RECENT DEVELOPMENTS IN THE INDUCTION SKULL MELTING AND INVESTMENT CASTING OF TITANIUM ALUMINIDES

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There is a growing interest in using gamma titanium aluminide alloys for high performance applications in the aerospace and automotive industries. Investment casting is considered to be the most cost-effective production technique, particularly for intricate thin wall components such as turbine blades, but further research is required to develop a robust process. This paper describes recent research in which computer modelling and practical experimentation have been combined to understand and optimise the high power Induction Skull Melting process and various mould filling techniques with the ultimate target of producing defect-free castings.

Key words: melting, casting, TiAl

SÚČASNÝ STAV VÝVOJA INDUKČNÉHO ŠKRUPINOVÉHO TAVENIA A PRESNÉHO ODLIEVANIA ALUMINIDOV TITÁNU

Záujem o využitie aluminidov titánu na báze TiAl pri vysokoteplotných prevádzkových aplikáciách v leteckom a automobilovom priemysle narastá. Presné odlievanie sa považuje za cenovo najefektívnejšiu výrobnú metódu, osobitne pre zložité tenkostenné súčiastky, akými sú turbínové lopatky. Na vyvinutie ich masovej výroby je však potrebný ďalší výskum v tomto smere. Príspevok opisuje súčasný výskum v tejto oblasti. Počítačové modelovanie sme kombinovali s praktickými experimentmi, aby sme pochopili a optimalizovali proces vysokovýkonového indukčného škrupinového tavenia a rôznych spôsobov plnenia foriem a dosiahli základný cieľ – výrobu bezchybných odliatkov.

1. Introduction

The continuing drive to improve energy efficiency and to reduce polluting emissions in transport and energy generation sectors is being partly met by reducing the weight of engineering components. There is particular interest in the emerging family of gamma titanium aluminide (γ-TiAl) alloys [1] which are strong candidates for a wide range of components including turbine blades [1, 2], turbocharger rotors

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[2, 3] and exhaust valves [3, 5–7]. To date, much of the effort has concentrated on alloy design and structure-property relationships, and there has been much less research to optimise the production routes. These alloys are difficult to hot work, cold work or machine, and hence casting – particularly investment casting – has great potential for producing thin wall complex shape components cost effectively.

In common with other Ti alloys, TiAl alloys are very reactive in the molten condition which normally precludes melting in a refractory crucible. It is common practice to melt them in a water-cooled copper crucible or hearth using an arc, electron beam, plasma torch or induction coil to provide the energy. The first metal to melt immediately re-solidifies on the inside of the copper container and acts as a protective layer for the remainder of the melt. After casting the molten metal into a mould, a thin skin of metal remains in the crucible and is referred to as a 'skull'. Of the various skull melting processes, Induction Skull Melting (ISM) is probably best suited for casting shaped components and it is the technique discussed in this paper.

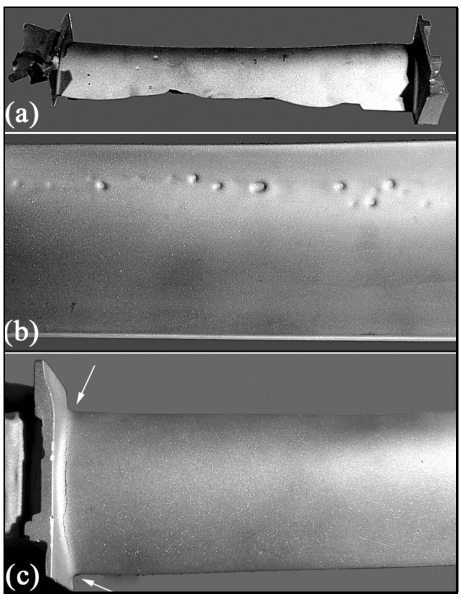

Fig. 1. Typical defects in commercial TiAl castings: (a) misrun; (b) HIP sinks; (c) cracks.

Although skull melting processes are capable of providing molten metal of high purity, they all have the disadvantage of providing only a low superheat since much of the energy applied is lost to the water-cooled crucible. As a result, it is difficult to fill thin castings which results in misrun edges (Fig. 1a). The low superheat is often counter-acted by 'dump' pouring the molten alloy rapidly into the mould, but it is now clear that the resulting surface turbulence can generate bubbles which are readily trapped by the rapidly solidifying metal. Many Ti and TiAl castings are therefore Hot Isostatically Pressed (HIPped) to remove such defects, but this operation adds a significant cost. Furthermore, the collapse of internal porosity can lead to surface 'sinks' which are unacceptable in many components such as turbine blades (Fig. 1b). Plastic deformation in the vicinity of large defects during HIPping can lead to a heterogeneous structure which may account for some of the scatter in mechanical properties that has been reported. Sometimes the solution is to cast components oversize and machine, but this adds further cost and defeats the potential benefits of net-shape casting. A further problem is cracking, particularly in areas where contraction is constrained by the mould (Fig. 1c).

