HOW CAN I MAKE A 99% GOLD JUG FROM SHEET?

Ann-Marie Carey - Associate Professor, School of Jewellery, Birmingham City University, UK. Martyn Pugh - Master Craftsman, Martyn Pugh Goldsmith & Silversmith, West Midlands, UK. John Wright – Metallurgist, Wilson-Wright Associates, West Midlands, UK.

Abstract

If anyone had said to me: "How can I make a large 99% gold jug from sheet" I would have replied "don't try; it will not hold its shape". This paper draws together several strands of craft activity and discussions involved with the realisation and material understanding of a micro-alloyed gold claret jug. It was produced by leading British master-goldsmith, Martyn Pugh. Pugh brought together a team of craftspeople willing to impart their expertise and share in this challenging project. It succeeded by merging new and old techniques and reassessing workshop practice without initially having a practical working knowledge of this unfamiliar gold alloy. The finished jug challenged metallurgical thinking that near pure gold is too soft for load bearing applications. The chosen alloy was expected to be finished with a deliberate age-hardening treatment but that final stage was abandoned. Other anomalies during the jug's creation were noted. Subsequently, reflections and detailed discussions between goldsmiths and metallurgists produced a better understanding of the interface between craft and metallurgy. This was not confined to gold. There was a common desire to bridge knowledge gaps through experimentation, clear communication and respect for each other's discipline.

Background to the commission.

No one would deny that the request for a 'pure all gold jug' raised eyebrows; not just in the sheer audacity to ask but the technical implausibility of a jug in a metal as soft as gold. At the time of the request it was politely but authoritatively dismissed by Pugh given his 30 years of silver-smith experience. Nevertheless, this improbable and potentially career defining conversation lingered in his thoughts, stored away under the heading of "amazing project, if only". Four years later in a conversation on metallurgy with Jerry Arkinstall of Argex bullion dealers, Pugh's interest was reignited. During the conversation, new information about high carat alloys emerged. Exploratory conversations began, initially with a handful of people who had first-hand experience of the various alloys[i],[ii],[iii],[iv] and subsequently with the client to gauge their interest. With a positive response from the client and a shared vision of experimentation in place between client and craftsman, the commission was initiated.

The result was a functional gold jug (Figure.1, Gold Jug) 360mm in height with the capacity to hold and pour a bottle of claret. For Pugh, the jug represented a significant professional achievement, a triumph of craftsmanship and a once in a lifetime commission (incredibly this commission lead to a further once in a life time commission but that's another paper!).

Figure 1, Finished All Gold Jug, photo credit Keith Leighton

The creation of Pugh's claret jug and the journey of its craftsmanship is documented in the Santa Fe Symposium paper of 2010[v]. The paper presented the first creative exploration of the alloy in a craft workshop, consolidating the experience of a live commission, the necessity to 'figure things out on the job', and ultimately the delivery of the jug. The 2010 paper is an important point of reference because workshop experiences from the perspective of the craftsperson normally stay within the confines of the workshop. Rarely does this form of proprietary knowledge go beyond the workshop. Craftsmanship was the focus of the 2010 paper and captured the journey through the creation of the jug enabling that knowledge to be accessed by other craftspeople and interested individuals beyond the world of craftsmanship.

In some respects the 2010 paper treated craftsmanship and metallurgy as independent factors. In simple terms Pugh took the product of the metallurgy research lab (the alloy) and utilised craftsmanship skill to transform it into his product (the jug). However, it is difficult to understand how craftsmanship alone can fully explain how this jug was possible. The authors (Carey and Pugh) of the 2010 paper are both crafts people and although the behaviour of the alloy was definitely unusual and noted, the impact and interaction between the craftsmanship and the metallurgy of the alloy, was not fully recognised. This present paper aims to highlight aspects of the jug's manufacture where the dynamic between craftsmanship and metallurgy worked together to realise the jug, to gain a greater understand of the mechanisms at play at that time.

A Metallurgical Enigma

A 99% gold jug should not exist (gold being too soft) but it does and is a formidable example of the complexities of working precious metal on this scale. The jug is elegant and irrefutable evidence that disrupts our established thinking. How is this possible? The catalyst for Pugh to embark on the commission was the emergence of metallurgical advances in high carat gold alloys. The ‘pure all gold’ wording of the commission related to two aspects:

- the entire jug had to be made in gold as pure as possible. Previously, Pugh’s claret jugs were made with a glass body.
- the central body of the jug could be formed from large enough sheet to obviate soldering[vi].

One of the high carat alloys discussed with Arkinstall presented a number of promising logistical and material factors. It was a micro alloy of 99% gold 1% titanium and also had age hardened properties. Age hardening would be applied as the last workshop process before finishing for presentation and applied to the whole structure, so conceivably smoothing out any local differences in the completed structure. This characteristic was crucial for Pugh from a manufacturing perspective and a commission on this scale in gold.

