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COLTS

Casting of Large Titanium Structures

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(i) EXECUTIVE SUMMARY

The COLTS project (Casting of Large Ti Structures) aimed to combine critical developments in casting technology with computer modelling, to demonstrate that large, thin walled castings of the Ti alloy, Ti6Al4V could be produced to specifications required by Airbus and by the European Space Agency (ESA). In the aerospace industry some large cast components are welded together or weld-repaired and as part of the work in COLTS, electron-beam welding has also been investigated in order to ensure that finished cast components could be produced. If successful, this approach would result in major cost-savings and environmental benefits.

There is considerable experience in casting and in electron beam welding of Ti alloys in China and the laboratories involved in COLTS had made it clear that they wished to increase their skill level so that they could cast and weld large thin walled components which met aerospace requirements. The European partners brought expertise to the partnership in computer modelling of casting and welding and in the assessment of microstructure and properties.

The challenges to be overcome arise from the fact that molten Ti alloys are very reactive and have to be melted in a water-cooled, cold-wall induction furnace, which produces a skull of solid alloy between the copper induction coils and the molten alloy. This limits the temperature of the molten alloy, to only about 50°C above the melting point and makes mould filling of thin sections very difficult, especially in large castings.

Both gravity casting and centrifugal casting have been investigated and detailed computer modelling of these processes, and of electron beam welding, have been used to optimise the processing conditions, so that the specified dimensional tolerances and the mechanical properties required could be met. The demonstrator components identified by ESA were a large cylinder and a cubic space frame and by Airbus were a doorframe and cross connectors, which contained many very difficult-to-fill thin sections. These components had maximum dimensions up to about 0.75m.

Strong waxes were developed, which limited distortion of the wax mould during handling and during coating with ceramic to produce the final mould. The optimum temperature to which moulds were pre-heated was determined and an yttria-based coating of the moulds developed which eliminated attack by the molten alloy, although it was noted that yttria inclusions were found even in the final castings produced. Optimum feeding and gating systems were developed in conjunction with the modellers. Other novel casting technologies were also developed including the addition of 0.04wt%B to grain refine the castings and the addition of redundant parts of castings which acted as sinks for porosity during centrifugal casting.

Welded and cast components were produced which were close to the specifications for the dimensions and surface-finishes and the required mechanical properties, with the exception of the space frame and welded wedge-shaped sections. In the case of the space-frame both experiment and modelling showed that thin cross members distorted during cooling and that insulation, which limited the cooling rate in these sections, would be required to overcome this problem. The welds on wedge-shaped samples tended to show undercuts, but the evidence suggests that this problem can also be overcome with a small amount of further work, using the experience gained on welding and modelling the welding of plates.

Examples of these components are exhibited in ESA's museum in the Netherlands, which show how successful this European-CAE joint-funded programme has been.

Dissemination level: public

(ii) SUMMARY OF PROJECT CONTEXT AND OBJECTIVES OF COLTS

Context of COLTS The COLTS proposal was submitted in response to the call for collaboration between the EU and China in the field of casting large components from Ti alloys. There were many factors, which suggested that the area of large castings of Ti alloys would be an excellent area for a cooperative research programme between the EC and China. Thus, with the exception of one USA-based company, which produces large diameter (of the order of 1m) cast aeroengine casings, virtually all large Ti alloy components are manufactured by thermomechanical processing. This process-route reliably produces components with excellent properties, but it is associated with a very poor fly-to-buy ratio, with up to 90% of an original ingot being turned into machining swarf. It was considered that if casting technology could be developed, so that reliable, large castings could be produced, the economics of the process would strongly favour the use of castings over forgings. At present the USA-based company has a virtual monopoly so that their castings, which generally require significant weld-repair, do not offer the potential cost-reductions that should be available to end-users. When the COLTS proposal was being drafted it was apparent that no European company was prepared to make the major investment required to develop industrial scale casting of large components from Ti alloys. On the other hand there was considerable experience in this area in China and two partners were interested in further developing this technology, which required extensive development of casting, including work on the development of the moulds and waxes required for large investment castings. The European partners were able to bring expertise in computer modelling of casting together with property and microstructural assessment and measurements of the dimensional accuracy of large components. Because electron beam welding is required both to repair castings and to weld together components, work was carried out in COLTS to develop this technology. The partnership was thus further enhanced by expertise in China in electron beam welding and by European expertise in computer modelling of electron beam welding. It was decided to work on the development of both centrifugal casting, which increases the speed of mould filling and on gravity casting, since some components cannot be made using centrifugal casting.

