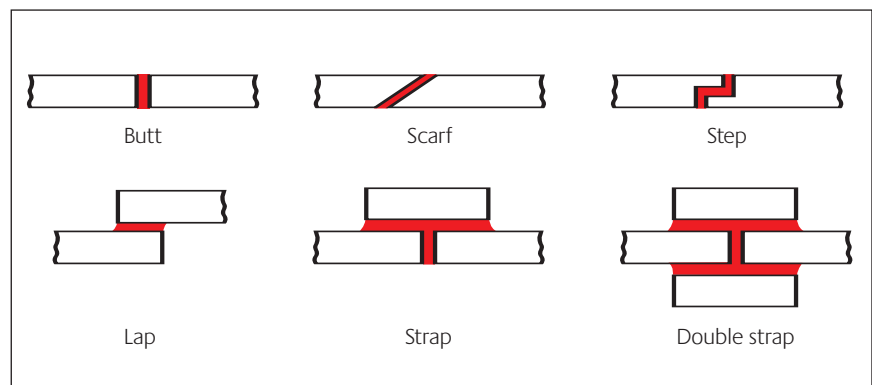


Figure 3.5 Typical joint configurations

For joints where one part is soldered at right-angles to the other, *ie* a T-joint, again strengthening can be achieved by inserting one part into a hole or groove machined into the other, as shown in Figure 3.6a. It is worth recognising that fillets can also give enhanced strengthening and toughness, Figure 3.6b. Note the ideal shape of the fillet; the contact angles approach zero at the fillet ends and the fillet surface is concave.

3.4 DISCUSSION

The first reaction to the above sections on joint design among jewellery manufacturers and craftspersons may be that although these are matters of great importance for engineering components they have little relevance, or cannot be applied, to making jewellery. This reaction arises because the joints are relatively small and cannot be made to tight engineering tolerances, the pieces of jewellery have to retain their aesthetic appeal, and it may be thought that joint strength is of secondary importance. There is a certain validity to these arguments. Nevertheless, joints in jewellery do fail in service because a consumer has been a little heavy-handed or the joint is too weak for its intended purpose. Such failures may have been avoidable if more consideration had been given to the joint construction.

Designers and manufacturers should have a good knowledge of the factors governing quality control at every stage of the manufacturing process and this includes joint design. It is accepted that it will not usually be possible or necessary to make precise measurements, say in joint gap or area, but there is nothing to stop thoughts and questions about:-

- How does the solder flow into the joint?
- Can it be made to flow in one direction only and reduce the chance of trapping pockets of air and flux?
- Is it possible to alter the joint configuration to strengthen the joint without upsetting the aesthetic appeal of the piece?
- Can strengthening fillets be incorporated into the joint?
- Can the joint be moved to a more unobtrusive area with the opportunity for additional strengthening?

There are, of course, other questions that designers and manufacturers need to address that are concerned with the practical aspects of making soldered and other joints and which will arise from the following sections in this Handbook.

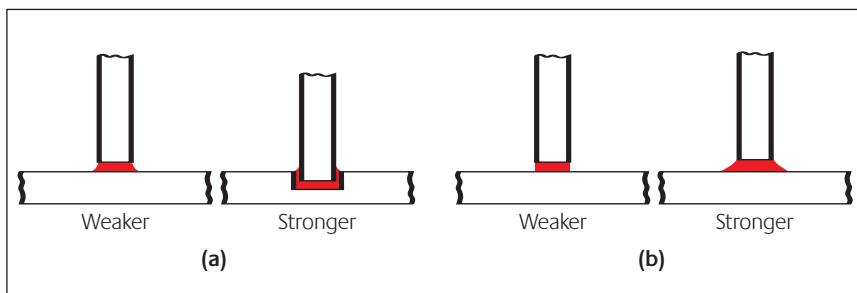


Figure 3.6 T-joints

(a) Showing the strengthening effect of inserting into a hole
(b) Showing the effect of a fillet

4 THE SOLDERING PROCESS

After attention has been given to joint design, the practical aspects of the soldering process have to be considered. These include the following:-

- * The form of the solder to be used.
- * How the component pieces are to be held in place, i.e. jiggging, fixture boards, etc.
- * The method of heating the joint to the soldering temperature.
- * Joint surface preparation and cleaning.
- * The application of the solder to the joint.
- * The possibility of the need to use a multi-step soldering technique.

Each stage of the process is important if a good quality joint is to be obtained. This section of the Handbook is concerned with a discussion of the practicalities of soldering.

4.1 THE FORMS OF THE SOLDER ALLOY

Solder alloys have to be selected for their colour, caratage, melting range and mechanical properties. Generally, with a few exceptions, the caratage has to be the same as that of the pieces being joined and the colours should match as closely as possible. These and other matters concerning solder alloy compositions will be discussed in more detail in Section 6. The form in which the solder is to be applied during the process is also an important factor in making successful joints.

It is common practice with jewellery to cut thin solder alloy strip into small pieces called '*paillons*' that are then placed between the joint surfaces or on top of the joint gap. It is recommended that a good supply of *paillons* be kept in a borax solution so that they are already fluxed and ready for use. If they are placed between the surfaces, the parts will adjust to a suitable joint gap when the solder melts, as mentioned previously.

Alternatively, a fluxed joint may be heated to temperature with a torch flame and the tip of a solder strip or wire will melt and flow into the joint on contact. It is always good practice to heat the parts and allow the solder to be melted by contact with the hot surfaces. Fortunately, the carat gold solders generally have good ductility and can readily be worked to sheet, strip and wire.

Other forms are solder pastes, with or without flux additives, which are becoming widely used and which lend themselves to mass production and semi-automation, solder-cored wire for chainmaking and solder-flush sheet and strip for stampings.

The manufacture of these various forms will be described more fully in Section 5.

4.2 JIGGING AND FIXTURING

The individual parts have to be held in intimate contact and in a certain position so that they do not move during the soldering process, Figure 4.1. Jewellers working at the bench will often find that they do not have enough hands to hold the pieces together whilst using a torch or blowpipe and applying the solder. In these circumstances, it is necessary to wire the parts together or to place them in a suitable jig or fixture board.

If binding wire is to be used, then this should be iron wire of about 22-26 standard wire gauge (0.71-0.46 mm diameter). Iron is used in preference to copper or brass

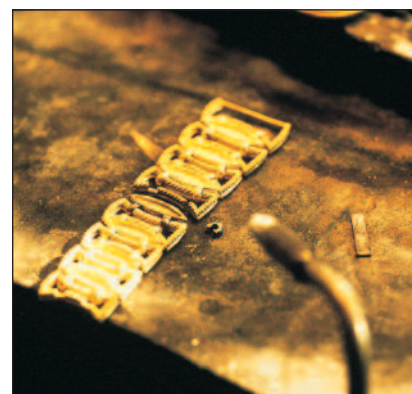


Figure 4.1 Torch soldering a bracelet

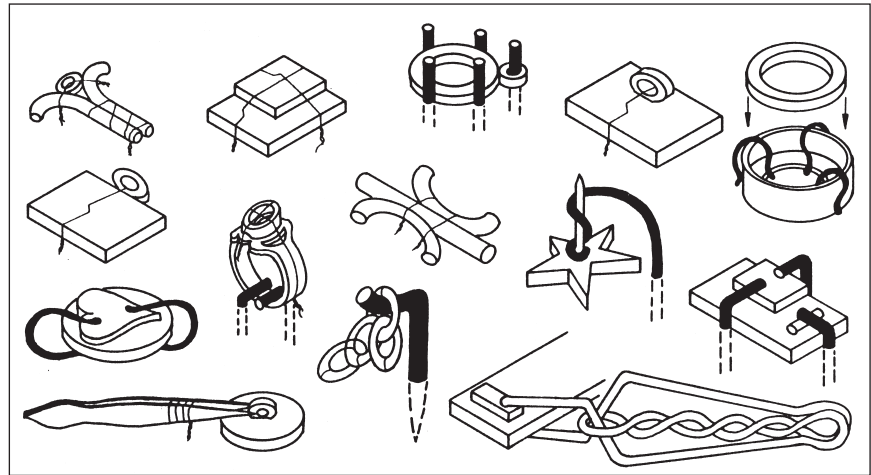


Figure 4.2 A variety of jiggging and support systems. (Courtesy Murray Bovin, Bovin Publishing, New York 1979)

because it is less likely to be absorbed into the solder. The wire should not be over-tightened. Allowance must be made for expansion differences between the wire and the parts being held otherwise they might buckle or distort. There is also the danger that the wire may adhere to the soldered joint necessitating additional polishing with its attendant increased labour and finishing costs. This may be avoided by using steel clips that hold the parts in place without contacting the joint area. Steel clips have the advantages that they have a relatively low thermal diffusivity, which means that heat is not readily conducted away from the heated zone, direct contact between the clip and a torch flame can be avoided, and they can be re-used. One disadvantage is that they may have to be designed and custom-made for particular soldering operations and this makes them less attractive for low volume production runs. Figure 4.2 shows a variety of jigging and support systems. Figure 4.3 shows the 'third hand', which is a pair of tweezers with heat-resistant tips stiffly pivoted on a base. Other jigging methods include pegging the parts to a bench-top support, which may be a heat reflecting refractory board, a charcoal block, soft firebrick or an investment plaster mould. (Note that charcoal or silica-based refractories must not be used when soldering platinum as these can react adversely with platinum.)

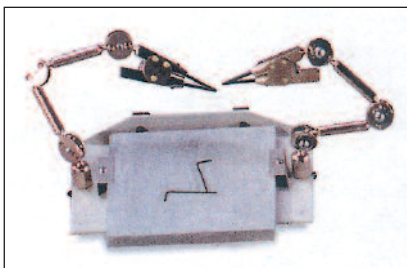


Figure 4.3 Two examples of the 'third hand' for support. (Courtesy Degussa and Rio Grande)

Another method is tack welding which is best suited to holding heavier parts together during heating. The technique involves clamping two jewellery pieces between welding electrodes and passing an electric current through the pieces to cause localised heating or melting. The heating is due to the resistance to the flow of electric current across the interface and hence the process is termed 'resistance welding'. Tack welding permits parts to be held together securely with sufficient joint strength for further process handling. There are different types of welding equipment on the market. It has been reported that capacitor-discharge uni-polar power supplies provide an exact, fast rise time pulse of weld energy, which is ideal for tack welding. Disadvantages are that each type of tack-joint configuration requires its own unique equipment settings, there is a danger that the electrodes will damage the surface of the jewellery, and that highly skilled labour is required.

Fixture boards, such as carbon boards, are easy to use and require little training by personnel. They are particularly suitable for furnace soldering and give excellent

results. There are two types of fixture boards, namely, soft and hard boards. Soft dry boards provide a fixture with very little set-up time and at low cost. The parts are pressed into the board to give an impression that holds them together and the boards are ready to use, Figure 4.4. They are particularly useful for one-off jobs and short production runs. However, they are very soft and the dimensional tolerance of the impression rapidly decreases with re-use. This lack of dimensional control can be overcome to some extent by using hardenable dry fixturing boards. Again the master is pressed into the block which is then brushed with a proprietary hardener liquid and heated to cure. These hardenable boards are more expensive but can be re-used many times and, therefore, tend to be more cost-effective.

Three-dimensional CNC machined carbon (graphite) boards are better when tight tolerances are required and they have a long life. They are more versatile in that allowance for two-dimensional thermal expansion of the parts being soldered can be made. 'Double decker' boards with locating holes and pins enable soldering at right angles and multi-step soldering to be accomplished in a single pass through the furnace, Figure 4.5. Machined carbon boards are expensive and time-consuming to produce but are very beneficial for high volume production runs.

4.3 HEATING METHODS

Originally, the traditional method of heating was to use a mouth blowpipe where air is blown through a candle-wax or paraffin oil flame, Figure 4.6. Considerable skill is required to direct the flame to where it is needed and to control the amount of heat. A later development was a mouth blowpipe where gas is introduced via a side tube and ignited. Blowing down the straight tube produces a clean hot flame.

The advent of high calorific gases led to the development of air-gas and oxy-gas torches. They are designed using little excess oxygen to give a very precise bright hot flame that can be directed with pinpoint accuracy. The torches can have interchangeable tips. The nozzle/tip dimensions need to be matched with the fuel gas and oxygen ratio and the flame size required, Figure 4.7. The fuel gases in common usage are hydrogen, natural gas, propane, butane and acetylene. Lower flame temperatures are obtained with compressed air compared to oxygen because air contains 80% inert nitrogen that also has to be heated in the flame, Table 4.1. In practice, the temperature of the work-piece will be considerably lower than the flame temperature because the gold alloys will conduct heat away efficiently. Gold and the carat gold jewellery alloys have a high thermal conductivity, or more strictly, thermal diffusivity. This means that a surprising amount of heat has to be applied at a high rate to attain the temperatures for bulky components and large joints. Thermal diffusivity (Q) is defined as the thermal conductivity (k) divided by the product of the specific heat (c) and the density (ρ) of the metal or alloy concerned.

It is important to control the fuel gas:oxygen ratio, remembering that the oxygen may be provided either from compressed air or from using oxygen itself. If the volume ratio is such that the molecular ratio is correct for complete combustion, eg $2H_2 + O_2 = 2H_2O$, the flame will be neutral. An excess of oxygen will give an oxidising flame and an excess of fuel gas will give a reducing flame, Figure 4.8. High carat golds are not adversely affected by heating with a slightly oxidising flame but the lower caratage alloys require neutral or slightly reducing conditions to prevent oxidation of the base metal constituents.

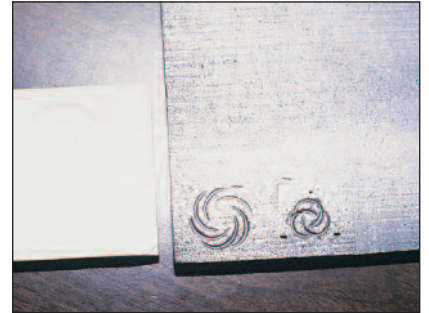


Figure 4.4 A soft fixture board. (Courtesy N. Krohn, Krohn Industries Inc.)