A further consequence of the high reactivity of molten Ti alloys is the need for careful selection of the mould material. Failure to do so results in an oxygen-enriched alpha case which compromises the mechanical properties of the component and must be removed by chemical, electro-chemical or conventional machining [8]. There is some evidence [9] that the alpha case forms less readily on TiAl alloys than on conventional Ti alloys, and its incidence can be significantly reduced or even eliminated by using refractories such as yttria [10] or zirconia [11].

It is therefore apparent that although current foundry technology is capable of producing TiAl castings, additional processes such as HIPping and machining are often required to achieve the quality levels demanded by the customer. The high cost of these is inevitably impeding the wider use of these materials.

This paper reviews recent research at the University of Birmingham and elsewhere to develop improved techniques for manufacturing net-shape γ-TiAl components using ISM and investment casting.

2. Progress in melting TiAl alloys

2.1 High power ISM

Since their introduction in the 1950's, ISM furnaces have used power supplies and crucible designs which lead to complete contact between the melt and the internal walls and base of the crucible (Fig. 2a). This results in a relatively thick skull (and hence poor yield during melting) and extensive heat loss to the cooling water (and hence poor energy efficiency and low superheat). By the mid 1990's, furnace manufacturers had refined the design of the crucible and the power supply so that sufficient power could be applied to the metal to push it away from the side walls (Fig. 2b). It was anticipated that this would increase both the superheat and the yield.

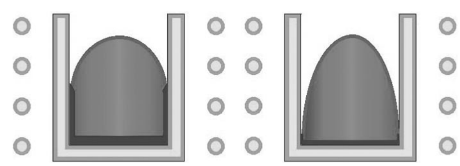

Fig. 2. Schematic views of (a) low power; (b) high power ISM furnaces.

The IRC has a modern 5 kg capacity ISM crucible in a vacuum melting chamber and a 350 kW power supply, giving one of the most powerful units in the world. This has been used to melt a variety of alloys, particularly a Ti-46Al-8Nb-1B alloy developed at the IRC [12]. Melting under a typical industrial vacuum of $\sim$ 4 Pa leads to extensive evaporation, resulting in black 'soot' on the chamber and 'flaky' deposits on the crucible (Fig. 3a). The deposits can be up to $\sim$ 1 mm thick and analysis shows them to contain high levels of Al and Mn; some also contain oxygen

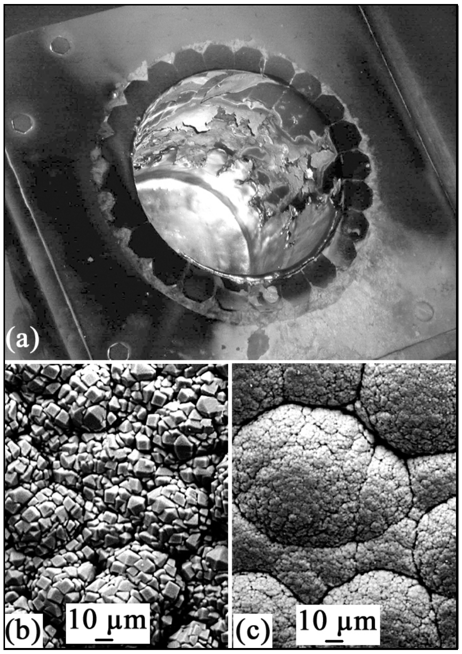

Fig. 3. (a) Deposits on ISM crucible after melting TiAl under vacuum; (b) SEM image of one area: 49 % Al, 42 % O, 8 % Mn (wt.%); (c) SEM image of another area: 85 % Al, 12 % Mn (wt.%).

(Figs. 3b,c). There is clearly a high risk that they might be washed by the metal stream into the mould during pouring, thereby resulting in inclusion defects. This is prevented by melting under a partial pressure of argon (normally 20 kPa).

2.2 Temperature measurement

The ability to measure and control temperature is a fundamental feature of all foundry processes. In the case of TiAl, temperature measurement is not easy since the molten alloy readily dissolves most thermocouple sheath materials, although some success has been achieved using a proprietary Mo-Al_2O_3 cermet sheath [13]. A twin wavelength infra-red pyrometer should be capable of compensating for variations in emissivity, obscuration of the target, etc., but extensive trials have shown [14] considerable discrepancies between the temperatures measured using the 2 techniques. This was particularly so when melting under argon and was attributed to a build-up of metal fume in the furnace atmosphere.