It became apparent several months after the jug was completed that it was not only a substantial piece of craftsmanship but also a puzzle of unexplained metallurgical behaviour. In a conversation with John Wright (metallurgist and amateur craftsman) the perspective of the metallurgist came to bear upon the project. This opened up intriguing discussions on the manufacture of the jug and more widely on the interface and interdependence between craftsmanship and metallurgy. Above all, a common terminology had to be established.

The unexpected final manufacturing decision

At the time Wright was aware of the jug and was very interested in knowing more about its manufacture. Our conversation began: “Who did the age hardening?” My response: “it wasn’t age hardened” …..followed by a moment of silence and then an incredulous “What!” Obviously not the answer Wright was expecting. From his point of view this didn’t make metallurgical sense. The alloy was specifically designed to be age hardened in a controlled environment; why had the final technical procedure not been adhered to? Wright was more than curious to know what was behind Pugh’s thinking.

During the manufacture of the jug Pugh brought together a network of trusted craftspeople for aspects that were beyond the scope of his own workshop. They and Pugh shared their expertise and intuitively applied their different skills to various aspects of the manufacture. Workshop trials (casting, spinning, fabrication, soldering, laser welding, finishing, silver-smithing, wire-drawing,) provided valuable insight on the working characteristics of the alloy and informed the manufacturing route. Each craftsperson adapting their own approach to manipulating the alloy and developed a heightened awareness of how the alloy behaved in response to processes.

Pugh carefully researched and made all the decisions in the manufacture of the jug, but his final manufacturing decision - to not subject the jug to solution treatment and age hardening- was the most astonishing. Incredibly this decision seemed to contradict his own selection criteria and dismiss the guidance from alloy manufacturers and the few research papers[vii],[viii],[ix],[x] available. From his perspective as a master silversmith and jeweller, risk must always be carefully managed, and this was certainly the case in the final stage of the jug’s creation. The decision not to age harden may seem counterintuitive to those outside the craft workshop but it was a decision directly informed by his first-hand experience as a craftsman. During the creation of the jug, the alloy had been subject to comprehensive workshop trials through which Pugh had physically handled, acquired an understanding, and developed a tacit confidence in the alloy’s ability to perform. The age hardening concluded a series of recommendations for processing the alloy under controlled conditions. The finished jug was not age hardened and the craft workshop was as far from laboratory controlled conditions as one could get. The gold jug is a relatively large complex three dimensional object, which has been subject to multiple shaping techniques with varying degrees of work hardening and annealed several times. In final assembly there could be residual stresses between wrought, cast and machined components joined by solders or laser welded. Having invested several years of his life, contributed his and his network of crafts people’s expertise, Pugh had achieved a beautiful and functional jug. He had borne the risk of the bullion markets, the design decisions and the experimental approach of the craftsmanship process. In his view there was nothing to be gained other than an unacceptable level of risk in proceeding to ‘cook it’ in an oven!

Reflective Questioning

The jug is a unique piece of craftsmanship and the largest decorative object made in this alloy, an alloy designed to be age hardened but in this case was not. How is it possible to produce a functional jug that can hold and pour a bottle of claret, while not performing the age hardening process? Were there other mechanisms at play that enabled the realisation of the gold claret jug?

Incredulity at Pugh’s decision and the need to rationalise this decision led Wright to look for possible explanations as to what was going on within the alloy; were there correlations between the observations of craftspeople and a greater understanding of the mechanisms within the alloy? In his 2011 Santa Fe Symposium paper ‘Buy By Weight: Think Volume’[xi], he points out that we almost always use weight percentages in rating alloying elements and impurities particularly in precious metals and their alloys. 1 gram of titanium and 99 grams pure gold make 100 grams of alloy, which does not seem too much contamination. But, titanium is much less dense than gold so you need a lot more titanium atoms to make up 1 gram than you do 1 gram of pure gold. So, on a volume or number of atoms basis in 100 grams of alloy you have 4.3% titanium atoms (which is beginning to seem very different from 1% by weight). If you then realise that titanium can form up to four different intermetallic compounds with gold (Figure 2, Phase Diagram) our 1% titanium by weight is capable of reacting with over 20% of the gold.