Figure 4.5a A CNC machined carbon board and paste solder

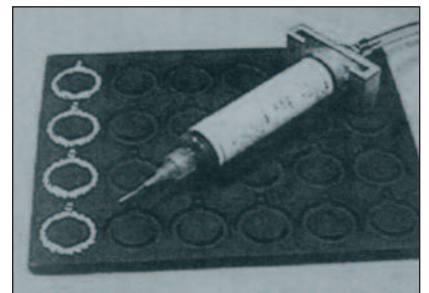


Figure 4.5b Board with components placed on it

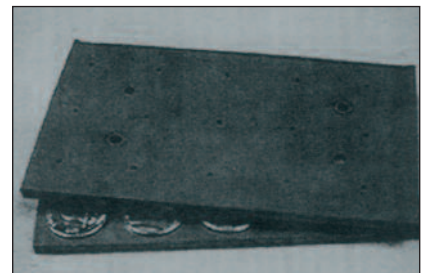


Figure 4.5c Double-decker carbon board fixture with post holes in the top, ready for soldering. (Courtesy N. Krohn)

4 THE SOLDERING PROCESS

Table 4.1 Approximate theoretical temperatures of fuel gas flames with oxygen or air

With	(°C)	Oxygen	Air
Hydrogen, H ₂	2810	2150	
Natural Gas, CH ₄ +C ₂ H ₆	3100	2000	
Propane, C ₃ H ₈	3185	2100	
Butane, C ₄ H ₁₀	3150	1900	
Acetylene, C ₂ H ₂	3270	2320	



Figure 4.6 Mouth blowpipe and candle wax flame

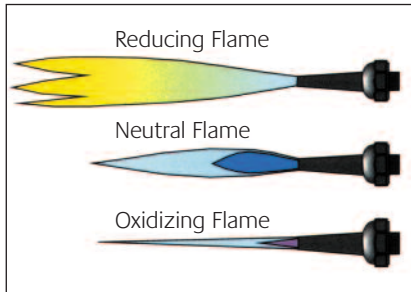


Figure 4.8 The characteristics of three types of flame



Figure 4.9 A micro-welder. (Courtesy Sherwood Scientific Ltd., Cambridge)

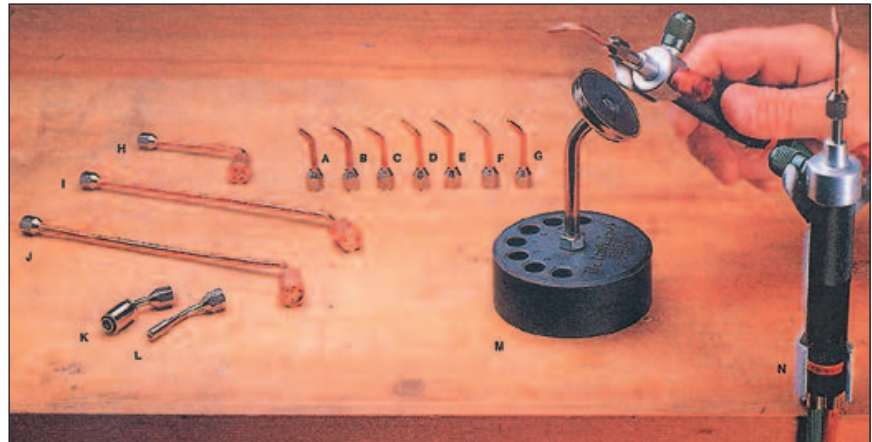


Figure 4.7 Gas-air torch with interchangeable nozzle tips. (Courtesy Rio Grande)

Small flames have a tendency to lift off the torch tip and be extinguished unless the oxygen or air pressure is tightly controlled. It may be necessary to have an additional low-pressure regulator working at about 5-15 kN m⁻² (1-2 psi) pressure to regulate volume flow. Fuel gases are usually supplied from gas bottles. Butane micro-torches, with cartridge refills, are completely self-contained and are very handy to use. **[Warning.** Do not use any torch equipment with oxygen that has previously been used with compressed air unless the oxygen hose is replaced and a correct oxygen regulator is fitted. Small traces of oil and grease from the use of compressed air can be highly explosive in the presence of oxygen.]

The Micro-welder (sometimes referred to as the 'water welder') is a transportable unit that does not require a separate external fuel source, Figure 4.9. The water in an electrolyte solution, such as potassium hydroxide, is electrolysed and split into hydrogen and oxygen gases. These are held in separate reservoirs and can be fed separately at low pressure to calibrated burner jets. The flame size can be varied very precisely to allow delicate work such as soldering chain links and claw (prong) repairs or, at the other end of the scale, to solder large pieces. The oxy-hydrogen flame is essentially a neutral flame and it is difficult to see despite its high temperature. Provision is often made for the gas to pick up small amounts of water vapour and organic volatiles, such as methyl alcohol or acetone, to colour the flame and make it slightly reducing.

The soldering cycle should be made as brief as possible for the following reasons:-

- It will reduce the risk of 'spending' (exhausting) the flux in preventing oxidation. Even so, it may be necessary to add more flux, particularly if the joint areas are large.
- Overheating the parts will increase the risks of oxidation, distortion and melting the item being soldered.
- Volatilisation of low melting and high vapour pressure constituents in the solder can lead to pinholing on the surface and possibly trapped porosity.

First, the joint area should be pre-heated with a larger flame. It is a matter of skill to judge when the joint has reached the appropriate temperature from the appearance of the flux and the metal. Secondly, the flame is adjusted to give localised heating. When the solder flows it should be moved along the seam with the flame so that it flows towards the hotter part. At the completion, the flame is removed and

extinguished.

Although the heating methods described so far are widely used, and will continue to be so, they have the disadvantage that a certain degree of skill is required by the operator and temperature control and reproducibility is difficult. Labour costs will be high particularly for high volume production. Some degree of automation can be achieved by passing the work through a set of burners on a moving chain or turntable. However, for the reasons stated, manufacturers tend to look to furnace soldering as an answer to these problems. The volume of production must be sufficiently high to justify the capital equipment cost. The reduction in skill factor, labour costs and finishing costs together with achieving good quality joints greatly improves efficiency and productivity. Furnaces may either be a batch type furnace or, preferably, a continuous belt furnace, Figure 4.10. Parts with the solder in position are placed either directly onto the mesh belt, Figure 4.11, or in fixture boards that are then placed on the belt. The temperature is controlled as the items are moved into and through the heating zone. They then pass on through a chamber, having an external water-cooled jacket, before being removed from the belt at the other end. Apart from temperature control, the other great advantage is that oxidation of the parts is prevented by a protective gas atmosphere within the furnace chamber or muffle. This is particularly necessary when soldering jewellery of lower caratage because of the tendency of the base metal constituents to oxidise. The atmosphere generally used is 'cracked' or 'dissociated' ammonia supplied from a separate generator in the workshop. The ammonia (NH_3) is split into its component gases, 25% nitrogen and 75% hydrogen. It is a dry atmosphere with a very low water vapour content (dewpoint $\sim -30^\circ\text{C}$). Nitrogen is an inert gas and the hydrogen provides reducing conditions that prevent oxidation. Other similar protective atmospheres are endothermic gas, obtained by combustion of air and liquid petroleum gas in a generator, and forming gas, a mixture of 80-90% nitrogen and 20-10% hydrogen provided from gas cylinders. These latter two atmospheres tend to have a higher water vapour content. Soldering in these atmospheres gives bright, oxide-free results minimising or eliminating the need for subsequent cleaning and polishing. The use of a protective atmosphere will usually mean that a flux is not required. Indeed, the accumulation of flux deposits may have an adverse effect on the life of the furnace. The only exception may be in cases where it is difficult to expel any residual air trapped in between parts.

To ensure good results, it is vital that the furnace parameters are set correctly. The temperature reached by the work is governed not only by the set furnace temperature but also by the rate at which it moves through the furnace, i.e. belt speed. It has been recommended by N. Krohn that the furnace temperature should initially be set at 38°C (100°F) above the flow temperature of the solder. If fixture boards are used, this should be increased to 66°C (150°F) on account of the thermal mass of the boards. Similarly, a starting belt speed should be about 25 cm (10 in.) per minute or 20 cm (8 in.) per minute for fixture boards. Trial runs should be done and adjustments made to the parameters after inspection of the joints. If fixture boards are used, either in trial runs or during production, empty dummy boards should be sent through first to allow the furnace temperature to compensate for the heat loss caused by the boards. Larger pieces and the joints will require more time in the heating chamber. Remember to keep detailed records of all decisions made on



Figure 4.10 A typical continuous belt furnace. (Courtesy IECO srl, Italy)



Figure 4.11 Soldering of stamped jewellery on a conveyor belt in a continuous furnace. (Courtesy IECO srl)

temperatures and belt speeds for each type of soldering application and for each furnace. No two furnaces will be exactly the same. Check temperature-measuring devices, eg thermocouples, at regular intervals. These include both the furnace thermocouples and the long temperature probes passed through on the belt to ascertain that the solder flow temperature is reached. The quality of the furnace atmosphere can be checked with a dewpoint meter or an oxygen probe. The latter instrument measures the actual oxygen content of an atmosphere.

4.4 JOINT SURFACE PREPARATION AND CLEANING

It is essential that the molten solder wets and spreads over the joint surfaces. Therefore, it is important that attention is paid to the cleaning and preparation of surfaces if good quality joints are to be obtained. First, oil and grease should be removed using a suitable degreasing solvent, taking care that adequate exhaust and ventilation is provided to avoid the operator breathing in dangerous toxic solvent fumes. This is often done in an ultrasonic cleaning tank to ensure complete removal. Oxide films and dirt can be removed using an acid pickle, say 10% sulphuric acid prepared by adding one part of concentrated sulphuric acid to nine parts of water. **[Warning. Always add the acid slowly to the water.** Adding water to the acid produces a large amount of heat due to an exothermic reaction. This may be sufficient to cause boiling and it is a hazardous situation for the operator.] Alternatively, these films may be removed by cleaning with a file or emery paper. It is good practice for the operator to wear white cotton gloves to prevent any further contamination by perspiration and grease.

If soldering is to be done at the bench, the parts will be heated in air and there is the problem of surface oxidation of base metal alloying constituents, particularly with lower caratage jewellery. Films of oxide and carbonaceous residues can be removed by fluxes. Fluxes are chemical compounds that clean the joint surfaces either by dissolving these films or by penetrating underneath the films and lifting them off. The flux then provides a protective surface cover, thereby preventing further oxidation during heating. It also promotes wetting of the surfaces by the molten solder as it flows through the gap and displaces the flux. The flux itself must be molten and active before the solder melts and should remain so until the solder has solidified.

The most common fluxes for gold soldering are based on borax (sodium tetraborate $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$), which is fluid above 760°C (1400°F). These are usually in the form of a cone that is ground in water or a weak detergent solution to provide a flux paste. The paste is then applied with a brush or solder pick to the joint area and solder paillons, if they are used, prior to heating. Heating is done gently at first to boil off the water from the paste and to prevent spitting. As the temperature is raised, the flux becomes milky white and the combined water of crystallisation, present in the borax, is driven off. During this process, the flux tends to bubble and may not completely cover the joint area. This may necessitate both the application of additional flux and a re-direction of the torch flame. Fused borax glass is sometimes used. Here, borax is heated until the water of crystallisation is removed and it melts to form a glassy phase. This is ground to a powder and mixed with alcohol to be used as a flux. At the soldering temperature, the flux must be clear, molten and active. It may be necessary to use a flux with a lower melting temperature and increased

fluidity when low carat gold solders are used. For this reason, commercial fluxes are available on the market that are tailored to cover a range of soldering temperature requirements. They contain borax or potassium tetraborate, boric acid, potassium bifluoride and, sometimes, potassium silicofluoride. Potassium salts are used in preference to sodium to avoid a yellow glare in the torch flame. The fluorides lower the melting range of the flux and also give an improved fluxing action. As stated earlier, fluxes are not required generally for furnace soldering operations and they can be deleterious to the furnace.

The flux residues are usually water-soluble and they are sometimes removed by quenching the assembly in water once the solder has solidified. It may be necessary to lightly brush the joint to assist in the removal of residues. Removal is important because flux residues are usually corrosive particularly where low carat golds are concerned. Any oxides that have formed on unprotected areas can be removed by immersion in 10% sulphuric acid pickle followed by thorough rinsing in water. Where there are enclosed areas, which may trap the acid pickle, it may be better to rinse first in a solution of washing soda (sodium carbonate) in water to neutralise the acid. **[Warning. Never place jewellery containing porous stones in a pickle or soda solution.]**

The use of ultrasonic cleaning tanks is becoming more popular for removing flux residues. The ultrasound produces shock waves that rapidly break up any films into small fragments that are washed away, even from crevices. Recently, steam jet cleaners have come onto the market. The steam is supplied at pressures in the range 20-65 psi (1.4-4.5 bar) from a heated tank of water using a valve or foot-operated pedal. Use de-ionised water because tap water can leave residues when it dries off.

4.5 APPLICATION OF SOLDER TO THE JOINT

It has been mentioned that consideration must be given to the way in which the molten flux and solder will flow into and through the joint gap. It is important that areas of trapped flux, trapped gas and porosity are avoided if joints of good quality are to be obtained. This is best achieved by ensuring that the flow is uni-directional so that flux flows through the joint driving the air or torch gas out ahead of it and this is followed by the molten solder, which in turn drives out the flux. Where possible, the joint should be heated so that the solder runs towards the hotter part otherwise it may solidify prematurely giving a defective joint. If soldering is done in a furnace without a flux, the solder must still flow such that there is no entrapment of the protective atmosphere.

Methods of application include:-

- Placing paillons with a thin coating of borax on top of the joint gap and applying heat until the solder flows into the joint from one side. Alternatively, there are occasions when the paillons are placed in between the joint surfaces. In this instance, the solder should flow uniformly in all directions outwards from the centre to the edge.
- Applying 'dust', obtained by filing down solder. The dust may be mixed with flux in the form of a creamy paste and placed on the joint with a flattened piece of wire. This method is used for delicate work.
- Heating the fluxed joint until it reaches the temperature where the flux is clear and

it flows. The tip of a solder wire or strip is fed to the joint where it should melt and flow on contact.

- Placing an amount of solder paste from a dispenser on one side of the joint gap. Solder pastes will be described in more detail in Section 5.4 but it can be noted that they are supplied with or without a flux additive, depending on whether soldering is done in air or in a furnace with a protective atmosphere.
- Sweat soldering is used for joining larger flat surfaces such as hinges and brooch pins. One flat is fluxed and solder placed near one edge. On melting the solder flows across the flat. The flat is then cleaned. The other surface is fluxed and then the two are bound together and the whole assembly heated to complete the joining process.

The situation often arises where it is necessary to prevent the molten solder from flowing into areas where it is not wanted. This is achieved by brushing a 'stop-off' or 'stop-flow' agent onto those areas. Care should be taken not to introduce these materials into the joint gap where they would cause solder dewetting. Traditionally, jewellers rouge in water or methylated spirits has been used for this purpose but it is not really satisfactory since it may flake off and it gives no protection from oxidation. There have been favourable reports on the use of colloidal graphite suspended in alcohol and silica sol. It may be necessary to remove the residues afterwards by ultrasonic cleaning. Krohn has found that milk of magnesia (magnesium carbonate) works well for furnace soldering and it can be rinsed off with warm water leaving no visible marks on the surface. There are a number of commercially available products on the market.

4.6 MULTI-STEP SOLDERING

Complex jewellery assemblies may contain a number of soldered joints. This raises the problem that the first joints to be made may remelt with further soldering operations on the same piece. The problem is overcome by multi-step soldering where the first joints are made using solder of a high melting range and later joints are made with solders having lower melting ranges. The terms 'extra-easy', 'easy', 'medium', 'hard' and 'extra-hard' are used to describe solder alloys of a particular colour and caratage that have increasing melting ranges in that order. It is unfortunate that the terms 'hard' and 'extra-hard' have been used in this context because they do not refer to the strength or hardness of the solder alloy but simply to the fact that they need higher temperatures to melt them. Extra-hard or 'enamelling grade' solders, with high melting and flow temperatures are required when the item of jewellery is to be subsequently enamelled otherwise the joint will remelt in the enamelling furnace.