Temperatures measured using a thermocouple are summarised in Table 1. They show that a superheat of $\sim$ 33 ℃ was obtained when 4.5 kg of TiAl was melted in vacuum using 200 kW. This increased to $\sim$ 44 ℃ when melting under a

Table 1. Superheat measurements during the Induction Skull Melting of Ti-45Al-8Nb-1B with different applied power levels

Maximum superheat [℃]			
Atmosphere	200 kW	300 kW	350 kW
Vacuum	31; 35	40	–
20 kPa Ar	33; 40; 46; 48; 49; 49	60	53; 55; 56
80 kPa Ar	62	–	61

partial pressure of 20 kPa of argon and to 62 °C with an argon pressure of 80 kPa. These superheats are significantly higher than the values of 10–20 °C commonly quoted for 'traditional' low power ISM furnaces, but are still some way short of the superheats of > 100 °C normally used when casting alloys with a comparable melting point (e.g. steels). The higher superheat in argon confirms measurements by Rishel et al. [15], but this effect is not yet fully understood.

Following early trials at the IRC, most melts have been carried out under a partial pressure of argon in order to maximise the superheat, reduce the loss of volatile alloying elements and avoid the risk of sweeping re-precipitated material from the crucible wall into the mould during casting. No significant increase in superheat was obtained by increasing the power from 200 to 350 kW. It was very surprising to discover that there was little or no benefit of a high power : melt weight ratio. Part of the explanation is that increasing the power increases the melt temperature, but this reduces the thickness of the mushy zone and the skull and therefore increases the heat loss through the base. Hence an equilibrium is established. Increasing the power also squeezes the molten metal inwards and upwards, reducing the electro-magnetic coupling and hence the induction heating effect.

2.3 Computer modelling of the ISM furnace

Extensive collaboration has occurred with the University of Greenwich who have developed a computer model of the ISM furnace [16, 17]. The governing equations represent several coupled phenomena: turbulent fluid flow in the melt, heat transfer and phase changes, and electromagnetic interactions between the induction coil, the crucible and the conducting metal charge within it. An additional challenge is the time-dependent variation in the melt geometry. The instantaneous melt shape is a balance of gravity, electro-magnetic force, surface tension, and fluid inertia forces.

The IRC has carried out a significant number of practical trials to obtain data to input into and to validate the model [18]. The absence of the thermo-physical property data of TiAl in the molten condition required for input into the model has been tackled by collaboration between various European organisations [19–21]. The model has been invaluable in understanding certain aspects of the melting process and the key parameters which control the superheat. The model is being used to examine various design modifications, and will be a valuable tool for the design of larger ISM furnaces for future industrial scale-up. For example, Fig. 4 shows the flow field and temperature distribution when a 2.8 kg charge of an Al alloy is melted in an ISM furnace [22]. A maximum temperature of 683 °C is predicted, equivalent to a superheat of $\sim$ 33 °C. Figure 5 shows that the addition of a DC coil reduces the turbulent stirring near the base. This has the effect of reducing the heat loss through the base which increases the maximum temperature to 740 °C, i.e. the superheat is predicted to triple to $\sim$ 90 °C.

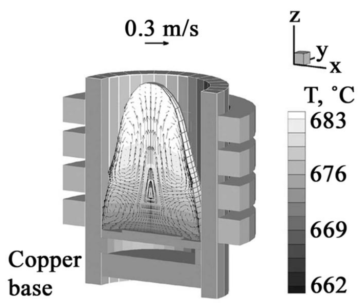

Fig. 4. Example of simulation of ISM furnace. 2.8 kg Al alloy melted with 5560 A coil current.

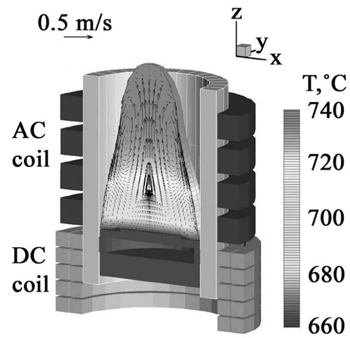

Fig. 5. Effect of superimposing a DC field (10 kA) on the flow and temperature in a 2.8 kg charge of Al alloy.

3. Progress in casting TiAl alloys

3.1 Introduction

To date, commercially produced TiAl alloy prototype castings have been made using the following techniques:

– Gravity casting (e.g. at Howmet [23] and PCC, USA)
– Counter-gravity casting (e.g. at Daido, Japan [3, 4, 7])
– Centrifugal casting (e.g. at Access, Germany [6, 24])

Of these, gravity casting is probably the most widely used at present, and considerable effort has been placed on its further development in recent research at the IRC.