The full partnership is shown in the table. There were in fact some problems at the beginning of the programme, when Rolls-Royce, who were part of the consortium, withdrew for internal management reasons, after the programme was approved for funding. This meant that BIAM had to supply the design for the demonstrator engine casing. Later on during the research, one partner ING, had to withdraw for reasons connected with the financial crisis in Spain, but they were replaced, with EC approval CIMNE, with no loss of expertise.

The overriding reason why casting of Ti alloys is difficult is connected with the reactivity of molten Ti alloys, which attack all refractories. This has the consequence that melting of the alloys has to be carried out in water-cooled, cold wall induction furnaces. This method of melting produces a skull of solid alloy, which separates the molten alloy from the copper induction coils that provide the heating required so that clean melting is achieved. However, the necessity of retaining the solid skull limits the extent of superheat, which can be achieved, to about 50°C above the melting point. Hence with this limited superheat, filling of large, thin wall castings is made difficult. There will also tend to be some interaction between the refractory used to produce the moulds and the molten alloy during the limited time for which the alloy is molten in the mould, which can produce a surface-hardened layer, downgrading the properties of the casting and it is essential that the extent of this interaction is limited. The research that was needed was thus to develop casting technology so that mould-filling could be achieved in large thin wall castings, despite the limited superheat and it was also necessary to use moulds which would not interact significantly with the molten Ti alloy. Additionally in order to obtain castings within the specified dimensional accuracy, the development of strong waxes used to produce accurately shaped ceramic moulds was also necessary, if very large castings were to be successfully produced. The feeding of castings and the gating systems used was improved by using computer modelling and the interaction between the modellers and the casting experts resulted in optimised casting conditions being developed.

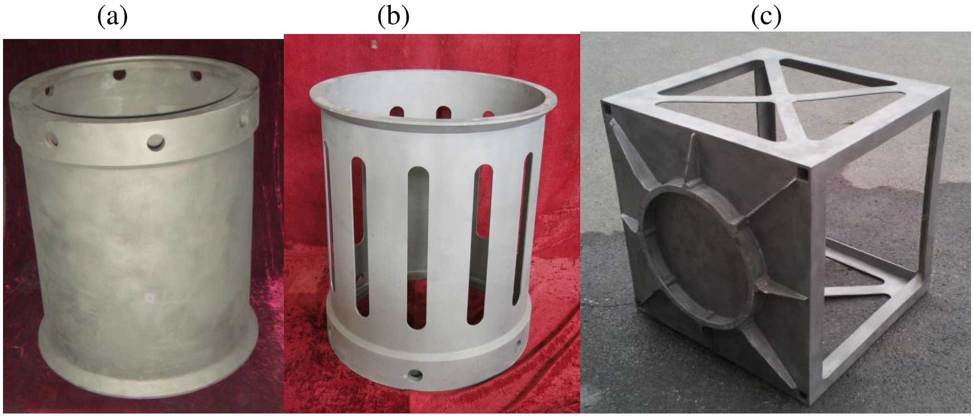
Table listing the members of the COLTS consortium

Participant No.	Participant organisation name	Participant short name	Country
1	IRC, University of Birmingham	IRC	UK
2	Airbus	Airbus	France
3	European Space Agency	ESA	Netherlands
4	Calcom ESI SA	CALC	Switzerland
5	Ingenia	ING	Spain
6	European Aeronautics and Space Co	EADS F IW	France
7	Chinese Aeronautical Establishment	CAE	China
7(a)	CAE-Beijing Institute of Aeronautic Materials	BIAM	China
7(b)	CAE-BAMTRI	BAMTRI	China
8	Huazhong Univ of Science & Technology	HUST	China
9	Institute of Metal Research	IMR	China
10	Tsinghua	Tsin	China
11	CIMNE	CIMNE	Spain

Objectives of COLTS The objectives of the COLTS programme were defined as: (i) To develop the technology of casting the Ti alloy Ti6Al4V and to produce large demonstrator components, the sizes, the dimensional tolerances and mechanical properties of which were defined by the end-users. (ii) To ensure that the ability to weld Ti6Al4V was developed, so that components could be welded together and also could be weld-repaired, as is standard practice with cast Ti alloy products. (iii) To develop appropriate process modelling of centrifugal and gravity casting and of electron beam welding and to use the understanding developed through modelling to optimise the casting and welding. (iv) To carry out detailed assessment of the microstructures and measurements of the mechanical properties of test samples cut from the large demonstrator components, together with 3D measurements of the dimensional accuracy of these components.

Achievements of COLTS The extent to which these objectives were reached is summarised here and an indication of further work, which would build upon the COLTS results is also identified. The components selected by ESA and by Airbus are all thin walled and large. Typical castings produced during COLTS by IMR and BIAM are shown in the figure.