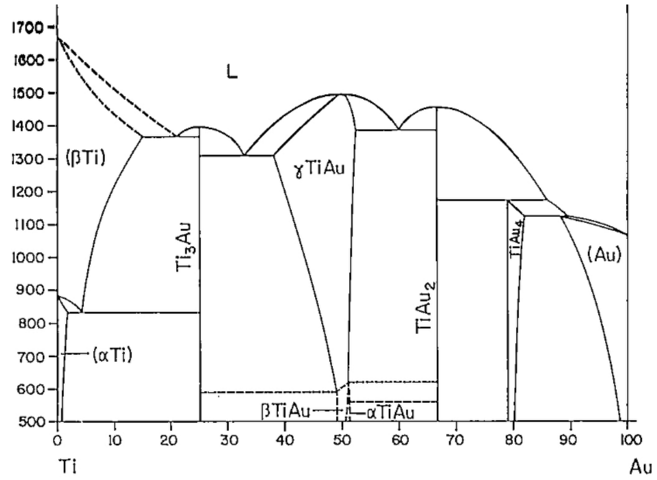


Figure 2, The equilibrium phase diagram for titanium/gold. The left vertical axis is degrees Centigrade. Note the high melting point of titanium. The horizontal axis is volume %.

The intermetallic compounds do not disappear seamlessly into the pure gold matrix; they form sizeable hard clumps with a different crystal structure from the highly ductile gold. In fact, the gold matrix is locally purer than before because most of the titanium is now concentrated in the intermetallic compounds. The high temperature solution treatment followed by lower temperature age-hardening mechanism intended for this alloy creates one of the intermetallic compounds but it is released at a much lower temperature and is very finely distributed evenly across the purer gold matrix.

Both Pugh in practice and Wright in theory initially assumed they were dealing with ‘a small amount of titanium more or less in solid solution in otherwise pure gold’ which normally work hardens steadily to exhibit good malleability and ductility. It can be stress relieved, tempered or annealed (which recrystallizes the gold and lowers the hardness back to the initial soft state). Once you realise the powerful volumetric effect of only 1% titanium by weight, the assumption that the alloy is extensively malleable and ductile is inadequate if not invalid. The workability of the now even purer gold matrix depends on the initial titanium distribution and how far the formation of intermetallic compound (possibly more than one type of compound) has progressed. That in turn depends on the production route for the alloy. For instance, it could have been made by:-

- mixing metal powders, compressing, sintering and working the compacted billet.
- melting and casting under argon then reducing the cast ingot to sheet, rod or wire.
- melting and casting under argon into a mould to create a shape.

Each stage of these processes introduces new variables.

We have yet to explore many variables but we also know gold is not the only metal that forms intermetallic compounds with titanium. In particular, silver forms two intermetallic compounds with titanium and there is good evidence that the silver system in principle is similar to gold. One of the common features is easy rolling/spinning malleability or wire drawing ductility allowing higher than normal reductions followed by a sharp increase in hardness and potentially sudden failure. This is one of the features that described the spinning of one of the parts of the main body of the gold jug.

Craftsmanship Observations

Pugh’s Jug provides an unintended and insightful case study on the gold-1% titanium alloy. The craftsmanship processes applied to the alloy through the creation of the jug have provided a wealth of empirical knowledge. All the craftspeople noted the unusual behaviour of this alloy, often drawing comparisons with high carat gold or silver alloys from their own experiences, as a means to make those differences relevant in a workshop context. The initial comparison with high carat golds also highlighted the preconceived view that 1% of additional ‘exotic’ material wouldn’t make that much difference! However the ‘not much difference’ notion was dismissed once they got their hands on the alloy in craft practice and they had to ‘figure things out’. A one third scale (11.5cm in height) trial jug body was created to experiment with workshop processes and inform the manufacturing route. This provided a knowledge and skills bridge to gain competency and crucially confidence in working this alloy. This began the hands-on learning-in-action that was a constant thread throughout the commission.

Three craft techniques are highlighted in this paper: spinning, laser welding and finishing. They describe how craftspeople engaged with the alloy, how it responded, and how they adapted their approach in view of the alloy’s behaviour. These observations are important because they are experiential and visual clues to understand the alloy’s unfamiliar behaviour, which from a craftsmanship perspective was more varied and pronounced than expected. This paper brings a metallurgical perspective to each of the craft techniques which emphasises the high volumetric effect of titanium in forming intermetallic compounds, in both gold and silver. Once Wright realised the possibility that the materials started their journey through the craft processes with coarse intermetallic compounds already in place in the almost pure gold matrix it is possible to explain a lot of the craft feedback. Had the materials been solution treated and age hardened (which was the recommended route), before final polishing, much of the metallographic evidence would have been lost, because the same intermetallic would have precipitated at low temperature in finely divided form.

Spinning: Stefan Coe is a master spinner with experience in spinning a variety of precious metal alloys and also in handling the complexities of spinning large objects e.g. trophies. However 1% titanium in gold was uncharted territory. The technical data, although a little abstract to the craftsman, identified good malleability, but there was no information on how the alloy would cope with the friction produced between chuck, alloy and spinning tool, characteristics by which the craftsman determined the ‘flow‘ of the metal. The work hardening during spinning is assessed in-process and guided by the resistance feed-back ‘feel’ through the spinning tool to the spinner. How far the alloy could be deformed was critical in calculating the required thickness of the discs, the spinning trial was fundamental to inform this calculation. The trial discs were successfully spun (Figure 3, 1/3 Trial Spinning), the flow was even and consistent with good malleability over the chuck.