3.2 Gravity casting

The majority of castings, whatever the process or alloy, are made in top-gated, gravity-filled moulds. Figure 6a shows a typical design. Research at the IRC over more than 10 years has shown [25] that this leads to uncontrolled metal flow and significant surface turbulence during mould filling. This can easily result in the thin oxide film present on the surface of most molten metals being folded over onto itself to form random double oxide film (bifilm) defects. In many cases, the oxide films do not bond to each other, resulting in unbonded, crack-like defects in the molten metal which persist in the solidified casting. These cannot be detected by non-destructive testing and their presence is often only revealed by the premature failure of castings at lower-than-expected stresses.

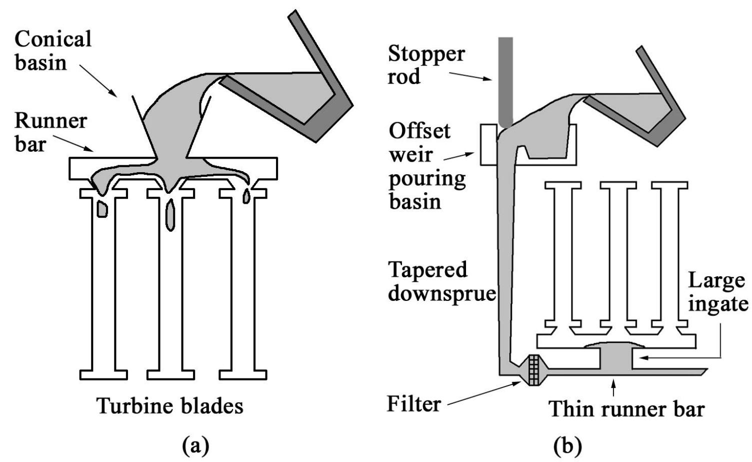

Fig. 6. Schematic mould designs for casting turbine blades using (a) top-gating and (b) bottom-gating.

Much of the poor reliability of castings is now attributed to the random presence of bifilm defects caused by surface turbulence. The latter also leads to the development and entrainment of bubbles which sometimes are trapped inside the solidifying metal and sometimes escape. There is also strong evidence [25] that bifilms act as sites where shrinkage and gas bubbles nucleate, and as weak points where hot tears nucleate if a casting solidifies under constrained conditions. The research has also shown that the corollary of this is that reducing surface turbulence during mould filling reduces bifilms and other casting defects such as bubbles, shrinkage and hot tearing, and increases the reliability of the castings in service (i.e. the scatter in mechanical properties is reduced).

Surface turbulence can be reduced by using bottom-gated gravity-filled moulds with the key features shown schematically in Fig. 6b. The simple conical pouring basin used by most foundries acts as a venturi and introduces air into the metal stream and should be replaced by an offset weir pouring basin to control the metal's entry into the downsprue. The latter should be tapered to compensate for the thinning of the stream as it accelerates due to gravity and a thin 'slot' downsprue helps to prevent the development of a vortex. A thin runner bar is essential to prevent 'sloshing' of the metal and the formation of a rolling backwave which would entrain gas bubbles. A ceramic foam filter helps to slow down and control the flow of the metal. A runner bar extension can be used to receive the initial stream of molten metal which is often the most seriously damaged. The overall aim should be to design the mould so that the velocity through the ingate into the casting is less than the critical value of 0.5 $m \cdot s^{-1}$.

It is widely believed that the high solubility of oxygen in Ti alloys precludes the formation of oxide films. However, experimental evidence is now available [26] for the first time that shows that oxide films can form in TiAl castings. It is not yet known how stable these are (they may be very transitory) or whether they could nucleate other casting defects or whether they have a significant effect on mechanical properties.

The main aim of IRC research on casting TiAl has been to minimise the formation of entrained bubble defects and any associated oxide films. Over 300 top- and bottom-gated moulds of different designs have been cast to produce test bars, turbine blades and exhaust valves in various TiAl alloys, and the quality of the castings has been evaluated by radiography and metallography. The following is a summary of the results.

Figure 7a shows a typical top-gated mould used for casting test bars. When a relatively low mould temperature of 500 ℃ was used, the bars were completely filled but contained a considerable number of bubbles (Fig. 7b). (Note: the radiographs were difficult to reproduce and so the bubbles have been ringed for clarity.) The bubbles were eliminated by increasing the mould temperature to 1000 ℃ (Fig. 7c) presumably because the higher mould temperature delayed solidification and allowed them to escape. However, a faint 'mottling' could be seen on the radiographs (Fig. 7d) and a macro section showed the presence of interdendritic porosity (Fig. 7e). This 'layer porosity' is commonly found when castings solidify under a low temperature gradient, for example, when Ni superalloys are vacuum cast in hot ceramic shell moulds [25].