(a) (b) (c)



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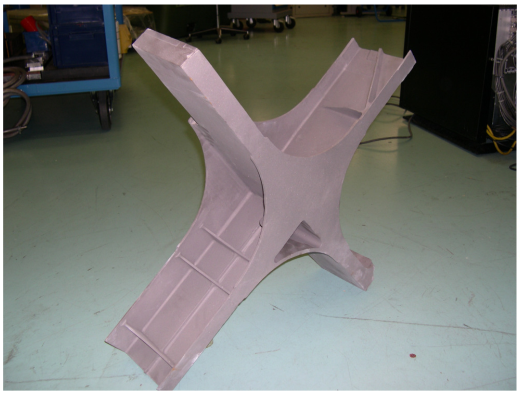
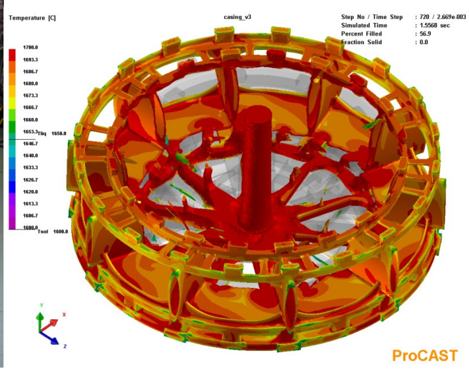




(e) (f)

Figure showing the components cast during COLTS; (a) and (b) shows thin-walled generic cylinders; (c) is the cubic space frame; (d) is the doorframe and (e) the cross connector; (f) shows the modelling of filling of the engine casing; brown and red regions are above the solidus.

The cylindrical samples are 600mm x 750mm with a minimum wall thickness of 4mm and the cubic space frame is 500mm edge length with wall thickness of 4mm. These components were required by ESA, to replace Al components, because of the higher modulus and lower coefficient of expansion of Ti. The cross-connector and doorframe are 500mm long and can clearly be seen to be complex with thin ribs. These components were designed by Airbus, with the aim of improving the fly-to-buy ratio by using castings rather than forgings. Both ESA and Airbus specified dimensional tolerances, quality of surface finish and the mechanical properties they required, and these specifications included the mechanical properties of electron beam welded samples.

Initial trial castings revealed significant problems, with inadequate filling, extensive porosity, and overall lack of control of dimensions, but these were eventually all mostly overcome with input from the modelling partners and by experimental developments. These included improvement of the strength of previously available wax patterns; improvements in the quality of the face-coat of the moulds and incorporation of complex gating and feeding systems. In order to eliminate the pores throughout the large cylinders extra rings were fitted inside the moulds, which under the influence of the centrifugal force, acted as sinks for the pores. The 3D shapes of some of these final castings were determined, together with the surface finish after sandblasting and polishing and carrying out any weld-repairs required; generally these met specifications. The cylinders were slightly outside tolerance. It is obviously necessary to take this into account in the manufacture of subsequent cylinders. The cross members of the space frame cube distorted during cooling because, as confirmed by modelling, these members solidified first and were then subject to compressive forces as the surrounding parts solidified. Further work is needed to confirm that this problem can be overcome straightforwardly by arranging that these cross members cool more slowly, either by providing insulation or by providing local heating.

Electron beam welding, of cast flat plates and of tapered wedge-shaped plates supplied by BIAM, were used to assess the quality of the electron beam welds and it was shown that they met Airbus standards. The modelling of the welding of flat cast plates was successfully undertaken and the calculated size of the heat affected zone and of the level of internal stress were in close agreement with the measurements. In the wedge-shaped plates, which were used late in the programme to simulate welding of airframe components, some undercut was observed which is not present when welding flat plates. The partner developing electron beam welding is confident that the undercut could be eliminated, although more welding trials are needed to confirm

The mechanical properties of samples cut from the castings and from welded samples have been measured and all generally met the property requirements defined by ESA and by Airbus, although in thin regions low ductility was found. The properties were improved by hot isostatic pressing and by heat treatment of the castings, but also by casting technology and through the addition of 0.04wt% B to the alloy to act as a grain refiner.

It can thus be seen that the four objectives listed above have been largely achieved, although further work is required to confirm that the buckling of cross members of the cube and the small undercut in the welded wedge-shaped samples can be eliminated. Additionally dimensional tolerances could be improved and yttria inclusions need to be eliminated. The work on the engine casing was limited to modelling because there was no end-user requiring this component.