Figure 3, 1/3 trial spinnings, even thickness and accurate seam alignment.

Coe made several assessments on the alloy behaviour; there were differences in the processing time and the alloy feed-back (resistance) through the spinning tool. The work hardening curve of malleability was gradual over a longer period of time providing a larger working window in which to move the metal, but work hardening was sudden and abrupt with little to no lead-in to indicate and importantly anticipate the change in condition to the work hardening phase. This acute work hardening must be a carefully managed process not just to avoid manufacturing mistakes but more significantly for one’s personal safety. These workshop trials determined the size and shape of the spinning's to create the overall shape of the body, two spinnings were required which would need to be joined.

When the full sized spinning discs for the actual jug arrived at the spinners Coe realised there was a difference in 'feel' of the alloy - there was no play. This was an uncomfortable surprise and the confidence gained in the trial spinning dissipated and uncertainty crept in, Coe attempted to torch anneal the discs but was not confident; the alloy was expensive, the quantity large, processing mistakes would take time and money, Coe was so concerned he returned the discs to Pugh. When a master craftsman returns metal with the comment 'this is different I'm not sure I can work with this alloy' alarm bells rang.

To have metal rejected was worrying, why was it different and why did Coe feel so uneasy he returned it? After the initial shock, frustration and exasperation Pugh sought answers, in discussion with the bullion dealers, nerves were quickly calmed as the discrepancy was ascertained. The original trial discs had been delivered in an annealed condition ready for spinning, the full size discs had been sent out in a hard condition. The difference was unknown at the time but of huge significance to the craftsman. The discs simply required annealing, but Coe had attempted this and sent them back; why? The optimum condition of alloys for spinning is often debated; fully annealed, half hard, somewhere in between, in stages and ultimately dependent on the craftsman's preference and intuition, not an exact science and lying somewhere between craftsman's art and alloy crystallography.

Annealing the gold alloy in the workshop with flame and hearth led to further nuance understanding of the alloys behaviour with basic workshop processes. Annealing in the craft workshop is gauged by the changing colour of the metal as it is heated by the torch, this requires experience to look beyond the bloom that appears on the surface of the metal as it heats through. Hearths are often placed in the darkest corner of the workshop usually shielded from direct light in order to identify the colours correctly as they are crucial indicators of temperature. When annealing the gold alloy it appeared to be much hotter (a very bright red) than it was because it was not muted by the bloom that we would usually associate with annealing high carat alloys, consequently the alloy looked much closer to the melting point than it actually was (the reason why Coe had returned it). The unusual alloy behaviour was now a constant and annealing was no exception. From Coe's experiences and talking to the bullion dealers Pugh realised that he needed to recalibrate the colour sequence in relation to the lack of bloom over the surface, in a similar manner to platinum - so bright you can barely look at it. Pugh successfully annealed the discs and returned them to Coe for spinning.

From a metallurgist's perspective it is very likely that Coe was working sheet that had been fully annealed for the actual jug spinning. Given a high enough temperature, titanium atoms will diffuse to a pattern that reduces the total energy of the alloy and it forms an intermetallic compound. In so doing it 'locks up' a lot of gold atoms in the form of up to four intermetallic compounds. Most intermetallic compounds are much harder than the matrix from which they grow; they have a different crystal structure and appear as a second phase in the parent matrix. Their presence modifies the mechanical working properties of the alloy as a whole. The now even purer gold matrix is very malleable and work hardens slowly while the intermetallic 'clumps' do not want to conform at all. The net macroscopic effect is that the gold tends to move around and past the $AuTi_3$ which puts up considerable resistance to follow suit. Taken to the limit, this behaviour would lead to separation of the matrix and the intermetallic compound particles. That would quickly lead to complete fracture at the highest stress points. The intuitive feedback to the spinner made him stop well before that point was reached. Meanwhile he experienced an extraordinary amount of spinning ability. As part of his attempt to use 'bridging terminology' what Wright describes is comparable to Coe's experience. As the alloy was cold worked in the spinning process, the intermetallic compounds ‘get in the way’ of the otherwise smooth malleable pure gold matrix, becoming much more reluctant to conform to the spinner actions and thus respond with increased resistance on the spinning tool. The second set of spinning discs sent out from the bullion dealer were in a hard condition: intermetallic compounds already formed hence ‘no play in the metal’ that Coe experienced and illustrated the work hardening impact of the intermetallic compounds. Pugh annealed the material and it recrystallized to a soft state (lower total energy state) which Coe was able to form by spinning.