The bottom-gated design principles in Fig. 6b were adapted for use in the ISM furnace, and a typical casting is shown in Fig. 8a. A mould temperature of 500 ℃ again led to a serious number of bubble defects (Fig. 8b). When the mould temperature was increased to 1000 ℃, the bubbles appeared to coalesce at the top ends of the bars, and a further increase to 1300 ℃ eliminated them (Fig. 8c).

Casting thin wall turbine blades introduced the additional problem of misrun (incomplete filling). Figure 9a shows a top-gated mould cast using a mould temperature of 1000 ℃. All 8 blades were misrun along their trailing edges and radiography showed a large number of small bubbles (Fig. 9b). (Again, the bubbles have been ringed for clarity.) Increasing the mould temperature to 1200 ℃ eliminated the misrun and significantly reduced the bubble defects (Fig. 9c). Some blades were free of any visible defects, which suggests that it should be possible to produce defect-free castings once the process has been mastered. It is anticipated that the small remaining bubbles would be eliminated by HIPping. The use of a bottom-gated mould led to severe misrun and gas bubble defects when TiAl was melted under 80 kPa of Ar and poured into a mould at 1300 ℃. Reducing the Ar pressure to 20 kPa reduced the size and number of bubbles, but even melting and casting under vacuum failed to eliminate them.

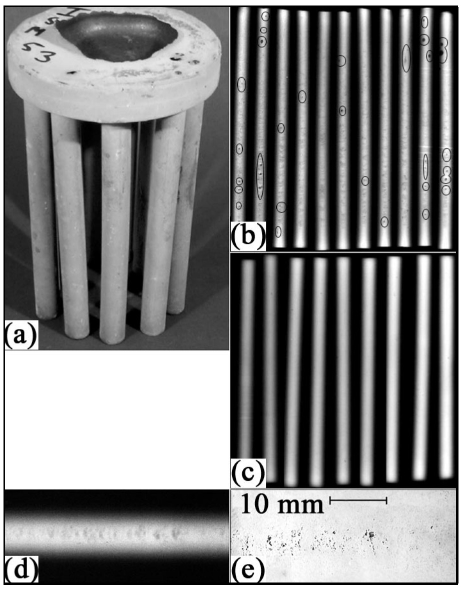

Fig. 7. (a) Typical top-gated mould used to cast 20 mm diameter bars (the pouring bush is missing); (b) isolated bubbles in bars cast in mould at 500 °C; (c) absence of major defects in bars cast in mould at 1000 °C; (d) radiograph and (e) macrosection showing layer porosity.

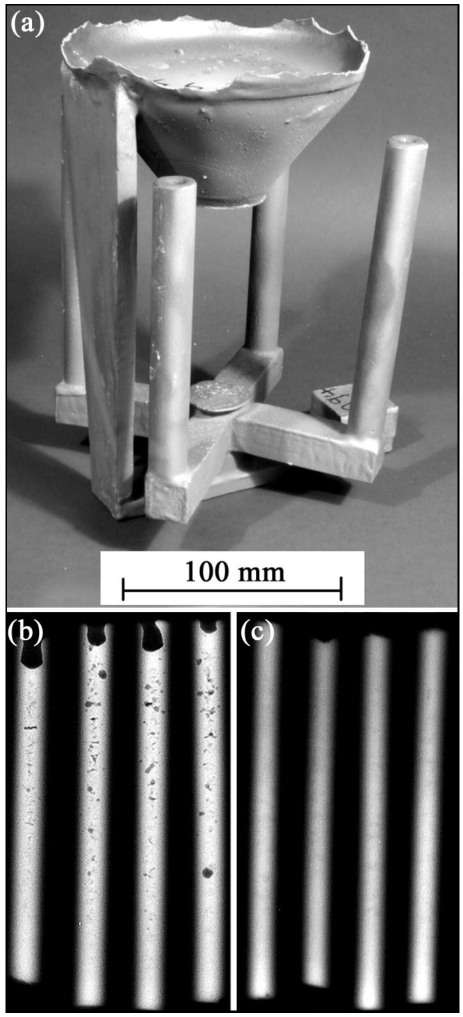

Fig. 8. (a) Bottom-gated mould used to cast 20 mm diameter bars; (b) extensive defects – mould temperature 500 °C; (c) defect-free bars – mould temperature 1300 °C.

Similar effects of melting atmosphere and mould design and temperature were obtained when casting TiAl exhaust valves.