(iii) DESCRIPTION OF MAIN RESULTS

Introduction. The work carried out in COLTS was divided into ten work packages (WPs) and in the following report the objectives are listed and the achievements of each WP are summarised in turn. This makes it straightforward to assess the work that was done during this three-year project in terms of the original objectives. The conclusions, which can be drawn from the COLTS project are listed at the end of this report.

WP1-Management The objectives defined in the proposal for WP1 were:
(i) To manage the project such that the scientific milestones and deliverable are achieved as defined in the project submission and the project is delivered on time.
(ii) To set up an effective communication infrastructure within the consortium.

Assessment of the achievement of these objectives There were some initial delays, mainly associated with the fact that after the proposal was approved for funding, one of the partners, Rolls-Royce decided not to participate. This meant that BIAM had to submit an aeroengine component design to CAE for approval, before funding was released. In addition Professor Wu resigned from Birmingham to take up a position in Monash University, Australia and in order to maintain her involvement with the programme a sub-contract had to be agreed between Birmingham and Monash. Despite these problems virtually all deliverables were confirmed as completed at the final meeting held in mid September 2013 and the few that were outstanding have by now (November 2013) all been completed. It should also be noted that towards the end of year 2 one of the partners, ING, was not able to continue to support the work financially and a new partner, CIMNE, was approved by the partners by the EC and by CAE to complete the work.

The communication between partners worked increasingly well as the work progressed, with the website being set up within the first month. Because there were some difficulties experienced by

Chinese partners in accessing the website, CALC set up Chatterbox as an alternative way of transferring large documents and minutes of meetings to all partners. Other electronic methods of communicating between partners, including Dropbox and teleconferences were used in addition to meetings between partners. Discussions between the modellers and partners producing the castings and welded samples ensured that modellers used appropriate conditions in their models and that they were then able to feed information back to the casters/welders aimed at improving the quality of the end-products. In addition, those measuring the properties (and dimensions) sent their data to those producing the castings and the waxes so that modifications could be introduced if the properties did not meet specifications or the dimensions did not meet tolerances. Meetings were held in Nanjing, (China) (kick-off meeting); Toulouse (France) and Beijing (China), (telecom); Toulouse (European partners only); Beijing (China); ESA (Netherlands); Birmingham, (UK); Villars (Switzerland) and the final meeting in Shenyang, China.

Overall it was found that, despite the fact that management was split between partners in the UK, Australia and China, communication worked well, without any major problems in this jointly funded European/Chinese research programme.

WP2 Specification of Properties and Tolerances The objectives for WP2, defined in the proposals were: (i) To define properties required and dimensional tolerances of the spacecraft components. (ii) To define properties required and dimensional tolerances of the airframe component**s.** (iii) To define target costs of components.

Demonstrators, and related specifications were provided by ESA and by Airbus as described in the following paragraphs.

For satellite structures, the rationale of using titanium instead of conventional aluminium alloys is justified by its higher stiffness and lower coefficient of thermal expansion as a means to minimise thermal stresses and strains on internal components resulting from temperature variation due to the changing exposure to sunlight. Two large components, illustrated in figure 2.1 were proposed by ESA as demonstrators. The components were designed as generic frames for small satellites, which describe a class of satellite with a wet mass, including fuel, ranging between 100 and 500 kg. These small satellite designs have been at the core of the PROBA (Project for On-Board Autonomy) program, which since 2001, has seen four launches as a part of earth observation missions. One component was designed as a hollow cylinder, 750 mm in height, 600 mm in diameter, and a minimum wall thickness of 4 mm. A cubic frame was also proposed as a demonstrator containing more complex features. The side length of the cube is 750 mm and the frame is composed of a reinforced base plate, hollow square tubing at the four corners, and four L- shaped connectors at the opposite side to the base plate. The minimum wall thickness for the cube frame is 5 mm. For both components, the mechanical property requirements are: a yield-strength (YS) of 800MPa, an ultimate tensile strength (UTS) of 900MPa, and 10% elongation (A). The general geometrical tolerance is +/-2 mm and +/-1 mm on wall thickness dimensions. For aeronautic structures, the main driver of current research is the improvement of the Buy-To-Fly ratio (weight of bought material /weight of final part). Currently, the door-surrounding structure is made of β-treated Ti-6Al-4V die-forged blanks. The replacement of hot die forgings by a casting would allow significant improvement of the Buy-To Fly ratio in addition to an increased accessibility to additional structural details that would be difficult to form by forging due to the very expensive