We were tempted to test the remaining ‘scrap’ material but desisted because it is unique. We have access to more specimens of silver-titanium alloys. The AgTi system is simpler but otherwise similar in principle to AuTi. Figures 4 and 5 (microstructures) show the result of hot extruding a shell of pure silver containing a mixture of silver and around 5% titanium. This was rolled to rod and drawn to wire. It was possible to cold draw the wire about 90% reduction in diameter before the draw tag broke in tension. Figure 5, (50 µm cross-section) is a compelling example of the volume of silver that can be tied up as a second phase by 5% by weight of titanium. Most of the intermetallic particles were near spherical at the start. The larger ones resisted conforming to rod shape until the slow work hardening of the matrix had risen to a very high level. The lemon shaped ones show how the high draw stress is concentrated at the diameter of the larger spheres sufficient to break the bond between the intermetallic and the silver matrix, (Figure 5, Microstructure)

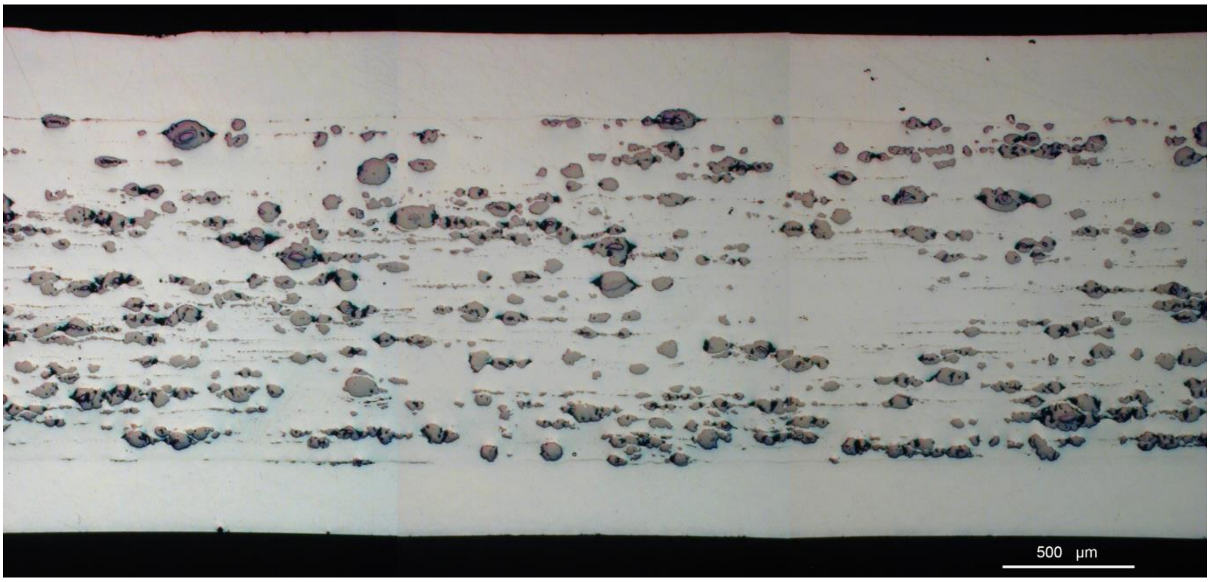


Figure 4, Microstructure of wire created by heavy cold reduction of hot extruded rod section. This starting as a cylindrical silver shell enclosing a mixture of silver with approximately 5% titanium by weight.