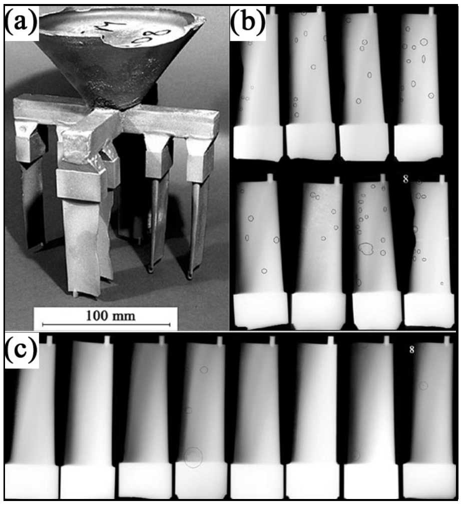

Fig. 9. (a) Top-gated mould of TiAl turbine blades; (b) many small bubbles formed with a mould temperature of 1000 ℃; (c) much improved quality with a mould temperature of 1300 ℃.

Thus the use of bottom-gating for casting TiAl does not result in the benefits found for other materials. Two explanations can be proposed. First, the moulds did not comply fully with all the design criteria since they used neither a filter (none are available for Ti alloys) nor the correct design of pouring basin (due to space limitations and the need to 'dump pour' the metal). Second, the more tortuous running system increases heat loss during filling which increases the risk of misrun if the superheat is low.

Overall, it has been concluded that although gravity mould filling can be used to cast TiAl, the castings are particularly prone to entrapped gas bubble defects. Although these can be reduced by using a high mould temperature, the slower solidification rate appears to promote interdendritic shrinkage porosity.

3.3 Counter-gravity casting

The benefits of avoiding surface turbulence by the counter-gravity filling of moulds have been recognised for many years and have been exploited in various processes, including:

– Low pressure die casting, in which gas pressure is applied to molten metal to force it uphill into a mould.

– The Cosworth process, in which an electro-magnetic pump is used to pump Al alloys into sand moulds.

– Various casting processes developed by Hitchiner Manufacturing Co. Inc. (USA), in which a differential pressure is applied to suck the metal uphill into the mould. The Hitchiner principle has not been widely used with an ISM furnace although Daido Steel (Japan) have used this combination for casting TiAl components; few details are available [3, 4, 7].

A simple counter-gravity (CG) mould filling process has been developed in recent research at the IRC and used to produce prototype car valves. These were initially made in an Al alloy to gain experience prior to using the process to cast TiAl valves.

Figure 10 shows a schematic view of the mould with an integral 'snorkel' sealed in a can which is attached to the end of a hollow driveshaft (a motor-driven immersion thermocouple with the wires removed). This is connected by a flexible hose to a vacuum pump via a receiver. Once the ISM melt reaches a stable temperature, the mould can is moved downwards to dip the snorkel into the melt and a pre-set differential vacuum applied to the mould can to suck the metal uphill. The snorkel is held in the melt for long enough for the mould to be completely filled and then removed from the melt. The vacuum is applied to the mould until the metal has solidified to prevent draining back into the crucible.

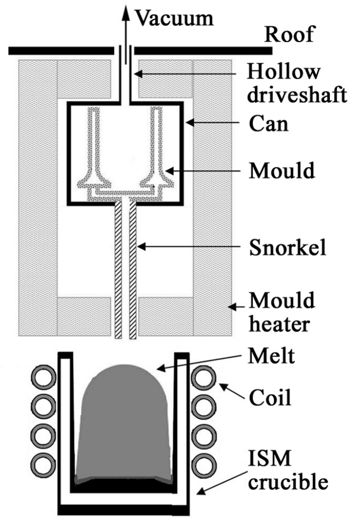

Fig. 10. Schematic view of the equipment used for counter-gravity casting TiAl components.

The original plan was to pre-heat the mould using a furnace surrounding the mould can, but excessive inductive pick-up occurred in the furnace shell from the adjacent high power ISM coil. The limited headroom available above the ISM crucible prevented the pre-heat furnace from being moved to avoid this problem. Hence, it was removed and all casting trials carried out using room temperature moulds.

Experimentation has enabled the design of the mould and the process parameters to be optimised. The most critical factor is the differential vacuum pressure: if this is too low, the metal only partly fills the mould before it solidifies whereas, if it is too high, the metal jets into the mould in a turbulent manner and generates bubbles similar to those found during gravity casting. There is a relatively narrow process window for the differential vacuum pressure, but it is thought that this would be wider if the mould could be pre-heated as originally planned.

Figure 11a shows a typical mould of exhaust valves cast in an A319 aluminium alloy once the process had been mastered. The mould cavity was completely filled with no sign of misrun and the castings had an excellent surface finish. This quality level was achieved on numerous repeat runs. The radiograph in Fig. 11b shows the absence of any defects, and this was confirmed by metallography (Figs. 11c,d).