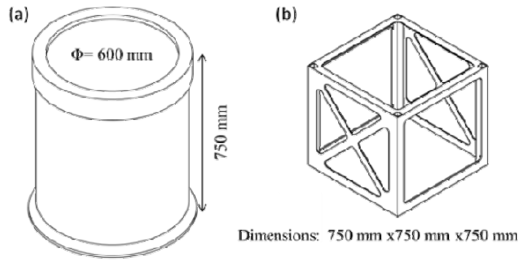


Figure 2.1: Demonstrator provided by ESA

machining cost. In the frame of the COLTS project an interesting approach has been considered; it consists of cutting the door surrounding components (frame, sill and lintel) into several cast components and to envisage their assembly by Electron Beam Welding. Two of these components, detailed in figure 2.2 have been selected as demonstrators. For Airbus, dimensional requirements are very important thus the quality of the demonstrator should comply with defined linear tolerance, straightness, flatness, angle tolerance, radius of curvature, surface quality. In addition, mechanical characteristic have to comply with usual cast part requirements (YS of 780MPa, an UTS of 860MPa, and A=5%) and aim to reached the level of those of β-treated Ti6Al4V forging, i.e. YS of 830MPa, UTS of 900MPa, and A=6%.

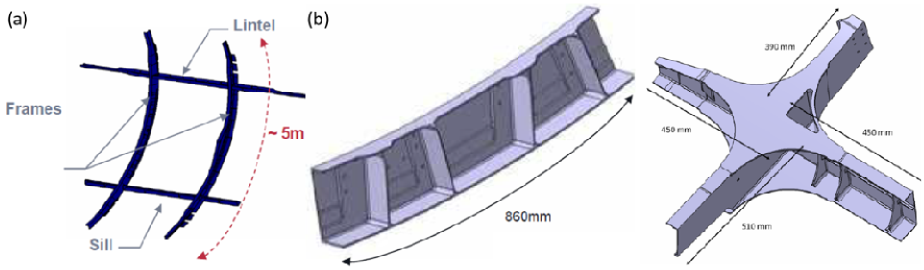


Figure 2.2: (a) schematic of door surrounding structure, (b) Demonstrator provided by Airbus: segment of frame and cross corresponding to lintel/frame intersection

WP3 Investment casting technology for large thin-wall Ti alloy components The objectives for WP3 were to (i) identify a process window for casting ESA component by optimising complex interacting factors that influence formability, dimensions and mechanical properties; (ii) provide basis and calibration to and verification of the modelling in WP6; and (iii) develop a centrifugal process for casting large thin cylinders and cubic frames as defined in WP2.
Target components and key problems to solve The two ESA parts to be cast are shown in **Figure 3.1**. The cylinder consists of a top collar with a bent-in lip, a bottom collar and a thin wall (4 mm thick), and has a large size (diameter 660 by 750 mm). The ability to form an integrated structure, dimensional control and mechanical properties are the key issues to solve in WP3.

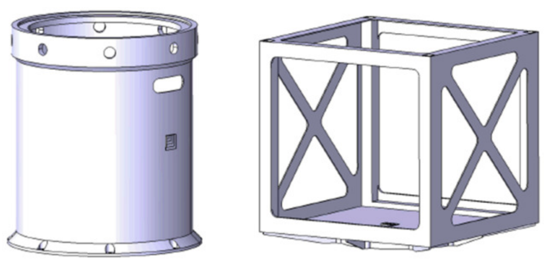


Figure 3.1: The two ESA parts to be cast: a cylinder and a cubic frame.

Figure 3.2: Designed (a), machined (b) and assembled (c) dies for making wax pattern. Specially designed support tooling is essential for ensuring the dimensional accuracy of wax pattern.

Dimension control of wax pattern Proper design and assembling of dies (**Figure 3.2**) and individual wax components (**Figure 3.3**) are essential to ensure the dimension of the wax pattern.

Properly designed support fixtures prevent distortion of the patterns during shell moulding (**Figures 3.4 & 3.5**).

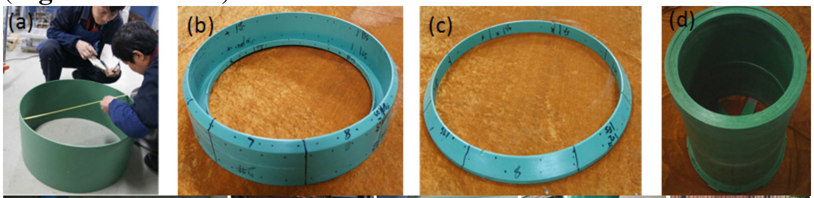


Figure 3.3: Individual (a-c) and assembled (d) wax pattern.

Figure 3.4: Inadequate support (a) causes cracking in addition to distortion of mould (b), while sound fixture (c,d) minimizes distortion of the cylinder mould (e).