5 FORMS OF SOLDER

5.1 SHEET, STRIP AND WIRE

One of the advantages of carat gold solder alloys is that their compositions are modifications of those of the carat golds used to make the jewellery parts for soldering. Therefore, generally their mechanical properties including strength, toughness, ductility and workability are similar. They can be cast into ingots and rolled to sheet and strip or drawn down to wire by conventional methods although it may be necessary to adjust working and annealing schedules. As mentioned earlier, sheet or strip can be cut into small square or rectangular pieces, called paillons, that are coated with flux and then placed by hand on top of the joint gap or between the joint surfaces. Equally, strip and wire can be applied to the joint gap or seam once the flux has melted and the joint area is hot enough to melt the solder and allow it to flow. Gold solders are used also in the form of 'dust' for delicate work. The 'dust' is produced by filing down a solder strip or rod. The filings can be graded according to size needed for a particular application. It is recommended that the filings be placed in a dish and mixed with flux and water to give a creamy paste. This is applied to the joint using a flattened piece of wire or a solder pick to pick up the paste.

5.2 SOLDER FLUSH SHEET AND STRIP

This is a composite structure where a thin sheet or strip of a gold solder alloy is bonded onto one side of a sheet or strip of a carat gold alloy, which is normally an alloy of the same caratage to conform with hallmarking regulations and of a matching colour. The solder layer is joined either by diffusion bonding in a protective atmosphere furnace, or by roll bonding, where long strips of the solder and carat gold layers are bonded together at high pressure in a rolling mill to effect pressure welding. The composite is rolled down further to the required thickness. The thickness of the solder layer is typically 5-15% of the total composite thickness. The product is well suited for high productivity applications where sheet metal stampings are to be soldered to a flat backing sheet or strip of the composite, Figure 5.1. The stampings are placed on the solder flush side and the assembly is passed through a continuous belt furnace with a protective atmosphere. Solder is drawn from the backing sheet into the joint by capillary action, Figure 5.2. Normandeau has described the production processes for solder flush strip in great detail.

One disadvantage of using solder flush strip is when scrap from the composite strip or sheet is recycled in-house. The presence of elements in the solder layer that depress the melting range, such as zinc, tin and indium, will have an adverse effect on the quality of any jewellery alloys prepared from this source.

5.3 SOLDER-FILLED WIRE

This is a product that is suitable for the manufacture of chain with soldered links. A cast billet of carat gold is prepared by drilling a central hole along the billet length. Alternatively, a continuously cast tube may have its inner surface bored out to give a clean prepared surface. A rod of the solder alloy is inserted into the hole or the tube and the composite is rolled down and eventually drawn to wire to give a product with a solder core for chain making, Figure 5.3. The ratio of core diameter to outer

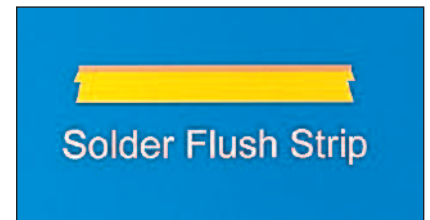


Figure 5.1 Sketch of solder flush strip

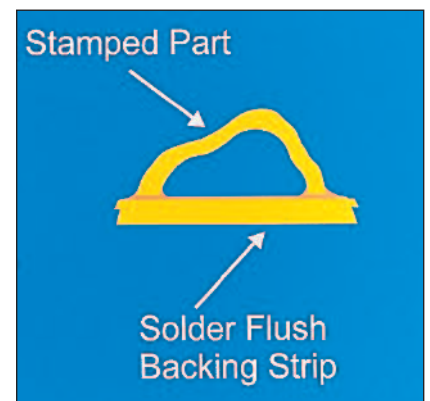


Figure 5.2 Sketch of stamped and soldered components using solder flush sheet

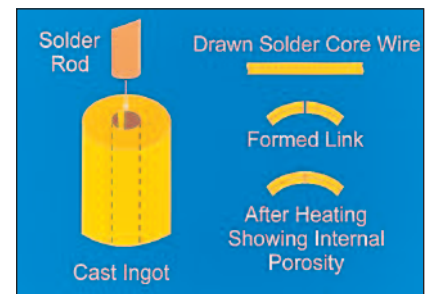


Figure 5.3 Sketch of making solder cored wire for chainmaking



Figure 5.4a Photograph of a cross-section of a 14 carat gold chain link joined using solder-filled wire. a) A good joint

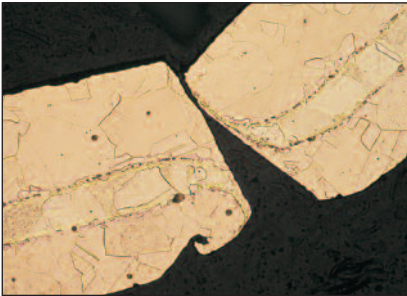


Figure 5.4b Poor joint due to smearing of cut wire

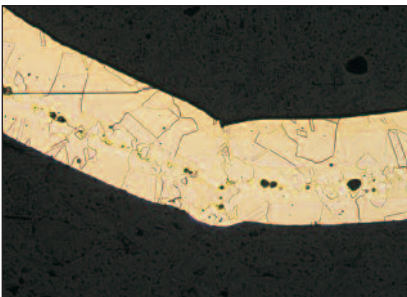


Figure 5.4c a joint showing porosity in the solder core (courtesy Cookson Precious Metals Ltd)

diameter is established at the outset and it is preserved through the rolling and drawing stages. Attention has to be given to working and annealing schedules to ensure that the hidden core does not fracture due to overworking. The core bonds to the outer jacket by pressure welding accompanied by diffusion during annealing. During the subsequent soldering of chain, the solder flows out of the core by capillary attraction into the gaps in the chain links to form the joints. Some consideration has to be given to link gap design to ensure a correct flow pattern during soldering. Ideally, the ends of the wire pieces are cut so that as the ends come together to form the links, a flat butt joint with virtually a zero gap is obtained, Figure 5.4a. If the ends of the links are not cut cleanly but smear due to a blunt cutter, then the solder may not be able to flow out from the core into the link gap, Figure 5.4b. The small amount of porosity created within the core does not cause any significant loss of strength and it is contained within the links, Figure 5.4c.

5.4 SOLDER PASTE

There has been a very important development within the last 30 years that is of benefit to both the craftsperson working at the bench and to the manufacturer of mass-produced jewellery, namely, the introduction of solder pastes. The pastes are homogenised mixtures of solder in the form of a very fine pre-alloyed carat gold powder combined with an organic binder, which may or may not contain a flux. The presence of a flux depends on whether soldering is to be done in air with torch heating or in a furnace with a protective gas atmosphere, in which case it is not needed. The paste is dispensed from a plastic syringe through a hollow needle of appropriate inner diameter, Figure 5.5a.

The requirements of a suitable carat gold solder paste are that it should have:-

- a controlled solder composition of the desired caratage, colour and working temperature,
- a controlled solder particle shape and size distribution,
- freedom from oxide contamination,
- a minimum storage life of at least one year,
- the ability to be dispensed with reliability through needles with inner diameters down to 0.25 mm.

The pre-alloyed solder powder is produced from the melt by gas atomisation in the presence of a protective atmosphere. This gives a powder that has a homogeneous composition, is free from oxidation and has a spherical shape. The powder is sized using standard mesh-size sieves, as size distribution needs to be classified according to the needle dimensions and the soldering application. The binder is based on organic constituents, which are stable for long periods of time and which volatilise on heating to leave no, or minimum, residue. The rheology (viscosity) of the paste must be appropriate for use and paste stability during storage. A flux addition is made to pastes for use with torch heating or where heating with a high frequency induction coil may be used in an automated set-up. As stated above, a flux is not required for furnace heating as the protective atmosphere prevents oxidation.

One leading manufacturer supplies a wide range of gold solder pastes as follows:-

- caratages from 8 ct to 22 ct in yellow, white and rose-pink colours,
- working temperatures from 'extra-easy' to 'hard',
- with or without flux,

- a variation in the percentage of solder powder in the paste, eg 65 or 78% for torch heating and 89, 91 or 94% for furnace heating with protective atmosphere.
- two different grain size classifications for needles with 0.4 mm minimum ID or 0.25 mm minimum ID.

With few exceptions, the solder pastes are cadmium-free and, therefore, do not give rise to toxicity problems when soldering at the bench. A coding system is used to denote each type of solder paste in terms of the above parameters so that the appropriate formulation can be selected for a particular soldering application.

Solder paste is generally available loaded in plastic syringes for dispensing. However, it is also available in plastic pots on special order. Syringe sizes range from 3cc, containing 8-10g paste, up to 30cc, containing 75-100g, depending whether they are to be used for torch or furnace soldering. The syringes may be fitted with interchangeable needles having internal diameters ranging from 0.25 to 2.2 mm. The hand-held dispenser, Figure 5.5b, is easy to use and is ideal for small jewellery workshops. With minimum experience, less than 0.001g of paste can be dispensed for each operation of the dispenser. For example, using a 3cc syringe containing 10g of paste and a needle of 0.40 mm ID, it is possible to dispense ~10,000 dots of paste.

Electro-pneumatic pulsed air dispensers, Figure 5.6, are best suited for dispensing paste in equal amounts for large production runs. A timer or a foot switch actuates the dispensing cycle. A compressed air supply is required. The amount of paste deposited is controlled by selecting a combination of air pressure, needle size and timer setting. Larger syringes containing up to 100g of paste are available for use in these dispensers. They can be incorporated into manufacturing lines giving a degree of automation. SEMCO cartridges containing up to 1000g of paste that can be incorporated in pneumatic and electro-pneumatic systems are available for large volume requirements. More recently, a computer controlled automated dispenser has been developed, which gives movement in the X, Y and Z directions together with rotational movement. The paste is deposited by a special dispensing head in which there is an archimedes screw. The head is positioned and moved according to a grid planned on the computer screen.

It is true that solder pastes cost more than the conventional strip and wire forms. This is because of the added costs of making the powder, mixing it with the flux and binder and in packaging the product. However, there are considerable benefits and many of these offer economic advantages in cost savings. The benefits include:-

- a) A reduction in the reject rate of soldered joints. This is significant in furnace soldering operations where paillons positioned by hand frequently are shaken out of place due to vibrations of the conveyor belt. One advantage of the paste is that it will stick where it is deposited.
- b) Productivity is increased because less time is spent in applying the paste to the joint, compared with the time spent in preparing and positioning paillons, and fluxing is eliminated.
- c) The solder paste can be positioned accurately (and stays in position during heating).
- d) The exact amount of paste in small quantities can be applied. This means that there is less wastage of an expensive solder alloy. The joint area is free of excess solder and subsequent finishing operations are easier to perform.
- e) The soldering operation can be automated for long production runs.
- f) It may be possible to reduce the number of personnel while still maintaining an



Figure 5.5a A hand-held solder paste dispenser. (Courtesy Hilderbrand & Cie SA)



Figure 5.5b A hand-held solder paste dispenser in use. (Courtesy Hilderbrand & Cie SA)



Figure 5.6 An electro-pneumatic solder paste dispenser. (Courtesy Hilderbrand & Cie SA)

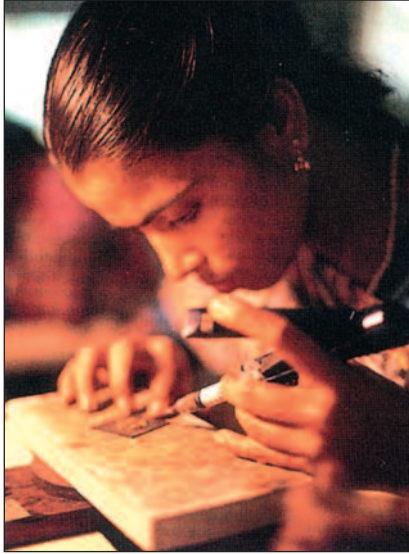


Figure 5.7 Application of solderpaste to traditional 22 ct gold jewellery

increased rate of production.

g) A relatively unskilled workforce can be easily trained to use the dispensing equipment and to solder jewellery quickly and efficiently, Figure 5.7.

There is no doubt that the introduction of solder pastes has greatly improved the precision and productivity of soldering operations in the manufacture of jewellery and watchmaking. Despite the higher initial cost, its use is cost effective in both small workshop and mass manufacturing situations. It can be particularly useful in making 'difficult' soldered joints that otherwise can be time-consuming to do. Because of the range of pastes available, it is important that manufacturers should discuss their requirements with suppliers of pastes and dispensers so that the optimum selection may be made for a particular application.

6 COMPOSITIONS OF SOLDER ALLOYS

The main requirements of gold solder alloys have been stated earlier, namely, that they should have:-

- the correct caratage, with few exceptions,
- a colour match as near as possible to the parent carat gold alloy being joined,
- suitable properties of strength, ductility, wear and tarnish resistance,
- a liquidus temperature lower than the solidus temperature of the parent metal,
- a suitable melting range, and
- no problems in melting, casting and working or with recycling scrap.

Ideally, the caratage should be the same as that of the jewellery alloy and this is stipulated within the hallmarking regulations of some countries, although there may be exemptions for certain categories of jewellery. The colour match is desirable for aesthetic reasons but is not always easy to attain, particularly with high carat gold jewellery. The higher the caratage, the greater the limitation on varying alloying additions to achieve the desired colour. It may be necessary to design the piece so that the soldered joint is hidden from direct view. Alternatively, a subsequent electroplated carat gold layer will present a uniform colour. If the mechanical properties are greatly different to those of the parent metal, subsequent finishing and wear and tear may accentuate the appearance of the joint.

The liquidus temperature and melting range of a solder alloy are governed by the metallurgy of the alloy system. Many solder alloys are based on and around eutectic compositions. A eutectic alloy has a melting temperature that is lower than that of the constituent pure metals (or intermediate phases) that make up the system. For example, the well-known lead-tin solders and the industrial brazing alloys based on the silver-copper-zinc system are eutectic in nature.