Considerably more difficulty was experienced when the process was used for casting TiAl, and it seems that the higher melting point combined with the room temperature mould gives a very narrow process window, which in turn results in

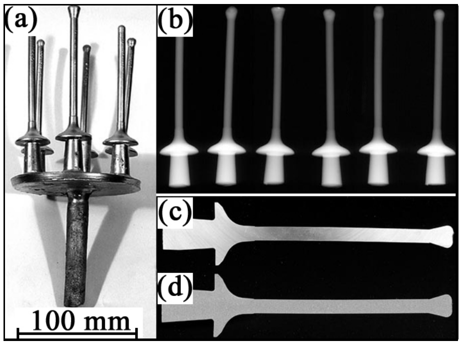

Fig. 11. (a) Mould of counter-gravity cast Al valves; (b) radiograph showing absence of defects; (c) polished macro-section; (d) etched macro-section.

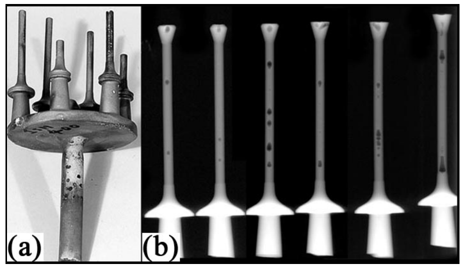

Fig. 12. Counter-gravity cast TiAl valves: (a) incompletely-filled mould due to too low a differential pressure; (b) radiograph showing turbulence-induced bubbles due to too high a differential pressure.

either incompletely filled moulds (Fig. 12a), or internal bubbles (Fig. 12b). Nevertheless, it is possible to produce completely filled castings (Fig. 13a), which appear sound when radiographed (Fig. 13b). However, very close scrutiny of the X-rays and digital enhancement reveals a very fine mottling effect (Fig. 13c), and a metallographic section shows fine centreline interdendritic porosity (Fig. 13d). It is possible that this could be tolerated for this particular application, but it should be readily removed by HIPping for more critical components such as turbine blades. The experience to date suggests that it is considerably easier to produce radiographically-

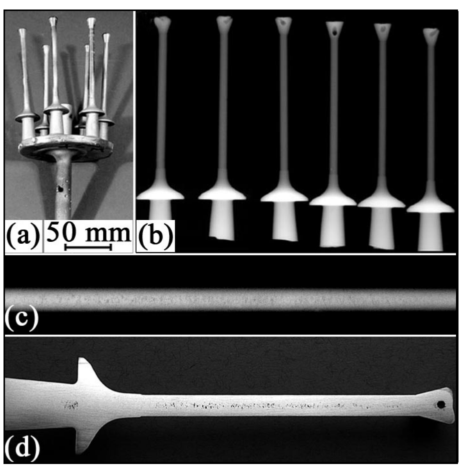

Fig. 13. (a) Mould of TiAl valves produced by counter-gravity casting; (b) radiograph showing absence of major defects in valve heads and stems; (c) digitally-enhanced radiograph of stem of valve #3 showing mottling; (d) macro-section through valve showing centreline interdendritic porosity. (NB the holes in the ends of the stems are in a 'flow-off' and not part of the final valve.)

-sound valves in an Al casting alloy than in TiAl alloys which probably reflects the fact that the latter have not been developed as casting alloys.

Repeated CG melts under nominally identical conditions have been found to give inconsistent results which suggests that the current system does not provide sufficient control of all the process variables, particularly the rate of application of the vacuum. The equipment is being modified to improve this.

3.4 Centrifugal casting

This technique is used widely by commercial foundries producing castings such as golf club heads in conventional Ti alloys. At first sight, the high level of surface turbulence introduced during mould filling would be expected to be detrimental, but it would appear that this is often more than offset by the beneficial effects of the centrifugal force on metal flow during mould filling and possibly of feeding during solidification.

The IRC has gained some experience of this technique in collaboration with the Institute of Metal Research, Shenyang, China. Extensive internal defects were

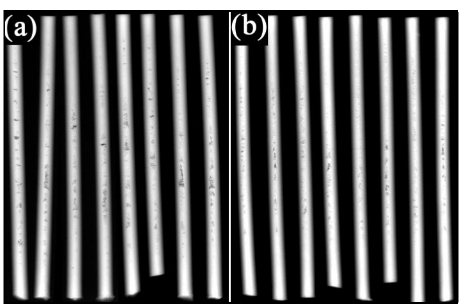

Fig. 14. 10 mm diameter TiAl bars centrifugally-cast in a multi-layer mould showing defects in (a) top layer; (b) bottom layer.