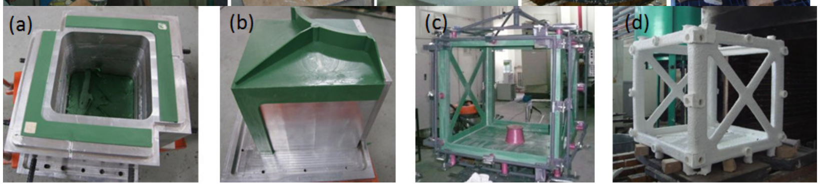
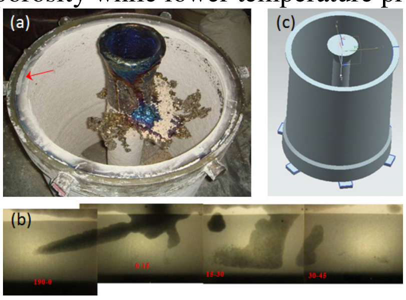


Figure 3.5: Tooling (a,b) and fixture (c) for preparing the cubic frame shell mould (d).

Development of centrifugal casting process Gating design was optimized to avoid misfill and minimize shrinkage cavities (**Figure 3.6** in the case of the cylinder). The best combination of casting parameters was identified: 600°C preheat temperature and 200 rpm spin rate. Lower spin rate or lower temperature simply causes misrun. Higher temperature increases tendency of shrinkage porosity while lower temperature produces more gas pores.



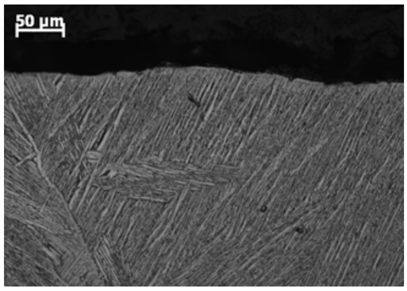
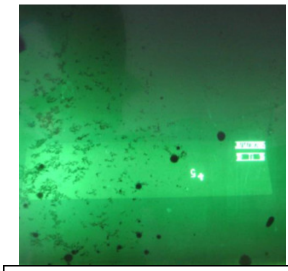


Figure 3.6: Gating design with runners connecting bottom collar produces misrun (arrowed in (a)) and cavities (b) at top collar. Optimised gating system is shown in (c).

Figure 3.7: Cross-section micrograph showing the lack of "α casing" on the surface of a cast part.

Yttria face coat is suitable for casting thin wall Ti alloy components because no α case forms on the surface (**Figure 3.7**). The combination of high temperature and high spin rate however may peel off the coating and cause inclusions in the castings as reported in WP8.

Feeder design to eliminate surface porosity Under the casting process conditions optmised to eliminate misrun, porosity cannot be avoided on the inside surface of the thin wall of the cylinder (**Figures 3.8 & 3.9**). A feeding system in the form of 3 equally spaced ribbons on the inside surface of the thin wall was designed and and its effectiveness in eliminating the surface porosty verified by both experiment (**Figure 3.10**) and simulation at Calcom ESI.



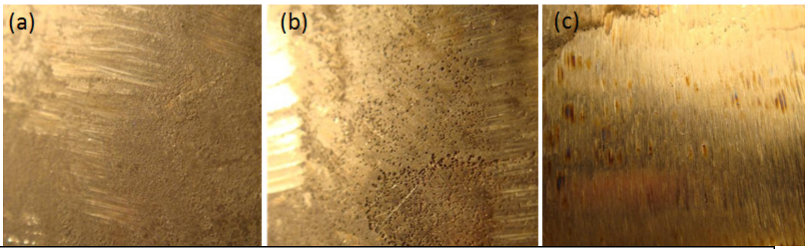


Figure 3.8: X-ray of thin wall area of cylinder.

Figure 3.9: (a) As-cast inside surface; (b) extensive porosity revealed by slight polishing; (c) porosity removed after polishing off ~0.2 mm.

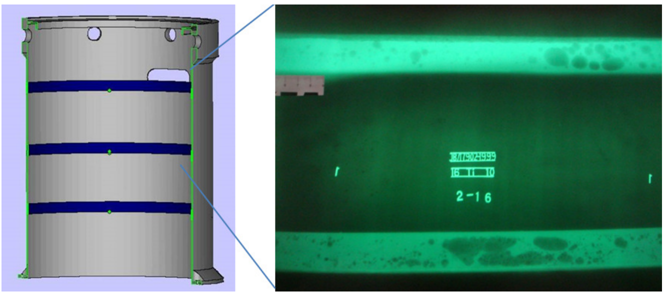


Figure 3.10: X-ray photo showing porosity collected in the ribbon-shaped feeders and such a design removes surface porosity on the thin wall.