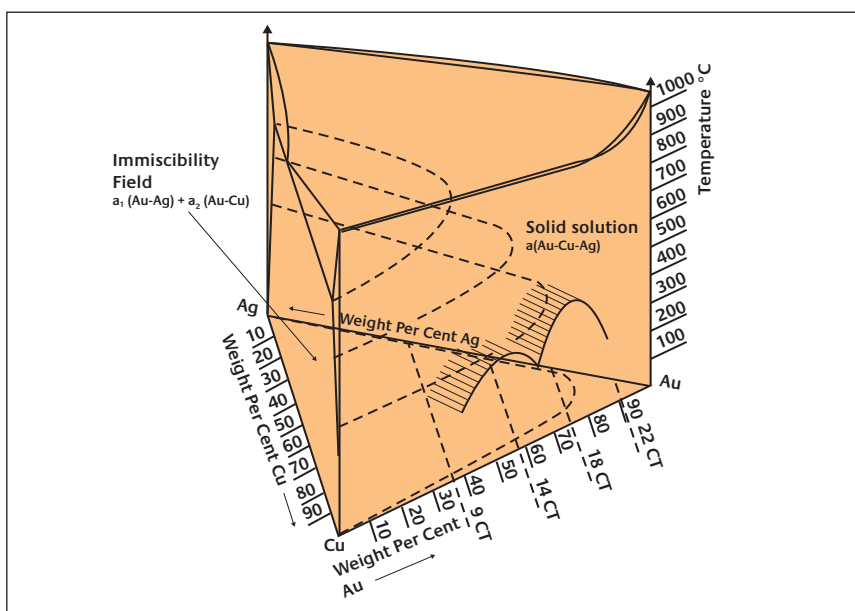


Figure 6.1 Ternary phase diagram for Au-Ag-Cu alloys

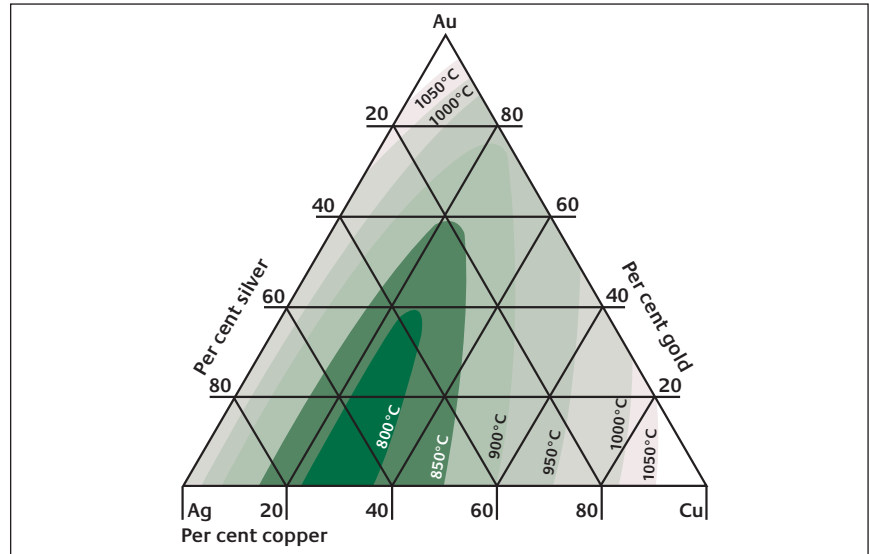


Figure 6.2 The liquidus surface of ternary Au-Ag-Cu alloys

The same is true, to a large extent, for the carat gold solder alloys. The phase diagram for the ternary gold-silver-copper (Au-Ag-Cu) alloy system shows a valley in the liquidus surface extending across the diagram from the binary eutectic in the Ag-Cu system on one side*, Figures 6.1 and 6.2.

In earlier times, gold solders had compositions based around the eutectic valley since these had the lowest liquidus temperatures and were often referred to as ‘self-type’ solders. They worked best for jewellery parts of a composition not close to the valley where the solidus is above the liquidus of the solder. Increasing the Cu:Ag ratio tends to lower the liquidus for a particular composition except for high ratios at low caratage, Table 6.1. It will be noted from the Table that the temperature at which the solder flows is higher than the liquidus temperature. The other problems with ‘self-type’ solders are that there is usually a colour mismatch and it is difficult to find a suitable solder composition for yellow gold jewellery because they have compositions also close to the valley.

Traditionally, zinc (Zn), cadmium (Cd) and nickel (Ni) additions have been made to the ternary gold (Au)-silver (Ag)-copper (Cu) alloys to lower the liquidus temperature and melting range and also to make adjustments within caratage for colour. Provided the zinc level is kept below ~5%, the vaporisation of zinc from the alloy is minimal. Higher zinc contents will lead to loss of zinc on heating and the risk of pinhole porosity in the joint. Furthermore, too much zinc will reduce the ductility and malleability of the alloy. Therefore, there is a limitation, particularly for high carat solders, on the amount of zinc that can be added in order to lower the liquidus temperature. The toxicity of cadmium has been referred to and will be discussed fully in Section 8. For this reason, there has been considerable research and development work on finding suitable alloying additions that replace the need for cadmium. Modern solder alloys contain tin (Sn), indium (In) and gallium (Ga), in place of cadmium, in varying amounts to control melting range, liquidus temperature, colour

* **Footnote:** There is a full discussion on phase diagrams and their interpretation in “A plain man’s guide to alloy phase diagrams: Parts 1 and 2” in Gold Technology, Nos. 29 and 30, 2000.

Table 6.1 The effect of varying the silver and copper contents on liquidus and flow temperatures. (After W. S. Rapson and T. Groenewald)

Gold	Composition wt. %		Cu:Ag Ratio	Liquidus temp. °C	Flow temp. °C
	Silver	Copper			
22 carat gold					
91.6	6.3	2.1	1:3	1024	1035
91.6	4.2	4.2	1:1	971	1003
91.6	2.1	6.3	3:1	954	979
18 carat gold					
75.0	21.4	3.6	1:6	976	1005
75.0	17.0	8.0	1:2	934	968
75.0	12.5	12.5	1:1	882	905
75.0	8.0	17.0	2:1	882	893
75.0	3.6	21.4	6:1	881	902
9 carat gold					
37.5	53.5	9.0	1:6	905	948
37.5	41.5	21.0	1:2	800	820
37.5	31.25	31.25	1:1	825	863
37.5	21.0	41.5	2:1	875	900
37.5	9.0	53.5	6:1	915	950

and caratage. Grain refiners, such as iridium (Ir), cobalt (Co) or nickel (Ni), also may be present in small amounts (~0.1%) to minimise grain growth in the solder layer within the joint.

Normandeau (Santa Fe Symposium 1989 and Gold Technology No.18) has discussed the development and properties of a wide range of cadmium-free solders. It was found (SFS 1990) that a surface corrosion layer of indium cyanide could be obtained in pieces that were subsequently chemically 'bombed' in hot cyanide/peroxide solutions, necessitating additional abrasion and polishing. This highlights the desirability of avoiding the use of 'bombing' in addition to the dangers posed by using cyanide. Ott has presented work on cadmium-free 21 carat gold solders (Gold Technology No.19). He showed that these alloys need a high Cu:Ag ratio for indium and gallium additions to be effective in lowering the liquidus. Generally, it has been found that the Cd-free solders can be produced with melting ranges suitable for easy, medium and hard solders and with mechanical properties and workability similar to solders containing cadmium. Cd-free solder alloys are now widely used in the industry with excellent results. Table 6.2 gives a list of typical compositions, melting ranges and properties for coloured solder alloys from 9 carat to 22 carat.

Generally, white gold solders have been based on the Au-Cu-Ni system with extra additions of silver, copper and zinc to adjust for a suitable melting range. Cadmium-free white gold solders have been formulated and are given in Table 6.3. However, little has been published on the availability of Ni-free white gold solders. This could be of importance in view of the directives that have been issued on the use of nickel in jewellery. It is possible that the relatively low nickel content of the solders, compared to the levels found in Ni-white carat gold jewellery, may mean that they can continue to be used provided the nickel-release test conditions are met. Bagnoud *et al* have stated briefly that manganese (Mn) additions of 3-5% give solder alloys with acceptable colour properties while having a melting range adapted to Ni-free white golds. However, details of composition, liquidus and melting range were not presented. Rapson and Groenewald refer to a white gold solder, originally

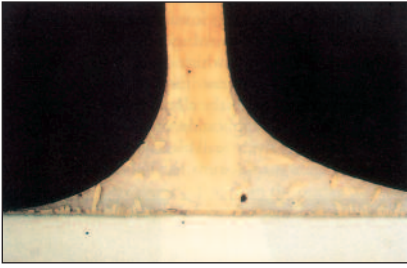


Figure 6.3 Photomicrograph of a soldered joint using the 22 carat Au-Ge-Si alloy

reported in 1929, having a composition of 75%Au-15%Ag-10%Pt. According to phase diagram data for the Au-Ag-Pt system, this alloy appears to have a liquidus temperature of ~1180°C. Thus, it would seem to be suitable for some of the commercially available Pd-white gold jewellery alloys.

Recently, low temperature high carat gold solders have been developed. They are based on the gold-silicon (Si) and gold-germanium (Ge) alloys used in the electronics industry. Sangha *et al* (Gold Technology No.19) and Jacobson *et al* (Gold Bull. Vol. 29 (1), 1996) describe a 22 carat Au-6.6%Ge-1.7%Si solder composition that lies in a eutectic valley in the Au-Ge-Si system. The alloy has a narrow melting range and is fully molten above 382°C. Soldering must be done without a flux in a furnace at 425°C with an inert nitrogen atmosphere. Holding the jointed assembly at 280°C for 30 minutes during subsequent cooling gives an excellent colour match between the solder and a 22-carat yellow gold, Figure 6.3.

The use of solder-filled wire or laser welding is being used increasingly for joining the links during chainmaking. For many years, the conventional method of soldering links has been to impregnate the link gaps with a solder alloy powder containing silver, copper and phosphorus with small additions of zinc and tin. The powder mix is dispersed in a carrier such as castor oil and an organic solvent with no flux (the alloy

Table 6.2 Compositions of some typical coloured carat gold solder alloys and their solidus to liquidus melting ranges

Carat	Au %	Ag %	Cu %	Zn %	Cd %	In %	Sn %	Ga %	Grade	Colour	Melting Range °C
22	91.6	0.4	3.0	5.0	-	-	-	-	Easy Medium Hard	Yellow	865-880
	91.6	-	-	8.4	-	-	-	-		Yellow	754-796
	91.8	2.4	2.0	1.0	-	2.8	-	-		Yellow	850-895
	91.8	3.0	2.6	1.0	-	1.6	-	-		Yellow	895-900
	91.8	4.2	3.1	1.0	-	-	-	-		Yellow	940-960
21	87.5	-	4.5	4.0	-	-	4.0	-	Easy	Yellow	662-813
	87.5	-	5.5	4.8	-	2.2	-	-	Medium	Yellow	751-840
	87.5	4.0	3.5	5.0	-	-	-	-	Hard	Yellow	834-897
18	75.0	12.0	8.0	-	5.0	-	-	-	Easy Medium Hard Hard	Yellow Yellow Yellow Yellow Red	826-887
	75.0	9.0	6.0	-	10.0	-	-	-			776-843
	75.0	5.0	9.3	6.7	-	4.0	-	-			726-750
	75.0	6.0	10.0	7.0	-	2.0	-	-			765-781
	75.0	6.0	11.0	8.0	-	-	-	-			797-804
	75.0	5.25	12.2	6.5	-	1.0	-	-			792-829
14	58.5	25	12.5	-	4.0	-	-	-	Easy Medium Hard	Yellow Yellow Yellow	788-840
	58.5	8.8	22.7	-	10.0	-	-	-			751-780
	58.3	14.4	13.0	11.7	-	2.5	-	-			685-728
	58.3	17.5	15.7	6.0	-	-	2.5	-			757-774
	58.3	20.0	18.2	3.5	-	-	-	-			795-807
10	41.7	27.1	20.9	5.3	-	2.5	2.5	-	Easy	Yellow	680-730
	41.7	29.4	22.2	4.2	-	-	2.5	-	Medium	Yellow	743-763
	41.7	33.2	23.9	1.2	-	-	-	-	Hard	Yellow	777-795
9	37.5	31.9	18.1	8.12	-	3.12	-	1.25	Extra Easy	Yellow	637-702
	37.5	29.4	19.4	10.6	-	2.5	-	0.62	Easy	Yellow	658-721
	37.5	36.3	18.2	8.0	-	-	-	-	Medium	Yellow	735-755
	37.5	29.8	27.5	5.2	-	-	-	-	Hard	Yellow	755-795
	37.5	26.1	27.4	9.0	-	-	-	-	-	Red	685-790

N.B. Some of these formulae may be patented.
Some of the data refer to the liquidus temperature as the flow point.

Table 6.3 Compositions of some typical white carat gold solder alloys and their solidus to liquidus melting ranges

Carat	Au %	Ag %	Cu %	Zn %	Ni %	In %	Sn %	Pt %	Grade	Melting Range °C
	83.3	-	-	6.7	10.0	-	-	-	Hard	855-885
	80.0	-	-	8.0	12.0	-	-	-		782-871
18	75.0	-	6.0	13.5	5.5	-	-	-	Easy	802-826
	75.0	-	9.0	7.0	9.0	-	-	-	Hard	843-870
	75.0	15.0	-	-	-	-	-	10.0		? - ~1180
	75.0	-	6.5	6.5	12.0	-	-	-	Easy	803-834
	75.0	-	1.0	7.5	16.5	-	-	-	Hard	888-902
14	58.33	22.0	4.42	12.0	1.25	2.0	-	-	Easy	695-716
	58.33	26.0	3.67	9.0	3.0	-	-	-	Hard	755-805
	58.33	15.75	5.0	15.9	5.0	-	-	-	Easy	707-729
	58.33	15.75	11.0	9.2	5.0	-	-	-	Hard	800-833
10	41.67	35.0	13.5	5.83	-	1.0	3.0	-	Easy	715-745
	41.67	42.0	9.83	3.0	-	-	3.5	-	Hard	770-808
	41.67	28.1	14.1	6.13	10.0	-	-	-	Easy	763-784
	41.67	30.13	15.1	1.1	12.0	-	-	-	Hard	800-832
9	37.5	33.4	23.1	-	-	3.0	3.0	-		725-735

N.B. Some of these formulae may be patented.

is self fluxing). The chain lengths are passed through this mixture and then rubbed or tumbled with talc to remove excess mixture from the surfaces. Heating drives off the oil, melts the solder and joins the links. It will be noted that gold is not present in the solder alloy and, therefore, the wire used to make the chain should be overcarated, say by 4 parts fineness, to compensate and ensure that the chain will have the required caratage.

It is recommended that one should buy gold solder alloys from specialist suppliers because it is rarely economic for the craftsperson or small scale manufacturing jeweller to make their own solders with controlled caratage, colour and melting range. This is particularly true for solder pastes which require specialised processing equipment and which are sold with different viscosities, grain sizes, and with or without flux.

7 OTHER JOINING METHODS

Although this Handbook is concerned mainly with soldering as the joining method most widely practised in the manufacture of jewellery, there are other joining techniques that have assumed a greater importance in recent years. This section describes some of these techniques and briefly discusses their important features.

7.1 LASER BEAM WELDING

Laser beam welding first came to prominence in jewellery manufacture as a means by which chain links could be joined as each link was formed during the chain making process. Since then, other jewellery applications, such as weld repairs and joining of ring shanks, have been made possible by the development of portable laser welding equipment. The word 'laser' is an acronym for 'Light Amplification by Stimulated Emission of Radiation'. The laser beam is a source of coherent monochromatic light that can be sharply focused with a controllable high heat input onto a very localised area of a workpiece.