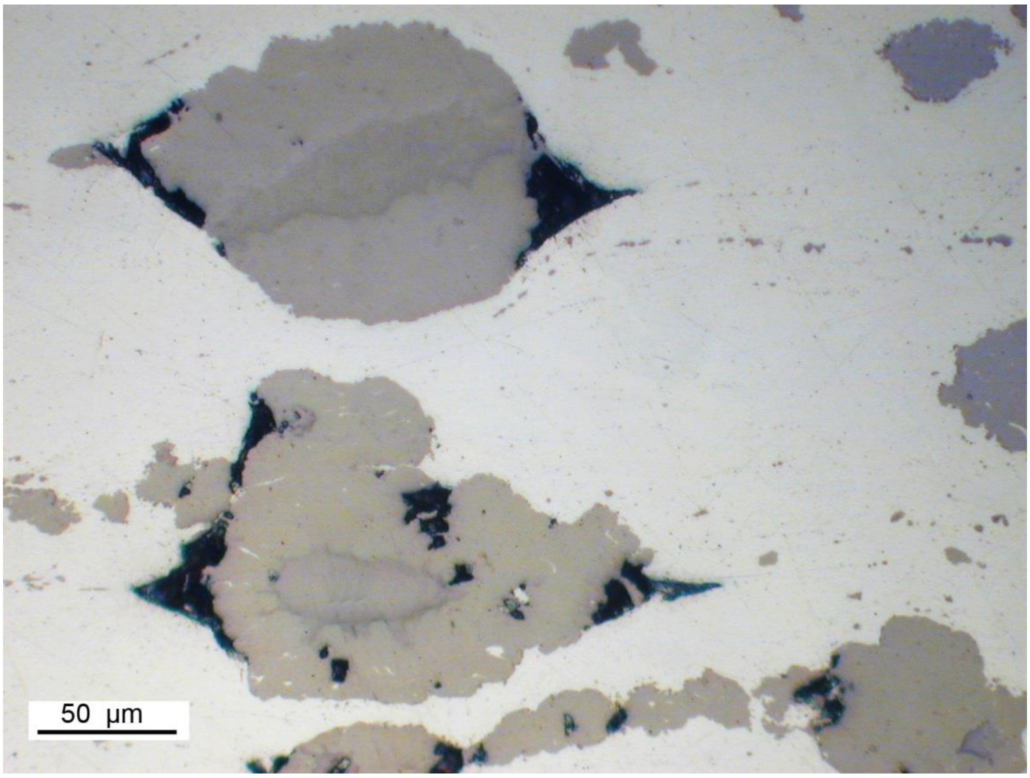


Figure 5, Large intermetallic compound spheres resist compression in the thickness direction and the pure silver flows around them. At high levels of stress at the ‘equator’ of the sphere the silver is dragged away from the interface with the intermetallic compound.

<u>Laser welding:</u> The spinnings produced by Coe were of consistent thickness and in offering one to the other they presented a seam of continuous contact. The join was located at a visually critical position around the largest diameter of the jug body; not a join that could be disguised along an edge or fold in the design (Figure 6, Working Drawing Of Jug). The join not only needed to be water tight but also invisible. With the join in such a prominent position and with an alloy of such a high carat (very rich in colour) soldering would leave a visible colour difference, not acceptable to Pugh’s aesthetic.

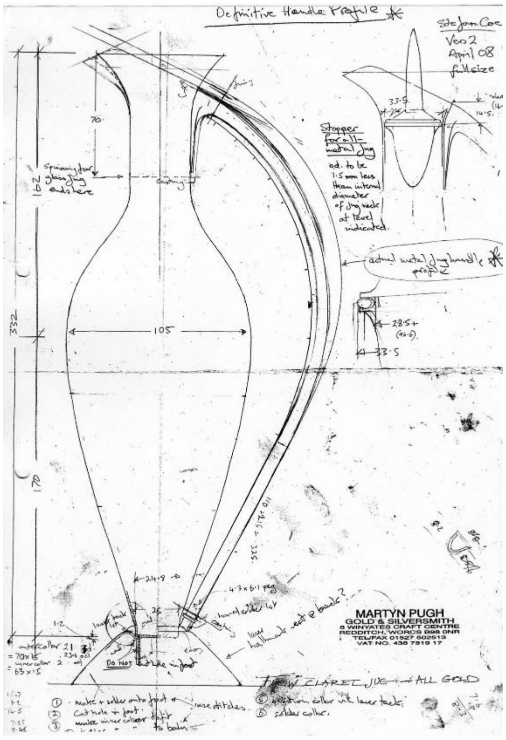
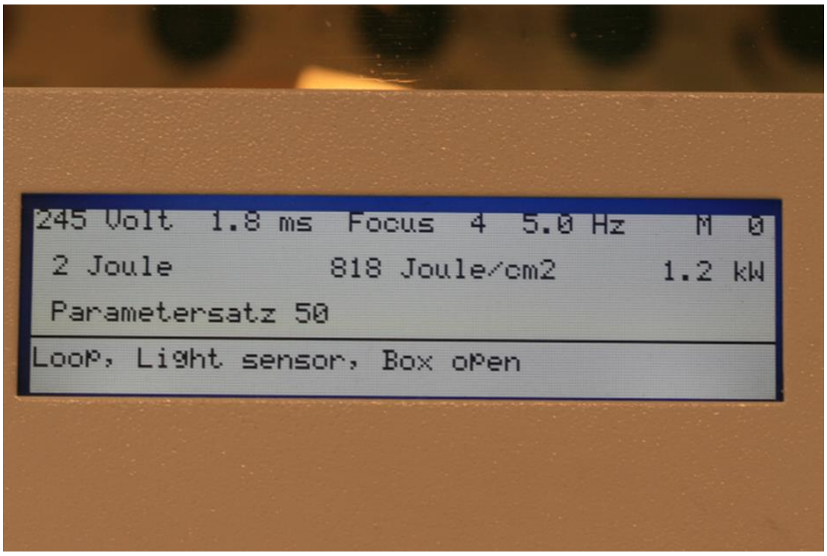


Figure 6, Pugh’s working drawing of claret jug, laser weld across the widest diameter of the jugs body.