Dimension of cast cylinder component The dimension of castings is determined by that of the shell mould, as well as solidification defects such as misfill and large pores the repair welding of which may introduce distortion. HIPping that closes porosity and pores may also cause distortion. The dimensions of the best-controlled cast cylinder had a largest deviation of ~2 mm.

Refinement of coarse grain size of thick sections Ti-6Al-4V alloy castings are well known to possess drastically different grain size, and in thick sections such as the top collar of the cylinder the grains are as large as 5 mm resulting in significant loss of strength. Changing mould preheat temperature is ineffective in solving this problem. We added a small amount of boron (0.04wt%) into the alloy and it significantly refines the coarse grains (**Figure 3.11**). No adverse effect on mechanical properties was found for such a level of microalloying.

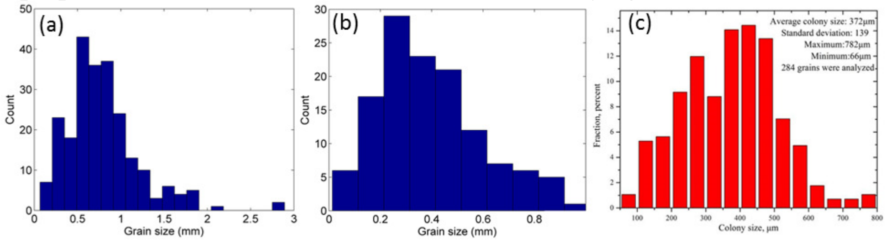


Figure 3.11 : Measured grain size distribution: (a) and (b) top collar and thin-wall area of casting Pattern B 2012-2, respectively (ESA), (c) thin-wall area of casting Pattern B 2012-7 (IMR).

Microstructural optimisation and mechanical properties For castings free of surface connected porosity, HIPping effectively closes casting defects such as shrinkage cavities, gas pores and porosity, and the microstructure can be adjusted through post HIPping heat treatment. **Figure 3.12** shows 3 typical microstructures of the alloy, with corresponding mechanical properties detailed in **Table 3.1**.

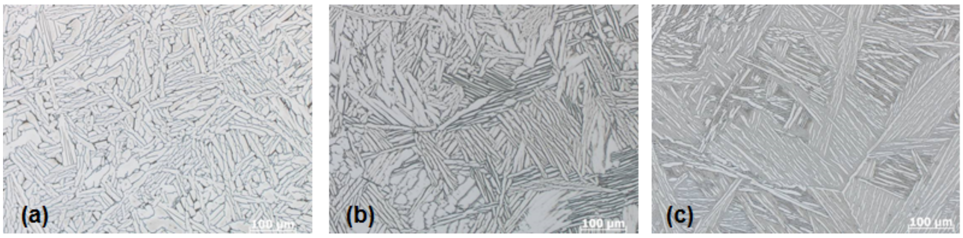


Figure 3.12: Typical microstructure of cast parts: (a) as HIPped, Coarse lamellar, (b) HIPped + aged, coarse lamellar + Widmanstätten, (c) HIPped + solution treated + aged, fine Widmanstätten.

Table 3.1 : Room temperature tensile properties of cast bars and thin-wall area of casting.

Sample	Microstructure	$\sigma_{0.2}$ (MPa)	σ_b (MPa)	δ (%)
Cast bar	Lamellar+Widmanstätten	832	925	10.8
		819	916	11.9
	Widmanstätten	857	960	10.2
		846	964	10.5
Thin-wall area of Pattern B casting	Lamellar+Widmanstätten	810	884	12.5
		829	918	11.5
	Widmanstätten	848	946	10.5
		850	947	10.5

Cast ESA components of COLTS Patterns B and C A total of 4 batches of the cylinder and 2 batches of the cubic frame were cast in this work. Photographs of cast parts delivered to ESA are shown in **Figure 3.13**.

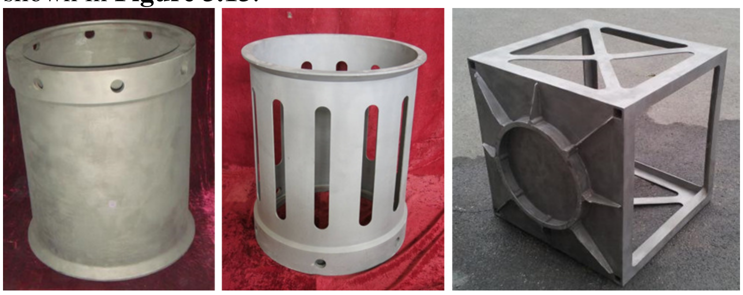


Figure 3.13: The cast ESA components: cylinder (COLTS Pattern B) and cubic frame (COLTS Pattern C).