A sketch of a laser generator is shown in Figure 7.1. The material used for generating the laser beam is a crystal rod of yttrium aluminium garnet doped with ~1% of neodymium (Nd-YAG laser). A continuous arc or flash lamp, such as a Krypton or Xenon lamp is the power source by which the Nd-YAG rod is excited to an energy level giving a stimulated emission of photons. Two mirrors facing each other at each end of the rod concentrate the photons into a beam of coherent monochromatic light, i.e. the light waves are in phase (coherent) and have a single wavelength (monochromatic). One of the mirrors is 100% reflective but the other only reflects ~80% allowing the beam to pass through it to a focusing lens system. The generator includes a Q-switch which when opened releases the laser energy as a high powered pulse. Although other laser materials can be used for various applications, the Nd-YAG laser is best suited for jewellery purposes. It has an operating wavelength of 1064 nanometres, which places it in the infrared range of radiation invisible to the naked eye. The flash of light seen when laser welding is caused by a plasma (ionised gas) produced at the weld site. **[Warning. Although invisible, the eye can still focus the beam onto the retina and cause permanent eye damage. See Section 8.]**

Table 7.1 Typical operating parameters for laser welding

Pulse voltage to trigger Xenon flash *	200-400 volts
Input power supply	115 or 200-240V/50-60Hz/single phase
Max. average operating power	30-80 watts
Focal spot diameter	0.2-2 mm
Pulse energy	0.05-80 joules (watt.sec)
Peak pulse power	4.5-10 kilowatts
Pulse duration	0.5-20 milliseconds
Pulse frequency	1-10 Hz

* Pulse energising voltage affects the laser beam output power

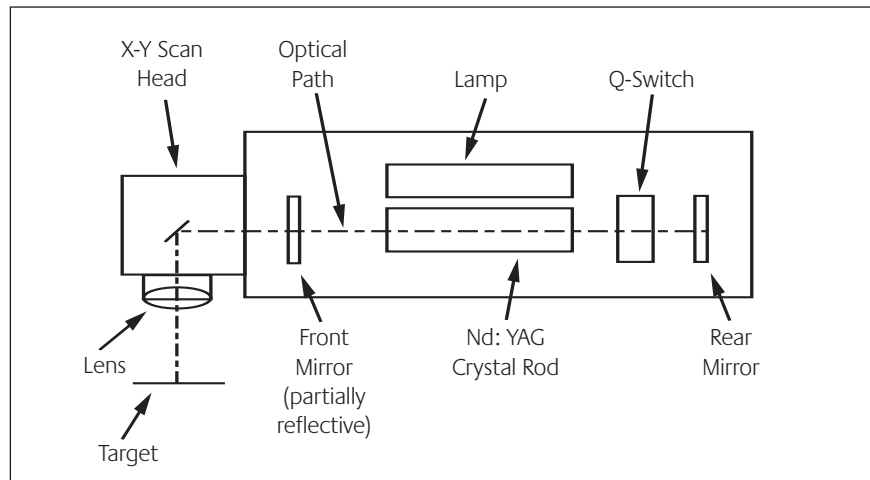


Figure 7.1 Sketch of a Nd-YAG laser generator

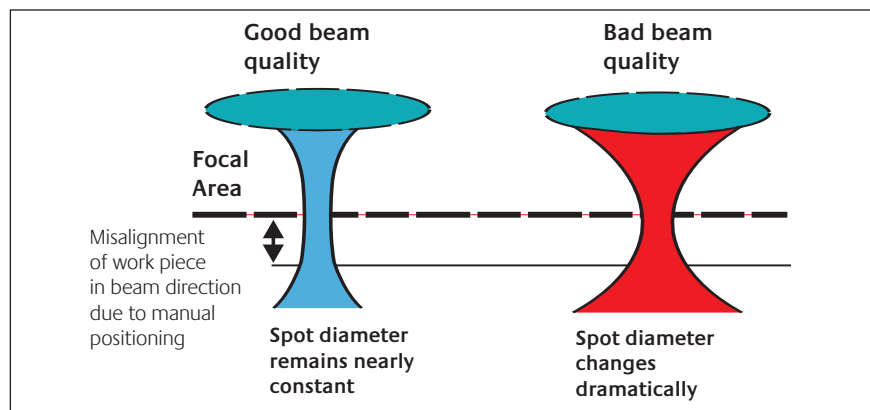


Figure 7.2 Diagram of laser beam shapes. (Courtesy J. C. Wright)



Figure 7.3 Typical laser machine used for jewellery operations

Lasers for jewellery production are relatively low powered and pulsed. Wright has presented typical operating parameters for jewellery laser machines, Table 7.1.

A multi-element lens system focuses and shapes the beam. Ideally, the beam should have a cylindrical shape in its focal area. This increases the depth of focus to several millimetres and allows for variations in manual positioning of the workpiece, Figure 7.2. Portable jewellery laser machines, Figure 7.3, have a stereomicroscope with cross hairs for positioning and targeting areas to be welded. Typical pulse energising voltages and pulse duration times for gold alloys are:-

	Pulse energising voltage	Pulse duration time
	V	ms
999 gold	300-400	10-20
18 ct yellow	250-300	2.5-10
18 ct white	250-280	1.7-5.0

Increasing the voltage increases the depth of penetration of the beam while increasing the pulse time increases the total pulse energy and radial heat flow. Increasing the beam diameter gives a greater heat spread rather than penetration. One problem with gold and its alloys is that they have a high reflectivity. The Nd-YAG laser is best suited to deal with this but it may be necessary in some instances, but not always, to increase absorptivity by darkening the target area. This can be done

simply by marking with a dark felt tip pen.

For chainmaking, the beam can be passed through several metres of optical fibre to the focusing lens, Figure 7.4, placed above the formed link at a working distance of 40-70 mm. The pulse is timed to coincide with the link ends coming together so that the weld is made simultaneously, Figure 7.5. The machine can easily deal with a production rate of 300 links per minute.

There are many advantages offered by laser welding. Little heat is generated outside the weld area and this means that:-

- Welding can be done close to gemstones, *eg* claws (prongs) can be repaired without the need to remove stones and re-set them afterwards.
- No flux is needed.
- The operator can hold the pieces to be joined in the hands so that less fixturing is required. Arms are put through openings on each side of the machine so that the hands and pieces are enclosed entirely within the machine.
- Several welding operations can be done on the same workpiece without the need to worry that earlier joints may re-melt because the heating is highly localised.
- Filler rods for weld repairs are of the same carat gold as the workpiece and, therefore, there are no problems with caratage or colour mismatch. This is particularly advantageous for high carat golds (>22 ct) where suitable solder alloys are unobtainable.
- Ring shanks can be joined by laser welding, Figure 7.6. More than one welding pass is required to achieve the depth of penetration and subsequent smoothing of the surface.
- Generally, experience has shown that laser welds are stronger and more ductile than the equivalent soldered joints and contain little or no porosity.
- The toxicity problems associated with some alloying elements in solders, *eg* cadmium, are avoided.

There are some disadvantages. Laser beam welding takes longer than the traditional soldering methods. With the exceptions of chainmaking and laser granulation, Figure 7.7, it is not easily suited to mass production joining. The welds tend to have a bulbous overlap, which needs to be removed by subsequent grinding and polishing. It may be impossible to make some joints because of their position, as laser welding is a 'line-of-sight' operation. Finally, although the cost of portable laser machines has come down considerably in recent years, they may be too expensive for the individual craftsman.

7.2 FUSION WELDING

Fusion welding can be defined as localised melting together of the joint surfaces, with or without the addition of a filler metal, caused by heating with a gas or plasma torch or the discharge of electricity when the surfaces of two parts connected to electrodes of opposite polarity are brought together. Fusion welding processes include tack welding for fixturing (described in Section 4.2), plasma arc welding and electrical resistance spot and seam welding.

Fusion welding processes are ideally suited to mass production operations as well as one-off and short production runs. This is true particularly for the production of jewellers findings, *eg* ear posts and clips, cuff link connections, lapel posts, screw posts, brooch joints and catches, etc. Alves has described the process where nibbed findings, such as posts, are brought into contact with a piece of jewellery. The

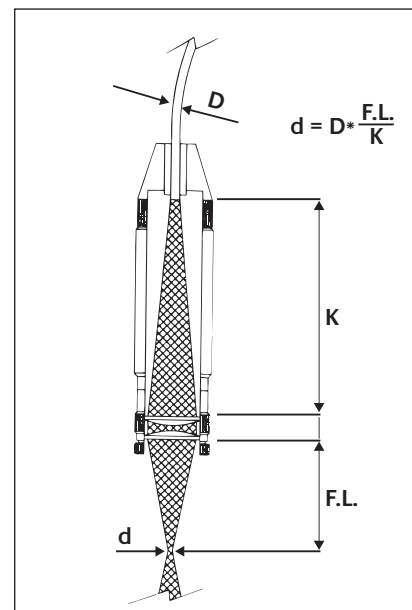


Figure 7.4 Laser beam passing through a focusing lens system

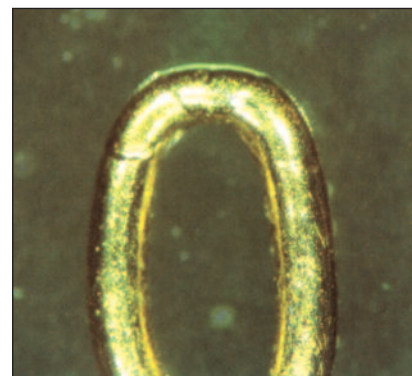


Figure 7.5 18 carat gold chain link welded by laser beam



Figure 7.6 Microphotograph of a laser welded ring shank



Figure 7.7 A 22 ct yellow gold sphere granulated by laser welding onto an 18 ct white gold sheet



Figure 7.9 Nibbed findings. (Courtesy J. Alves)

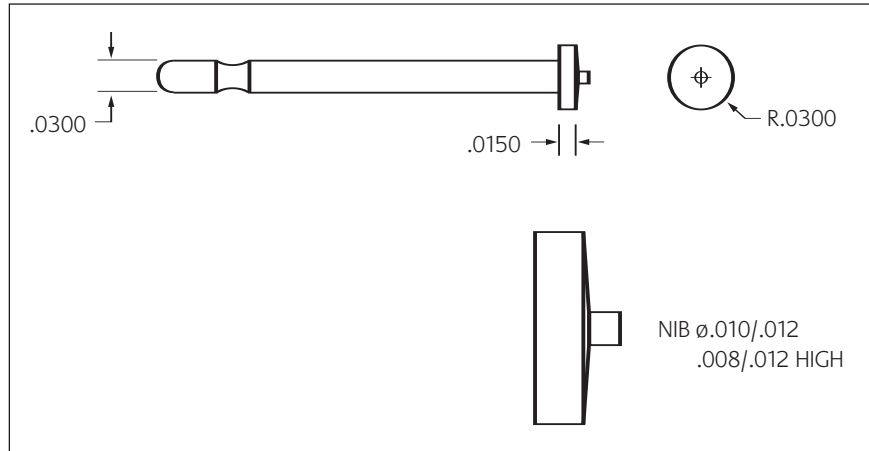


Figure 7.8 Sketch of nib arrangement for fusion welding. (Courtesy J. Alves)

discharge of electricity from capacitors vaporises the nib as it contacts the surface to be joined. The nib is an integral part of the finding and is not an additional part or a piece of solder, Figures 7.8 and 7.9. This causes a plasma arc to form that generates enough heat to melt the surfaces of the finding and the jewellery, Figure 7.10. Instant cooling gives a strong weld, Figure 7.11.

Advantages offered by the process are that:-

- fusion welding produces strong joints,
- there is little heat transfer to the surrounding area and, hence, no oxidation, discoloration or annealing,
- since solder has not been used to make the joint, the caratage should be assured,
- there are no environmental or toxicity problems,
- less skill and training are required compared to traditional soldering techniques,
- it is a fast mechanised process.

It is important that the correct voltage and current (amperage) settings are used for a particular application otherwise poor welds will result. Equipment manuals

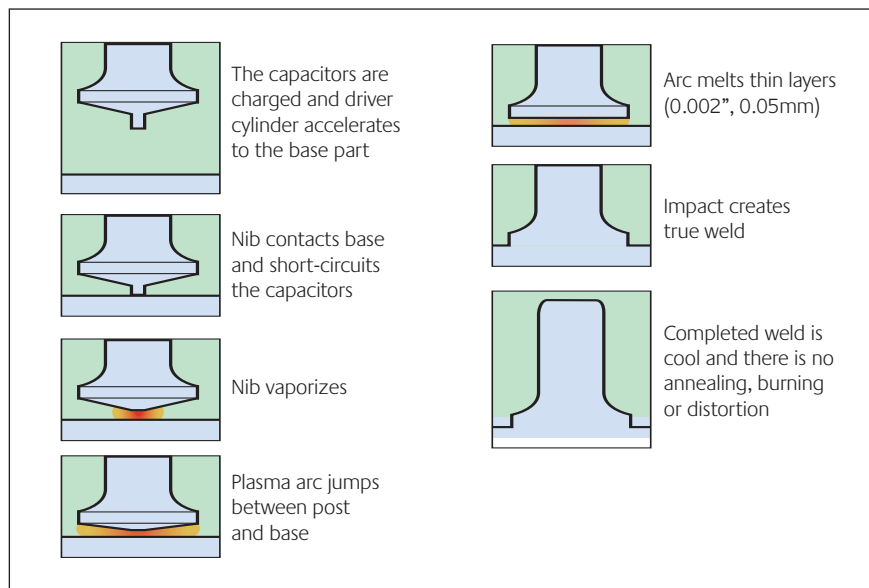


Figure 7.10 Process stages in electric discharge fusion welding. (Courtesy J. Alves)

should include guidelines for initial settings that can then be adjusted with experience by the manufacturer. Burn marks on jewellery are an indication that improper contact is made with the clamping jig, which is attached to one of the electrodes.

There is a wide range of fusion welding machines on the market. These are either automatic or manual feed with prices ranging from a few hundred to several thousand dollars, Figures 7.12 and 7.13. The low-cost welders are suitable for small workshops and do not require compressed air. An air compressor is required with the larger machines.

Controlled electric discharge welding has been adapted for the welding of carat gold chain links. It is similar to laser beam welding of chain in that the welding equipment is incorporated into the chain-making machine so that each link is welded as it is formed without the addition of any filler material. The welding nozzle is shown in Figure 7.14. An inert gas, such as argon, is ionised by the electrical discharge at a potential difference of 2000-3000 volts in ~ 0.2 milliseconds (ms). The ionised gas is strongly heated by the current passing through it. The hot gas flows out of the nozzle and strikes the piece to be welded. The discharge to weld cycle time is in the range 1-9 ms. The advantages are:-

- the chain is not handled and, therefore, there is no risk of opening the links before they are joined,
- all caratages up to 24 carats can be welded,
- the process is non-polluting,
- and it requires a low electric power input.