Laser welding provided an alternative, highly controllable technique, and maintained the integrity of the colour by utilising the alloy itself as the weld material. There were also other factors, the spot focus of the laser and the high thermal diffusivity of gold caused a minimal heat affected zone. This minimised differential movement or buckling and maintained most of the work hardening developed through the spinning process. Optimum laser welder settings were established with two small sections of AuTi sheet (10×10×1mm). They welded together well, but there were noticeable differences in how the alloy responded to laser spot welding in comparison to other yellow gold alloys. The expected laser power (for 18ct yellow gold) seemed too harsh, creating greater undulation in the surface of the weld than aesthetically acceptable. That would require further laser deposition from fine wire (0.25mm) for cosmetic not structural reasons. The alloy was ‘sticky’; it did not flow and there was a smaller melt pool than Carey’s experience would have predicted with those parameter settings. It was more difficult to ‘push’ the alloy around as if planishing with the laser beam. After experimenting with a range of parameters the alloy reacted well to parameter settings for platinum (Figure 7, Laser Welding Parameters) and indeed it behaved more like platinum under the laser.



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245 Volt   1.8 ms   Focus  4   5.0 Hz      M  0
 2 Joule           818 Joule/cm2        1.2 kW
 Parametersatz 50
Loop, Light sensor, Box open
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Figure 7 Laser welding parameters.

There were also inconsistencies in the alloy’s reaction; occasionally the weld would ‘pop’ and eject a small amount of material from the melt pool. Reapplying the laser to the ‘popped’ area allowed welding to continue. The energy of the laser beam appeared to be confined to a smaller area than expected and required more pulses to weld a section of seam. Aesthetically, the ripple effect of overlaying and merging laser pulses was more pronounced and it was blue, not acceptable to Pugh’s aesthetic! (Figure 9, Blue oxide from laser welding). The titanium in the alloy had become titanium dioxide and created an interference colour, in this case blue. It was highly visible but was removed with fine silicon carbide paper. The development of coloured oxides on the Au-1%Ti alloy was an issue that was raised in the research papers, the experience of the craft workshop was, although resistant to the standard silversmiths ‘pickle’, standard finishing techniques easily removed the oxide. Pugh also found that a coating of flux JM Tenacity or Easy-flo™ protected the surface and later on in the fabrication of the jug when the components had been subject to repeated heating operations the surface did not discolour but remained a rich gold.

Figure 9, Blue oxide from laser welding and occasional ‘popping’ of weld material.

Carey’s observations: the laser pulse created a smaller melt pool, the alloy was sticky, did not flow easily and behaved more like platinum which resonated with Wright’s metallurgical thinking and his calculations from the laser parameters. Gold has a high thermal diffusivity. That is to say, its high conductivity, density and specific heat combined, allow excess heat to ‘drain away’ quickly on a volume basis. That behaviour is rendered much less effective when intermetallic compounds (20% by volume) are present. They not only get in the way of the spinning process, they also disrupt the heat flow! Intermetallic compounds are also very good at locking up ions whose energy is the principle carrier of the heat. Pure platinum has a significantly lower thermal diffusivity than gold because it has a higher density and higher specific heat. So, it is not surprising that both Carey and Wright chose platinum laser welding settings and both said Au-1%Ti alloy behaved more like platinum: lower settings, less energy than you expected of high carat alloys which would account for the smaller melt pool size as each laser pulse does not leak energy away so readily. The lower laser setting works because the heat does not escape by spreading spherically away from the spot: the energy stays longer where you put it! On the other hand the spots have to be more numerous and closer spaced to complete the seam. Wright also noted the ‘popping’ effect in silver-Ti welds using the same type of laser machine as Carey. He concluded that this depends on how well the laser is shielding the spot all through the welding process. If there are any particles of titanium in the weld not covered with argon, they can react with not only oxygen but nitrogen in the air as well! Both reactions are very exothermic. That means the reaction with air gives out a lot of energy in addition to the laser energy. The TiO_2 and TiN are molten, even boiling, enough energy to eject the particles forcibly.