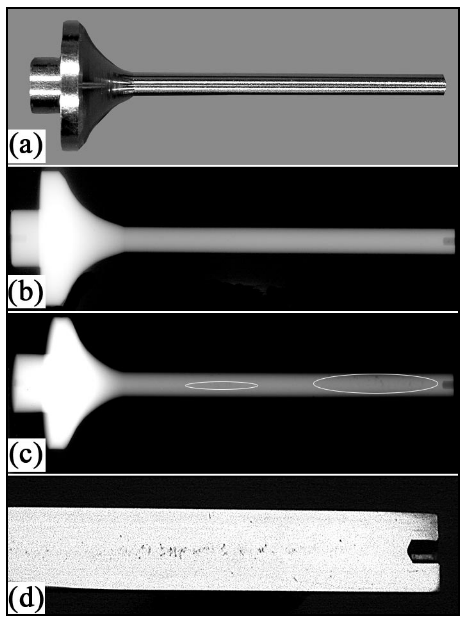

Fig. 15. Centrifugally-cast TiAl exhaust valves: (a) in machined condition; (b) radiograph showing absence of defects; (c) and (d) radiograph and macro-section showing fine centreline porosity.

found in 10 mm diameter bars centrifugally cast in multi-layer moulds (Fig. 14). On the other hand, large numbers of TiAl exhaust valves have been cast and most were free from significant defects (Figs. 15a,b). Some valves contained a few small defects (entrained bubbles or interdendritic porosity) (Figs. 15c,d), which were readily removed by HIPping.

Access (Germany) have been making a sustained effort to develop centrifugal casting for the high volume production of TiAl valves [6, 24]. In this case, a metal mould is used to minimise production costs and a controlled temperature gradient is imposed to promote directional solidification.

4. Discussion

The underlying feature of the casting trials has been the continuing problem of gas entrapment. As already explained, melting and casting are normally carried out under a partial pressure of argon to maximise the superheat, reduce the compositional changes and to avoid the risk of introducing re-precipitated material from the crucible wall into the mould during casting. For these reasons, melting in a vacuum is not the preferred route. Moreover, melting and casting TiAl in a vacuum does not eliminate the gas entrapment problem. It is presumed that in this case the bubbles contain a vacuum diluted by various contaminants and any mould gases which are released during filling of the mould.

Various strategies for eliminating gas bubbles have been evaluated. It was originally hoped that the high power ISM furnace would provide a significantly higher superheat than earlier models and that this would allow the molten metal to be handled in a more tranquil manner. Although a reasonably high superheat (~ 60 °C) can be achieved, this is still much lower than the typical values of ≥ 100 °C used when casting 'conventional' alloys using 'conventional' furnaces. This superheat is rapidly lost as soon as the TiAl collapses into the crucible when the latter is tilted to pour the metal into the mould. Therefore the 'dump pouring' technique appears to be essential, but the inevitable turbulence promotes gas bubble formation and entrapment.

Various attempts to apply the latest bottom-gated mould designs to reduce gas bubble entrapment were largely unsuccessful. It appears that the longer flow path of the metal results in excessive temperature loss, particularly for thin section castings prone to misrun. Most success to date has been achieved by using top-gated moulds for castings such as turbine blades.

This research has also shown that the incidence of gas bubble defects decreases when higher mould temperatures are used, presumably because the delayed solidification allows more bubbles to rise to the surface of the casting and thereby escape. However, the benefit of using a high mould temperature is offset by an increased risk of 'layer porosity' which is promoted by low temperature gradients.

The counter-gravity mould filling trials carried out in this work have shown that this process can produce high quality Al and TiAl castings free from large defects such as bubbles once the process parameters have been mastered. Limited experience of centrifugal casting suggests that it does not automatically guarantee success, but castings can be produced which are relatively free from defects once the process has been optimised.

5. Conclusions

1. The elimination of entrained gas bubbles remains a major challenge when casting TiAl components.

2. When using conventional gravity filled moulds, top-gated designs currently offer the best means of filling thin section castings such as turbine blades.

3. It may be possible to apply bottom-gated mould designs when casting heavier section TiAl components (e.g. $\geq$ 20 mm diameter) and thereby reduce the incidence of defects related to surface turbulence.

4. Counter-gravity mould filling has been shown capable of producing both Al and TiAl castings free from major filling-related defects.

5. The process window for counter-gravity mould filling appears to be quite narrow which suggests the need for a good control system. It is anticipated that the ability to pre-heat the moulds prior to casting would also widen the window.

6. Limited experience of centrifugal casting suggests that it can produce relatively sound components once the casting parameters have been optimised.

7. There is some evidence that TiAl alloys have a lower 'castability' than a typical Al casting alloy.

Acknowledgements

This research was supported by a grant (ref. GR/N14064/01) from the UK Engineering and Physical Sciences Research Council (EPSRC) and is gratefully acknowledged.

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Received: 26.2.2004