7.3 DIFFUSION SOLDERING

Diffusion bonding is a process whereby a strongly bonded joint is made by the migration (interdiffusion) of atoms to and across the interface at the surfaces to be joined. It may or may not require a filler metal, say in the form of an inserted foil, and it may or may not involve the formation of a transient liquid phase. This depends on

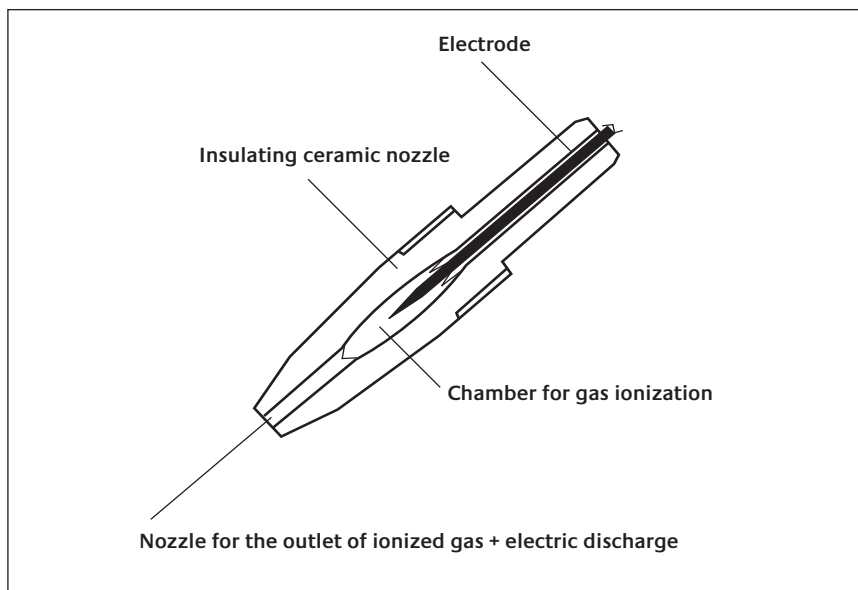


Figure 7.14 Welding nozzle for plasma gas electric discharge welding



Figure 7.11 A typical electric discharge fusion weld. (Courtesy J. Alves)

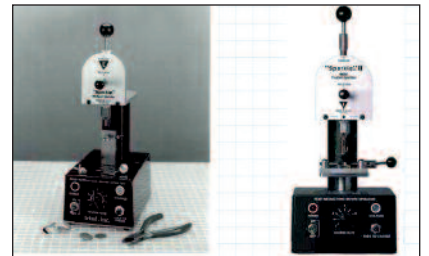


Figure 7.12 A low-cost fusion welder. (Courtesy J. Alves)



Figure 7.13 Higher cost fusion welder. (Courtesy J. Alves)

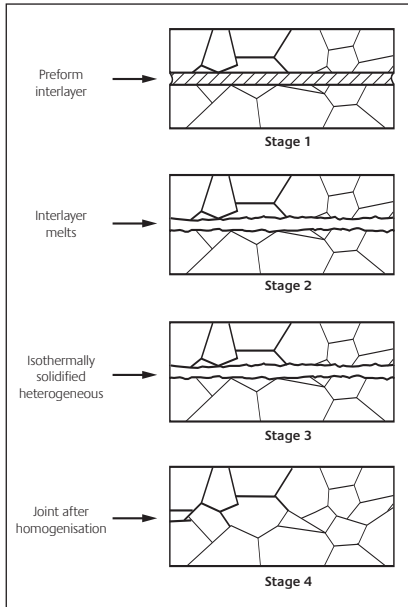


Figure 7.15 Sequence of steps in diffusion soldering with a tin layer

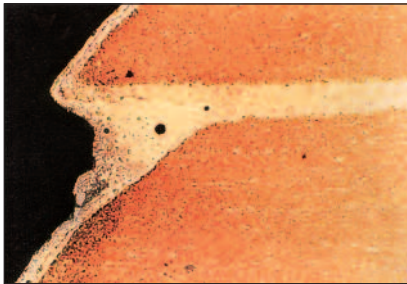


Figure 7.16 Microsection of diffusion soldered 18 ct gold joint before homogenisation showing the central gold/tin foil

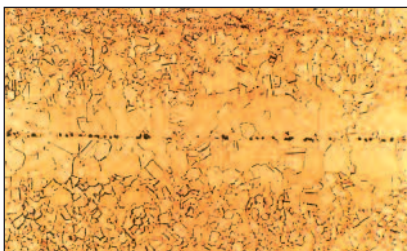


Figure 7.17 Microsection through a homogenised diffusion soldered joint in 18 carat gold. A different 18 carat gold alloy was used as the carrier foil

the materials being joined and on the metallurgy of their alloy systems. If a filler is used and there is a transient liquid phase, which implies a form of soldering, the term 'diffusion soldering' is more applicable. Figure 7.15 shows the sequence of steps in diffusion soldering. A thin preform of the solder is laid between the surfaces to be joined. The interlayer melts when the assembly is heated. Further heating causes interdiffusion by migration of atoms across the interface leading to the disappearance of the liquid phase and homogenisation in composition.

The technique has been used successfully for high carat gold alloys using a thin film of tin as the solder. Because a tin foil only a few microns thick would be too fragile, tin is electrodeposited on both sides of an annealed carat gold foil of 75 μm minimum thickness, which acts as a carrier for the solder. The caratage of the foil is slightly higher than that of the jewellery pieces to allow for the small addition of tin. The electroplated preform is dipped in a liquid flux that is chemically active at $\sim 250^\circ\text{C}$ and placed between the jewellery pieces. Tin melts at 232°C so that heating to 250°C allows the molten tin to flow, fill the joint and react with the surfaces and the gold foil to give isothermal solidification within a very short time of a few tens of seconds. A small compressive stress of $\sim 1\text{Mpa}$, obtained by applying a load in the fixturing jig of 100g per square millimetre of joint area, assists in forcing the joint surfaces into close contact. The item is then strong enough to be removed from the jig and transferred to a furnace at 450°C in order to homogenise the joints, Figures 7.16 and 7.17. The process is particularly suitable for 18 and 22 ct yellow gold wrought alloys but can be used also for high carat casting alloys containing zinc and 990 GOLD (gold-1% titanium alloy). Tests have shown that these joints are stronger than conventional soldered joints. The process has advantages as follows:-

- the relatively low temperature heat treatment means that the loss of strength and hardness in high carat gold jewellery with traditional soldering, due to high temperature annealing, is avoided,
- the joints are virtually invisible,
- and the flux is not needed if the heat treatment is done in a furnace with an inert nitrogen atmosphere.

Limitations are that the joint area has to be sufficiently large and flat for ease of assembly. Figure 7.18 shows parts of a bracelet and earrings made by diffusion soldering at 450°C .

7.4 ADHESIVE JOINING

Jewellers have tended to avoid adhesive joining as a major joining technique in the belief that adhesives lacked sufficient strength and service life. Consequently, its use has been mainly restricted to costume jewellery, primarily for holding stones or attaching findings. However, there have been considerable advances during the last fifty years in improving the quality of adhesives for engineering applications. Furthermore, most hallmarking regulations permit the use of adhesives in place of solder provided they contain no base metal constituents and are only in quantities necessary for joining.

An adhesive joint relies on both the adhesive strength of the bond between the adhesive and the adherend, i.e. the surface being joined, and on the cohesive strength of the adhesive itself. The overall strength of the joint is determined by the weaker of these two strengths. Various theories have been advanced to explain the nature of the adhesive bond. It is well known that bonding is much better on abraded surfaces than

smooth polished surfaces, indicating that some form of mechanical interlocking occurs with the asperities, i.e. hills and valleys, on the surface. In addition, stronger chemical bonding occurs between the adhesive and the adherend when the adhesive thoroughly 'wets' the surface of the adherend. The principles underlying wetting have been discussed in Section 2c of this Handbook. Good wetting will be achieved provided the adherend surfaces are absolutely clean and the surface energy of the adhesive is much lower than that of the adherend. Typical surface energies in mJ/m^2 are:-

Pure gold	1700
18 ct gold	1650
Organic adhesives (γ_{LV})	30-47

All dirt, oxide films and grease or oil must be removed otherwise the adhesive cannot wet the adherend. One or more of the following cleansing steps may be necessary, namely, acid pickling to remove oxides, vapour degreasing and ultrasonic cleaning with a suitable solvent. Additionally, the cleaned surface may be 'primed' by applying a dilute solution of the adhesive in a solvent so that it dries to give a thin film of $1.5\text{-}50\mu\text{m}$. This assists wetting, gives protection against corrosion, helps to prevent peeling and helps to hold the adhesive in place during bonding.

There is an equation (Stefan's Equation) that predicts that the adhesive bond strength will increase with the viscosity of the adhesive, with the area of contact and with the thinness of the bond layer. This is consistent with observations on adhesive behaviour and is the basis for formulation (composition) of adhesives. They have a low initial viscosity to facilitate wetting and spreading and then increase in viscosity with time through evaporation of a solvent and curing.

Adhesives have a poor resistance to peeling and cleavage and, therefore, to bending loads in certain types of joint configuration. They have a good resistance to compression and to shear. This should be borne in mind when designing jewellery with adhesive joints. In general, butt joints are the weakest joints and lap- or strap-type joints are recommended. Most of the stress is concentrated at the ends of lap joint and very little in the middle. In practice, there is a limit to joint length above which there is no further improvement in strength. Increasing the joint width is more important than increasing the length.

There are many different types or classes of adhesives and it is beyond the scope of this Handbook to describe them in detail. It has been found that epoxides, modified epoxides, acrylics and cyanoacrylates (also known as super glues) have good to excellent adhesion to precious metals but polyurethanes do not offer sufficient compatibility. The joints should be close fitting and squeezed tight with pressure when the adhesive has been applied. It must be remembered that the joint does not reach its maximum strength immediately. It may take several minutes, hours or even days to develop maximum strength and hardness – a process known as 'curing'. However, the assembly should develop sufficient 'green strength' within a few minutes to allow it to be moved carefully. Experience will decide when it is safe to remove the clamping jigs. The curing times and temperatures depend on the type of adhesive being used. The technical services of adhesive manufacturers should be able to advise on the best type of adhesive for precious metal jewellery, curing details and other matters relating to storage, preparation and application.



Figure 7.18 Parts of an 18 ct gold bracelet and earring set assembled by diffusion soldering at 450°C

7 OTHER JOINING METHODS

The advantages of adhesive joining with regard to jewellery are that:-

- it is faster and cheaper than other forms of joining,
- it is done at room or relatively low temperature,
- surface finishing processes may be simplified,
- similar or dissimilar materials may be joined,
- non-metals can be joined to precious metals,
- there may be cost-saving benefits.

The disadvantages of adhesives are that:-

- careful surface preparation is required,
- most adhesives do not withstand heating above $\sim 120^{\circ}\text{C}$,
- the joints are weaker than soldered or welded joints,
- domestic cleaning fluids, solvents, perspiration, etc may adversely affect them,
- it is difficult to cover visible 'glue lines' by subsequent electroplating as they are non-conducting. They can be a source of blistering of platings.

8 HEALTH, SAFETY AND ENVIRONMENTAL POLLUTION

There are a number of issues concerning health, safety and the environment that arise with joining processes. First, there are the materials used to prepare the joint surfaces and to clean away residues. These include solvents, acids, fluxes, defluxing agents, etc., and some of these may be regarded as hazardous materials. Secondly, there are the necessary precautions that have to be taken when using equipment such as gas/air or oxy-gas torches, furnaces with protective atmospheres and laser beam welding machines. Thirdly, some solder alloys may contain cadmium (Cd). This is potentially dangerous to the workforce because the fumes escaping into the atmosphere on melting are toxic. The problem has been referred to briefly in Section 6 but now will be discussed more fully.

It is a legal requirement in many countries that **Materials Safety Data Sheets** are provided by manufacturers of products such as solders, solvents, acids, fluxes, etc. They should be obtained by jewellery manufacturers when ordering such products from suppliers. Advice and information on current legislation on the use of such products can be sought from the relevant Health and Safety organisations in various countries.

8.1 CADMIUM IN SOLDERS

For many years, cadmium was considered to be a very important alloying addition in carat gold solders. It is highly effective in lowering the melting point and in imparting desirable molten metal flow and wetting characteristics. However, cadmium melts at 321°C and has a low boiling point of 765°C. It has a high vapour pressure which means that when it or any alloy containing it, melts, a relatively large amount of cadmium fume is produced. This reacts with oxygen in the air to form a brown vapour of cadmium oxide (CdO) which is poisonous. Long term exposure to cadmium oxide fume can lead to a number of diseases including the lung complaint emphysema, anaemia, bone damage (osteoporosis), kidney damage and cancer. Early symptoms arising from inhalation of fume are irritation and dryness of the nose, a cough, headaches, dizziness, chills, fever and chest pains. Cadmium accumulates in the body and has a biological half-life of 30 years. This makes it more toxic than other metals such as lead and mercury that have shorter half-lives. Furthermore, chelation therapy cannot be used to expel the metal from the body because of the deleterious effect of excreting it through the kidneys.

Government legislation in some countries forbids the use of, or even the import of cadmium-bearing alloys. This is because of the risks to the workforce in soldering operations and in the remelting of scrap. There may be regulations governing the amount of cadmium vapour permitted in the workplace atmosphere. For example, the OSHA 1993 Standard in the USA limits the cadmium level to < 0.01 mg/m³ in the workplace air for an eight-hour working day. This is extremely low. In those countries and workshops that still use cadmium in solder alloys, ventilation and exhaust systems

should be installed or, failing that, the workers should wear respirators, a remedy that will not be liked in hot countries. However, although some vapours and materials can be exhausted safely without any harm to the environment, this does not apply to cadmium. It remains a hazard because it can be breathed in by the general population and it will fall to the ground and get into the food chain.

It is for these reasons that even if legislation on the use of cadmium does not exist in certain countries, **it is strongly recommended that cadmium-free alloys be used for all soldering operations.** Workers using these alloys for the first time may complain that they do not flow as freely as the Cd-bearing alloys. The solution is simply a matter of adjusting the soldering techniques to accommodate any differences in melting and flow characteristics. Cadmium-free solders are widely used in many countries with success and there can be no justifiable excuse for continuing to work with alloys containing cadmium.

8.2 SOLVENTS, ACIDS AND FLUXES

Solvents are used to remove oil and grease from surfaces as part of the surface preparation prior to soldering. Organic solvents, such as the chlorinated organics, are hazardous for four main reasons.

1. They are neurotoxic and can damage the central nervous system.
2. Some solvents are flammable or even have an explosive tendency if combusted in a confined space.
3. Many volatile organic solvents cause air pollution when vented to the surrounding environment. Some countries have government legislation for Clean Air controlling the emission of hazardous air pollutants.
4. Waste solvents present a disposal problem.

Salomon has discussed the replacement of organic solvents with aqueous cleaners. These may be citric acid-based or alkali-based solutions used hot with ultrasonic agitation. They have a low disposal cost and experience has shown that operating costs are considerably lower.

Acid pickles are used to remove dirt and oxide films. The main hazards are acid fume inhalation, which can cause damage to the linings of the nose, throat and lungs, and physical contact, which may cause serious skin and flesh burns. The first of these necessitates the availability of a ventilation and exhaust system and the second means that workers should wear protective clothing, gloves and goggles. Eyewash stations should be provided. Acids can be neutralised by alkalis such as sodium carbonate or bicarbonate. As mentioned in Section 4.4, **when diluting concentrated acid to make a pickle, the acid must be added slowly to the water and not the other way round.** The exothermic reaction that occurs when adding water to sulphuric acid produces intense heat and may cause instantaneous boiling and spillage. Some workshops use 'safety pickle' as an alternative to storing and mixing sulphuric acid. This is sodium hydrogen sulphate that, when dissolved in water at a concentration of 220g/litre, gives what is essentially a dilute solution of sulphuric acid.

Many commercial fluxes are based on complex fluoroborates, borates, fluorosilicates and alkali metal chlorides. There are a number of potential health hazards that manufacturers should be aware of. Prolonged contact with skin may cause some irritation and extra care should be taken if there are any minor cuts or

abrasions. If this becomes a problem, the workers should wear gloves or use a barrier cream. Cuts and abrasions should be covered with waterproof adhesive dressings. It may be an advantage to use a flux paste since this eliminates the contact that may occur when mixing flux powder with water. Fluxes are an irritant also to eyes and any contact should be treated immediately by irrigating (washing) the eyes with water for up to 20 minutes. Medical attention will be necessary if eye damage is suspected.