Polishing: The jug is a fabrication of component parts – body, handle, spout, foot and stopper. Each component was prefinished before final assembly. This allowed unhindered access to all surfaces of the component and preliminary finishing can highlight blemishes that can be rectified. The work hardened condition of the jug gained through its manufacturing enabled it to be fit for purpose. Polishing was the final process on the jug which had been subject to and must retain its varying degrees of work hardening to be functional. Therefore further annealing was not appropriate and the surface had to be polished in its work hardened state. Pugh noted that polishing with a mop produced a mottled surface (orange peel) with alternate areas of dull and high polish smudged across the surface, not the consistent lustre one would associate with high carat gold alloys. The polishing appeared to create hard areas that were accentuated when the softer surrounding gold was removed when polishing, creating waves in the surface. In a final mop finish it is usual to generate friction and therefore heat between mop and surface which causes the surface of the metal to flow. The alloy flowed but not consistently, therefore the surface had to be carefully abraded, this again has similarities with platinum. In filing the alloy it was found to be tough and sticky, with lemel accumulating in the teeth of files, creating drag marks on the surface. It was preferable to use finer and finer grades of silicon paper (1500 grit) applied with lubricants. The use of cold finishing by hand produced a more consistent finish. The final stage of polishing came in the form of Brasso™, a fine abrasive and chemical stain remover in one. The resultant finish is softer than mop-polished and ironically less brassy thus achieving the desired aesthetic of gravitas rather than ostentation!

Wright suggested that the intermetallic compounds would be very hard in comparison to the matrix of very soft gold and therefore it would be very easy to inadvertently remove gold revealing the harder more durable areas. Some of the intermetallic compounds would get stuck in files and even paper abrasives causing scratches when reapplied, hence the ‘sticky’ description.

Concluding summary: The interface of craftsmanship and metallurgy

The manufacture of the jug was completed in the environment of the craft workshop and governed by the single mindedness of a master craftsman with the vision to complete a challenging and complex live commission. Virtually none of the empirical materials understanding gained through making the jug was subject to control conditions nor was it gained within the context of a research project. It is fair to say, that at some point in the manufacturing history of the gold jug, practically anything could have happened. Nevertheless this heat treatable alloy, originally designed to give watches more wearability and rigidity has in the hands of a master craftsman produced a beautiful and functional claret jug - that wasn’t heat treated!

Subsequently discussions between crafts people and metallurgists revealed the extraordinary interplay between craft and metallurgy that was the defining feature in the success of this commission. The initial assumption by craftspeople that the addition of 1% of titanium wouldn’t make that much difference was based on a comparison with their existing working knowledge of alloys e.g. sterling silver has up to 7.5% of alloying metals so 1% of titanium by comparison would have little influence! The alloy was subject to comprehensive craftsmanship processes which (unknown at the time) significantly influenced the metallurgical structure and crafts people’s opinion of the alloy behaviour. Pugh and his network of craftspeople successively and successfully worked the alloy, relying significantly on their intuitive skill to read and respond, developing a deep hands-on understanding of the alloys material characteristics in the context of the craft workshop. Crafts people applied their skills to capitalise on and adapt to, the ambiguous material properties that the intermetallic compounds presented, to achieve the improbable (jug) and in so doing prompting a step change in metallurgical thinking (volumetrically). Pugh, unquestionably stretched the boundaries of what the alloy was designed for but he did not necessarily realise how far at the time. Equally the impact of 1% titanium had enormous bearing on the behaviour of the alloy because in metallurgical terms 1% by weight translated to an active compound of 20% by volume. The convergence of master craftsmanship and an alloy with 20% work hardening potential, provided the manufacturing and metallurgical mechanisms to realise the gold jug. The jug is a remarkable case study in the coalescing of craft and metallurgy knowledge, an interdependency which was not fully recognised at the time but one we are just beginning to appreciate and understand.

Pugh’s final manufacturing decision - to not age harden initiated this research. Had Pugh followed the age hardened route recommended, the question of ‘why not?’ would not have been asked and as a consequence much of the behaviour we have discussed in this paper would have gone unrecognised, probably ‘covered up’ by the age hardening process. Much has been gained from Pugh’s unexpected decision.

The observations of crafts people underpinned with metallurgical thinking present a convincing case for a greater understanding of the mechanisms at play and interdependency of the craft process and alloy behaviour. We hope this paper is an example of the learning that can be achieved in generously sharing expertise for greater understanding - ‘theory without practice is fruitless, practice without theory is rootless’[xii].

Acknowledgements

This paper would not have been possible without the patience, dry wit and generosity of expertise that Carey, Pugh, and Wright brought to the project. Our many discussions generated ideas, resolved dead ends, prompted theories and finally 'figured out' of how the jug came to be. Working together, a curious practitioner/academic Carey, a master craftsman Pugh, and a theoretical and physical metallurgist Wright brought a comprehensive and insightful perspective to this investigation.

Ann-Marie Carey - Associate Professor, School of Jewellery, Birmingham City University, UK.

Martyn Pugh - Master Craftsman, Martyn Pugh Goldsmith & Silversmith, West Midlands, UK.

John Wright – Metallurgist, Wilson-Wright Associates, West Midlands, UK.

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