Fluxes are harmful if accidentally ingested and they should be kept away from foodstuffs and drinks. It is advisable not to smoke and hands and fingernails should be thoroughly washed and cleaned prior to meals. If flux is swallowed, medical aid should be sought and in the meantime the patient should drink milk with calcium carbonate (chalk) mixed in. The recommended medical treatment is to intravenously inject 10% calcium gluconate at hourly intervals. Powder fluxes should be mixed in a special flux tray that is especially reserved for the purpose and they should never be put in a container such as a cup, a mug or a bottle.

Fluxes will fume slightly on heating and cause irritation to the eyes and nasal passages unless there is adequate ventilation and exhaust. This is another good reason for avoiding overheating in soldering operations. Hydrogen fluoride (HF) and boron trifluoride (BF₃) have been identified as gaseous decomposition products. Generally, concentrations within the breathing zone are relatively low but if excessive inhalation occurs, the operator should be removed to fresh air and given oxygen if necessary. Continuous observation for 48 hours may be required also because of the risk of pulmonary oedema.

Burnt gases from torch soldering are oxides of carbon and nitrogen. They are unlikely to cause problems provided that the torches are used in well-ventilated conditions.

Fume cabinets or ventilation and exhaust systems should always be in place in workshops where fumes from solvents, acids, fluxes, etc. can be hazardous to the workforce. System designs have been published (Schneller and Prior). It is important that the system is efficient in drawing away dangerous fumes and dust clouds from the face of the worker. This can be checked by a velometer or a 'smoke test'. The velometer reading should be 30-40 metres per minute (~100 feet per minute). The smoke test is done by placing a tray of dry ice (solid carbon dioxide) and hot water in the vicinity of the worker and seeing that the stream of smoke is drawn into the system in a straight unwavering line. The point away from the exhaust where the line begins to waver is approximately where the flow rate is 100 fpm. Fumes are being vented to the surrounding environment and any legislation concerning air pollution must be adhered to. It must be ensured also that the exhaust is positioned so that the fumes are not sucked into adjacent buildings via air intakes.

8.3 FURNACE SOLDERING AND GAS SUPPLIES

Certain precautions have to be taken when soldering is done in a furnace with a protective atmosphere. Regular maintenance of the furnace, temperature measuring devices and gas generating equipment, *eg* dissociated ammonia plant or cylinders, should be undertaken for both quality control and safety reasons. Hydrogen is present in both dissociated ammonia (75% hydrogen/25% nitrogen) and forming gas (80-90% nitrogen/10-20% hydrogen). Hydrogen is flammable and can cause explosions. It is important to make sure that the gas is burned off as it exits the furnace.

In many instances, protective gas is supplied in tall, slender gas cylinders. It is important that these are securely fastened by chain to a wall or supported in a cylinder stand to prevent accidental overturning. Gas regulators should be checked routinely. Plastic tubing connecting the cylinders to the furnace or torch should be in good condition and securely clamped to the connections. If connected to a piped gas supply, the piping system should be regularly checked for leaks or damage.

8.4 EYE PROTECTION AND BURNS

Eyes may need to be protected if oxy-gas torches are used for high temperature soldering. There is a high proportion of ultraviolet radiation in the white light emitted at temperatures $>1000^{\circ}\text{C}$. Short exposures can leave an 'after image' on the retina that may affect positioning and colour judgement. Long exposures can cause the condition known as 'arc eye', a gritty sensation in the eye. This can eventually lead to retina damage and even blindness. Welding goggles will give protection where such dangers exist. **Do not use sunglasses.** It is necessary to select a suitable filter system that will give a compromise between cutting out the dangerous radiation and leaving enough light intensity and colour to enable the worker to judge position, temperature and melting. Grade 5 filters (British Standard BS679) have been recommended for welding gold alloys or using high temperature solders. The purchase of goggles that flip down after positioning and initial heating may offer an advantage.

The emergence of laser welding as a major joining technique has meant that operators must be protected from laser radiation. The Nd/YAG laser emits infrared radiation that can cause eye damage even though it is invisible. The lens in the eye will focus the radiation onto the retina. The situation may be made worse when a microscope is used to assist positioning the laser onto the workpiece. There are four general classes of lasers but virtually all jewellery lasers are Class 1 and are inherently safe provided certain precautions are taken. Laser welding machines usually have in-built safety features. For example, eyes are protected from direct laser radiation by special shutters that flip down momentarily during the laser pulse. A laser protective filter window gives protection against secondary radiation, including both infrared and ultraviolet light. The laser cannot be generated until both arms have been inserted through the hand openings and interlock switches activated. Local burns may be experienced if a hand is hit by a laser beam. Generally, one or two pulses may only produce a mild discomfort but multiple pulses can give a local but potentially deep burn requiring medical treatment. Items of jewellery, such as rings, should not be worn when operating the machines as the laser beam may strike them and cause rapid heating and burns. Laser devices on chain-making machines should have guards with interlock switches that completely enclose the work zone. Alternatively, the operators must wear anti-infrared goggles. There is an IEC Standard for Radiation Safety of Laser Products (IEC 825-1 and BS/EN60825) and operators are recommended to read it as it gives specific instructions concerning the use of lasers.

9 ASSESSMENT OF JOINT QUALITY

9.1 CAUSES OF WEAK JOINTS

Joints are very often the weak link in items that have been soldered, welded or joined by any other technique. This may be due to any one of a number of causes.

1. The joint may have been improperly made. In the case of soldering, this is often referred to as a 'dry joint' or a 'cold joint'. This will be discussed later in this Section.
2. The joint may not be strong enough to withstand the stresses imposed upon it in service, i.e. while the item is being used. This could arise through poor joint design, or the presence of defects such as porosity, trapped flux and cracks. It could be true that the solder alloy itself lacked sufficient strength and ductility for a particular application. Fortunately, this is not usually a problem with the solder alloys developed for carat gold jewellery. Furthermore, reactions between the solder and the parent metal leading to the formation of brittle intermediate phases at the interface are unlikely to occur.
3. Jewellers who make their own solder alloys must ensure that impurities are not introduced during processing as this can lead to embrittlement of soldered joints.
4. Joints that are initially sound may fail eventually in service due to metal fatigue or some form of corrosion. Metal fatigue is a type of failure where an item fractures on repeated or cyclic stressing over a period of time at a stress level lower than that causing failure on a single application of the stress. This could be a major problem with some engineering components if joint failure has catastrophic results but perhaps is of minor importance with items of jewellery. The presence of an aggressive environment can cause corrosion leading to erosion, cracking and eventual failure. The additional presence of a stress, either applied or residual, may lead to stress corrosion cracking. Generally, the carat gold alloys and their solders have good corrosion resistance but some low carat golds are prone to stress corrosion cracking. Residual stresses (or 'locked in' stresses) can occur in items that are rapidly heated and cooled and can, therefore, arise in joints and the surrounding heat affected zones (The topic has been discussed in *Gold Technology, No.8, November 1992*). For this reason, it is a good idea to stress relief anneal after torch soldering by gently playing a flame around the joint area, while allowing the temperature to fall gradually rather than to quench into water or a pickle. It may, of course, be necessary to subsequently place the article in a cold pickle to remove any surface oxide films. Stress relief annealing should occur automatically in furnace soldering as the articles on the belt move out of the heating zone into the cooling zone.

9.2 EVALUATION OF JOINTS

Joint evaluation is of vital importance in many engineering applications particularly where failure may have catastrophic consequences. It is important also as a means of quality control in the manufacture of reliable products and this is true for mass produced jewellery items, such as findings, stud earring posts, lapel pins, chain, etc.

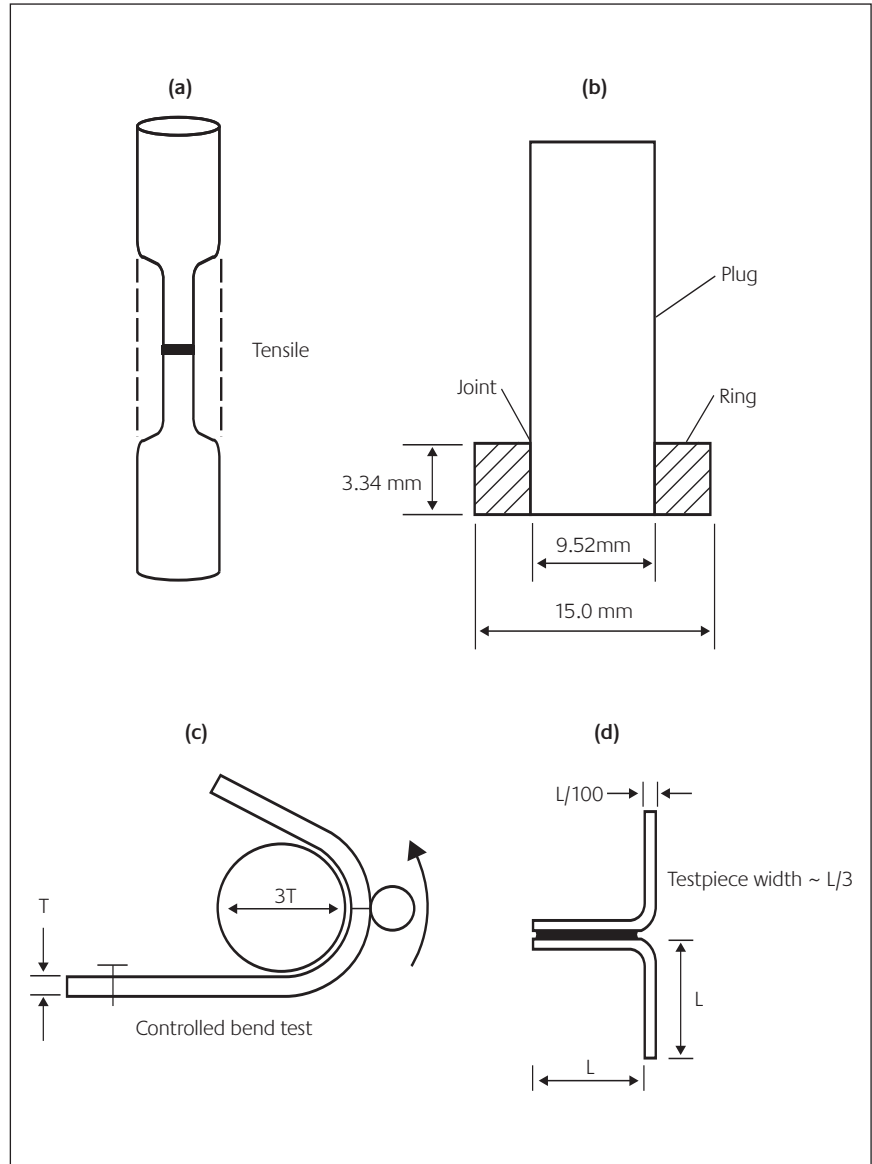


Figure 9.1 Testpiece configurations: (a) Tensile test on a butt joint (b) Ring and plug for test in shear (c) Controlled bend test (d) Peel test

It applies also to the craftsperson making one-off items or repairs who certainly will wish to ensure that the customer is satisfied with the work that has been done.

A wide range of tests exists to assess various aspects of solder alloys and their application. For example, split globule, meniscus rise and sessile drop tests assess wettability and spreadability of solders on parent metals. Figure 9.1 shows test piece configurations for measuring tensile strength, shear strength, bend strength and peel strength, respectively. The dimensions of the test pieces and the test procedures need to be standardised if the results are to have any meaning. The mechanical property tests may not identify the source of any weakness and further examination may be necessary. All of these tests require special equipment and facilities to set them up and would be beyond the scope of most jewellery manufacturers. However, such tests will provide valuable data for manufacturers of solder alloys for use in the

jewellery industry. Humpston and Jacobson (see Bibliography) describe them in detail in “Principles of Soldering and Brazing”.

The first stage in the examination of joints to assess their quality should be a visual inspection. This will only be a surface examination and it will be qualitative in that any interior defects, such as voids and cracks, will not be seen and it gives no indication of the strength of the joint. Nevertheless, it can yield valuable information on whether the joint has been made successfully, Figure 9.2. Visual inspection will be aided by the use of a jeweller’s loupe or a stereoscopic binocular microscope to give some magnification. For example:-

- The surface of the joint should be smooth and have a shiny appearance. This indicates good wetting and spreading. A rough grainy surface is an indication that the joint is ‘dry’ or ‘cold’. The solder has not flowed properly into the joint gap.
 - Fillets around joints should be examined to see if there has been sufficient solder added to complete the joint. These should appear smooth and have low contact angles to the jewellery surfaces. Alternatively, it will show if excess solder has been applied. This is wasteful and necessitates additional finishing. In the case of ear posts, lapel pins, etc., the joint should be concentric.
 - The use of excess solder paste or moving the parts out of alignment can cause smearing and flow of molten solder to areas where it is not wanted.
 - Pieces may buckle or move out of alignment if they are constrained from expanding in fixture board cavities. Ensure that the cavities have sufficient room in them to allow for expansion.
 - Visually inspect items in the fixture boards to see if all, some or none of the items appear satisfactory. Note the position of any defective items on the board. It may be necessary to adjust the belt speed, furnace temperature, spacing of items or the mass of the items in the board. Run dummy boards through first to ensure that the furnace conditions will be right for trial passes and production runs.
- Remember, only change one variable at a time and record all data for future information.**
- Discoloured items could be due to dirt or oxide. It will be necessary to check the fluxing or the furnace atmosphere.



Figure 9.2 Examination of soldered joint (courtesy Krohn industries)

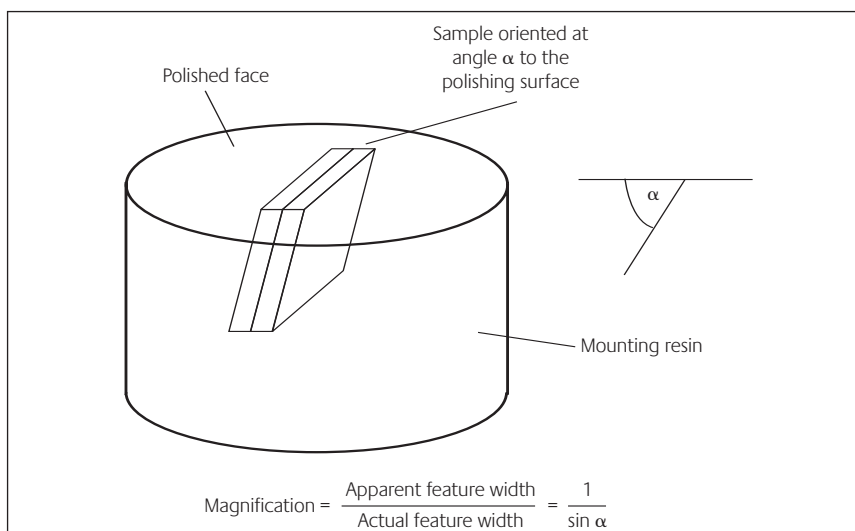


Figure 9.3 Method of mounting sample at a taper for magnification of joint width

- A small halo or bright circle should appear around good joints when findings are fusion welded to jewellery. The absence of a halo indicates that too little energy was used to make the weld. A lopsided or partial halo will occur if the finding is not perpendicular to the jewellery piece. An unsightly spatter shows that the amperage setting was incorrect and excess energy was stored and discharged through the nib. Burn marks are indicative of improper contact with clamps and electrodes.

The strength of joints can be assessed qualitatively by trying to pull or twist them apart using needle-nosed pliers. Naturally, this is destructive testing and is really only suitable for testing the quality of production batches, say using a sample size of 5 or 10 from a batch of 100 items. Dry joints will break in a brittle manner and inspection of the fracture surfaces are likely to show incomplete flow of solder through the joint gap, due either to an insufficient amount of solder or to an excessive joint gap clearance. It will also show the presence of dirt or oxide arising from incomplete fluxing.

The interior of soldered and welded joints can be examined by microscope on cross-sections through the joint. The item is sectioned and one half mounted in a suitable medium, such as Bakelite or a cold-setting polymer, so that the joint can be viewed from one side to the other. If the sectioned half is inclined at an angle to the surface of the mount, i.e. a tapered section, the width of the thin joint is effectively magnified allowing greater resolution, Figure 9.3. The surface of the mount is ground, polished and viewed in both the polished and the etched condition. Examination can reveal the presence of porosity and cracks and whether any undesirable reactions at the interfaces have led to the formation of brittle intermetallic compounds. Examples of microsections have been shown earlier in the Handbook.

Joint quality is affected by other factors concerned with cleanliness and maintenance of equipment and materials. Check that tubes of solder paste are stored in cool conditions (storage at high ambient temperatures (30°C+) can cause the paste to separate over time) and kept closed when not in use. They do have a good storage life but open tubes will allow the paste adjacent to the opening to dry out and it becomes difficult to force the paste out through the needles. Regularly check the thermocouples used to measure furnace and ammonia dissociator temperatures against a standard and replace them when necessary.

9.3 COMMON SOLDERING PROBLEMS

These are summarised in the following table:

COMMON SOLDERING PROBLEMS

Problem	Appearance	Possible Causes	Prevention
Dry or Cold Joints.	Joints fall apart. They appear to be brittle. The exposed joint surfaces show lack of penetration of the solder.	Presence of dirt or oxide. Underheating. Solder doesn't flow. Uneven heating of parts with different section thickness. Insufficient solder. Incorrect gap clearance. Incorrect fixturing or jiggging.	Check fluxing or furnace atmosphere. Check furnace temperature, belt speed or torch soldering technique. Applies to torch soldering. Direct flame to heavier section first until near solder flow temperature then heat uniformly. Use more solder. Check clearance. Redesign joint or fixturing if necessary. Redesign fixturing or adjust jiggging.
Discoloration of jewellery items.	Coloured patches close to joint.	Dirt, grease or oxide.	Check fluxing or furnace atmosphere.
Melting of items.	Rounding of edges; distortion of parts.	Melting of previously made joints. General overheating. Excess solder used.	Use multi-step soldering. Redesign item if necessary. Check furnace temperature and belt speed. Check torch soldering technique. Do not prolong heating unnecessarily. Apply less solder.
Pinholing.	Small round pores at or below the surface.	Overheating. Volatilisation of low melting point, high vapour pressure constituents in the solder, eg zinc. Trapped flux.	Check furnace and torch flame temperatures, belt speed. Do not prolong heating. Use a different solder alloy. Flux should flow out ahead of solder.

10 FURTHER READING

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Note: Gold Bulletin and Gold Technology are published by World Gold Council, London. Recent issues are available on the web site: www.gold.org

The Proceedings of the Santa Fe Symposium may be purchased from: The Santa Fe Symposium, 7500 Bluewater road NW, Albuquerque, NM 87121-1962, USA.
Tel: +1 505 839 3249, Fax: +1 505 839 3248, E-mail: ct@tbg.riogrande.com.
Web site: www.santafesymposium.org

The Proceedings of the IPMI Seminars can be obtained from the International Precious Metals Institute, 4400 Bayou Boulevard, Suite 18, Pensacola, FL. 32503-1908, USA. Tel: +1 850 476 1156, Fax: +1 850 476 1548.
E-mail: mail@ipmi.org Web site: www.ipmi.org

11 SOURCES OF SOLDERS AND EQUIPMENT

It is worth emphasising that, for reliable and consistent joining, it is worth buying solders and equipment from good companies with a reputation for quality and service. Carat gold solders, in particular, need to meet Hallmarking or marking regulations and so must contain the required minimum gold content.

It is impossible to give a comprehensive list of manufacturers and suppliers. Good advice is to visit an International (or your local) Jewellery Trade Fair and visit the material and equipment stands to see who supplies in your region.

Note: The following lists of suppliers do not imply endorsement of the company or their products by the author or by World Gold Council.

CARAT GOLD SOLDERS AND SOLDERPASTES

These are made and sold by most specialist carat gold alloy suppliers, often through local agents. The following is only a representative list of such suppliers. There are others. Many will also supply soldering fluxes and solderpaste dispensing equipment.

Cookson Precious Metals Ltd
59-83 Vittoria Street
Birmingham B1 3NZ
U.K.
Tel: +44 121 200 2120
Fax: +44 121 200 3222

C. Hafner GmbH
Bleichstrasse 13-17
D-75173 Pforzheim
Germany
Tel: +49 7231 920 230
Fax: +49 7231 920 207

Engelhard-CLAL UK Ltd
Davis Road
Chessington
Surrey KT9 1TD
U.K.
Tel: +44 181 974 3000
Fax: +44 181 974 3160

Alpha Guss Metalle & Legierungen
GmbH
Bleichstrasse 92,
D-75173 Pforzheim
Germany
Tel: +49 7231 927166
Fax: +49 7231 927168

DMC² AG (Degussa, Metals Catalysts
Cerdec AG)
Precious Metals Division
Rodenbacher Chaussee 4
PO Box 1345
D-63403 Hanau - Wolfgang
Germany
Tel: +49 6181 590
Fax: +49 6181 593030

Wieland Edelmetalle GmbH
Schwenninger Strasse 13
D-75179 Pforzheim
Germany
Tel: +49 7231 37050
Fax: +49 7231 357959

Heraeus Edelmetall Halbzeug GmbH
Lameystrasse 17
D-75173 Pforzheim
Germany
Tel: +49 7231 200961
Fax: +49 7231 200957

Engelhard-CLAL
Platexis sa
49 Rue de Paris
F-93136 Noisy-Le-Sec
France
Tel: +33 1 4850 5050
Fax: +33 1 4850 5151

Argor-Heraeus SA
Via Moree 14
CH-6850 Mendrisio
Switzerland
Tel: +41 91 646 0191
Fax: +41 91 646 8082

Valcambi SA
Via Passeggiata
CH-6828 Balerna
Switzerland
Tel: +41 91 695 5311
Fax: +41 91 695 5353

Metaux Precieux SA Metalor
Avenue Du Vignoble
CH-2009 Neuchatel
Switzerland
Tel: +41 38 206111
Fax: +41 38 206 609

Hilderbrand & Cie SA
[Solderpastes and dispensers]
29 Route de Jussy
Ch-1226 Thônex, Geneva
Switzerland
Tel: +41 22 349 0024
Fax: +41 22 349 0281

Engelhard-CLAL
H. Drijfhout & Zoon's
Edelmetaalbedrijven BV
PO Box 22666
NL- 1100 DD Amsterdam
Netherlands
Tel: +31 20 5648 600
Fax: +31 20 696 8129

Leg.Or Srl
Via San Benedetto 14/34 Z.I.
I-36050 Bressanvido (Vicenza)
Italy
Tel: +39 0444 660666
Fax: +39 0444 660677
E-mail: info@legor.com

Melt Italiana
Via Martiri della Resistenza 3
I-20090 Fizzonasco di Pieve Emanuele
(Milano)
Italy
Tel: +39 02 9072 2035
Fax: +39 02 9072 2892

ProGold Srl
Via Molinetto 40
I-36075 Montecchio M. (Vicenza)
Italy
Tel: +39 0444 492493
Fax: +39 0444 498336
E-mail: progold@tin.it

Pandora Srl
Via Galvani 14
I-20094 Corsico (Milano)
Italy
Tel: +39 02 4586 4035
Fax: +39 02 4586 9840
E-mail: pandora@aladata.it

Italabras
Strada del Balsego 6
I-36100 Vicenza
Italy
Tel: +39 0444 564423
Fax: +39 0444 960808
E-mail: italbras@italbras.it

Quimijoy SA
Políg Industrial Pla d'en Coll
c/. Gaià, 49
E-08110 Montcada I Reixac (Barcelona)
Spain
Tel: +34 93 565 0990
Fax: +34 93 575 1556
E-mail: quimijoy@quimijoy.com

Imperial Smelting & Refining Co of
Canada Ltd
451 Denison Street
Markham
Ontario L3R 1B7, Canada
Tel: +1 905 475 9566
Fax: +1 905 475 0703

Fusion Inc
[Solderpastes & dispensers]
East 355th Street
Willoughby, Ohio 44094, USA
Tel: +1 440 946 3300
Fax: +1 440 942 9083
[Also in UK, Germany & Japan]

Stern-Leach
49 Pearl Street
Attelboro, MA 02703
USA
Tel: +1 508 222 7400
Fax: +1 508 699 4030

Heraeus PMR Inc
11135 Walden Avenue
Alden
NY 14004
USA
Tel: +1 716 685 2200
Fax: +1 716 685 2699

Engelhard-CLAL LP
700 Carteret Road
Carteret
NJ 07008
USA
Tel: +1 732 205 5842
Fax: +1 732 205 7476

Metalor Corp.
255 John L. Dietsch Boulevard
PO Box 255
N. Attelboro
MA 02761
USA
Tel: +1 508 699 8800
Fax: +1 508 695 1603

United Precious Metal Refining Inc
23120 West Lyons Avenue, #5-491
Newhall
CA91321
USA
Tel: +1 805 254 0523
Fax: +1 805 254 0525

Rio Grande
7500 Bluewater Road NW
Albuquerque
N.M. 87121-1962
USA
Tel: +1 505 839 3300
Fax: +1 505 839 3310
E-mail: info@riogrande.com

Ijima Precious Metals Co Ltd
2-5-10 Nishi Nippori
Arakawa-Ku
Tokyo 116 0013
Japan
Tel: +81 3 3803 1301
Fax: +81 3 3891 0213

Ishifuku Metal industry Co Ltd
3-20-7 Uchikanda
Chiyoda-Ku
Tokyo 101 8654
Japan
Tel: +81 3 3252 3143
Fax: +81 3 3254 4497

Mitsubishi Materials Corporation
Shinmaru Building
1-5-1 Maranouchi
Chiyoda-Ku
Tokyo 100-8222
Japan
Tel: +81 3 5252 5430
Fax: +81 3 5252 5442

Tanaka Kikinzoku Kogyo KK
2-6-6 Nihonbashi Kayabacho
Chuo-Ku
Tokyo 103 0025
Japan
Tel: +81 3 3668 0025
Fax: +81 3 3667 6479

Tokuriki Honten Co Ltd
2-9-12 Kajicho
Chiyoda-Ku
Tokyo 101-0044
Japan
Tel: +81 3 3252 0191
Fax: +81 3 3258 1234

EQUIPMENT

This is a more difficult list to produce as there are very many companies who make gas torches, hydrogen/oxygen generators (water welders), soldering furnaces and other specialist equipment. The following is only a small selection:

Horbach GmbH
[General supplier]
Am Markt 7
D-6580 Idar-Oberstein 2
Germany

Rio Grande
[General supplier]
7500 Bluewater Road NW
Albuquerque,
N.M. 87121-1962, USA
Tel: +1 505 839 3300
Fax: +1 505 839 3310
E-mail: info@riogrande.com

Paul H. Gesswein & Co Inc
[General supplier]
255 Hancock Avenue
Bridgeport
CT 06605
USA
Tel: +1 203 366 5400
Fax: +1 203 366 3953
E-mail: gessweinco@aol.com

IECO Srl
[Furnaces]
Via Monte Verena 20
I-36022 San Zeno Di Cassola (Vicenza)
Italy
Tel: +39 0424 570313
Fax: +39 0424 570591

Laservall Spa
[Laser welders]
Zona Industriale, 5/bis
I-11020 Donnas (Aosta)
Italy
Tel: +39 0125 804478
Fax: +39 0125 804509
E-mail: help@laservall.com

Rofin-Sinar Laser GmbH
[Laser welders]
Berzeliusstrasse 83
D-22113 Hamburg
Germany
Tel: +49 40 733 630
Fax: +49 40 733 63100

Idroenergy
[Water welders]
Via dell'Artigianato 2
I-57121 Livorno
Italy
Tel: +39 0586 425668
Fax: +39 0586 425288
E-mail: idroenergy@interbusiness.it

Crafford Precision Products Co
[Laser welders]
1 Industrial Court
PO box 15155
Riverside
R.I. 02915
USA
Tel: +1 401 438 1500
Fax: +1 401 434 7260
E-mail: sales@crafford.com

Daisy Srl
[Electrical resistance welders]
Via Dell'Astronautica 12
I-36016 Thiene (Vicenza)
Italy
Tel: +39 0445 380444
Fax: +39 0445 380255
E-mail: daisy@pn.itnet.it

Schultheiss GmbH
[Soldering machines]
Pforzheimer Strasse 82
D-71292 Frieolzheim
Germany
Tel: +49 7044 94540
Fax: +49 7044 945440

Frisch GmbH
[Diffusion welding machines]
Sankt-Hubertus-Strasse 33A
D-75181 Pforzheim
Germany
Tel: +49 7231 788138
Fax: +49 7231 788139
E-mail: frisch-gmbh@t-online.de

Mario Di Maio Spa
[General equipment]
Via Paolo Di Cannabio 10
I-20122 Milano
Italy
Tel: +39 02 809926
Fax: +39 02 860232

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WORLD GOLD COUNCIL TECHNICAL PUBLICATIONS

Prices are current for 2002

1. **Technical Manual for Gold Jewellery** – A practical guide to gold jewellery manufacturing technology. Published 1997. Reprinted 2001.
Cost £45 sterling (about US\$75), including postage.
2. **Investment Casting** – A technical advisory manual for goldsmiths.
Published 1995. Cost £10 sterling (about US\$16) incl. postage
3. **The Assaying and Refining of Gold** – a guide for the gold jewellery producer.
Published 1997. 2nd Edition published 2001. Cost £5 (US\$8) incl. postage
4. **Handbook on Casting and Other Defects in Gold Jewellery Manufacture.**
Published March 1998. Reprinted 2001. Italian edition published 2002.
Cost £12 sterling (about US\$20), including postage.
5. **Finishing Handbook.** Published March 1999. (English & Italian editions available)
Cost £16 sterling (about US\$27), including postage.
6. **Handbook on Soldering and Other Joining Techniques.** Published 2002 (English and Italian). Cost: £16 sterling (about US\$27), including postage.

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Gold Bulletin – published quarterly, a journal on the science, technology and applications of gold. Recent issues available on the World Gold Council web site: www.gold.org

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