Conclusions Through the work conducted in WP 3, a centrifugal casting technology suitable for preparing three-dimensional large component with large area of thin wall has been developed. Technical obstacles in wax pattern assembling, shell mould preparation, and gating and configuration design were overcome. The following areas need further consideration.

- Yttria-based face coat is appropriate for casting Ti alloy component with large thin areas, but great care should be taken to avoid inclusions.
- The mould preheat temperature must be appropriately chosen: too low a temperature does not allow complete filling of the mould cavity and may entrap too much gas, while too high a temperature produces too much porosity.
- The use of ribbon-shaped feeders is necessary to eliminate surface-connected porosity on the inside surface of the thin-wall region of the cylinder.
- Both proper design of support fixtures and minimisation of solidification defects are crucial to ensure the dimensional accuracy of the large size components. Too extensive distribution of solidification defects causes unpredictable distortion of the component when the pores are closed during HIPping.

- Variation in grain size in sections of different thickness of cast Ti-6Al-4V component is unavoidable. Addition of a small amount of boron, 0.04wt% in this work, refines the grain size of the thick collars of the cylinder and improves the uniformity of grain size distribution.
- The crucial factors influencing the mechanical properties of cast Ti-6Al-4V component are metallurgical defects and grain size. Provided the solidification defects can be eliminated during casting or closed during HIPping, the ESA specification of mechanical properties can be met after heat treatment.

WP4 Development of gravity and centrifugal casting. The objectives of WP4 defined in the proposal were: (i) To develop gravity casting and centrifugal casting of large Ti64 airframe and space components within specified dimensions; comparison of the quality of castings using the two technologies. (ii) To carry out NDT and dimensional assessment of castings made using both casting technologies (iii) To assess the influence of HIPping and post-heat treatments on properties of castings of Ti6Al4V. (v) To provide components for welding trials in WP7

Melting was carried out in water-cooled copper crucible vacuum consumable electrode arc melting technology to make Ti6Al4V ingots. As noted earlier in this final report aircraft doorframe and cross connector castings were to be produced as demonstrator castings. The doorframe is a thin-walled, multi-ribbed, long and asymmetric structural component; its maximum size is 854mm and minimum wall thickness 4mm. The cross connector is a thin-walled, multi-ribbed, cross-framed structural component; its maximum size is 800×800×200 mm and minimum wall thickness 4mm. From the above structural features, it is evident that mould filling is difficult for these component castings; and the surface/inner quality control, dimension control and deformation control also pose significant problems.

An open gating system design, combined with the bottom pouring was used as shown in figure 4.1, to reduce turbulent flow so that fast smooth filling was achieved.

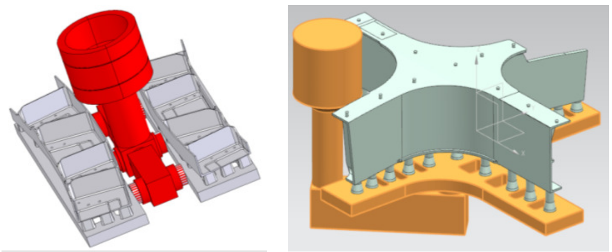


Fig.4.1 Pouring system of doorframe and cross connector

Casting wax patterns were prepared by laser rapid prototyping technology. During solidification, the residual stress is high and leads the casting deformation or cracks, so stiffeners have to be added. In order to accurately obtain the size and shape data, to control the casting dimension accuracy, 3D optical three-dimensional photographic, three coordinate measuring technology, was used to obtain complete measurement of wax patterns. The casting wax patterns are connected together with the casting runner gating system.

Because of doorframe's thin-walled, multi-ribbed, long and asymmetric structure and cross connector's thin-walled, multi-ribbed, large cross-framed structure, the wax patterns of the castings are easily deformed and led to cracks in the filleted corner. Modelling of the stress was carried out and on that basis stiffeners were added and the filleted corner angles enlarged. The wall thickness of the wax patterns was also increased to increase its stiffness to prevent the deformation when wax patterns are prepared and assembled since many risers are added on the wax patterns.

Molten Ti alloys react with most refractories. In the process of pouring and solidification, under the combined influence of high temperatures, gravity and centrifugal force, all these affect the quality of castings, so the selection of mould material and the preparation of mould is the key. Research on the preparation of mould and the pouring of casting has therefore been carried out. Melt pouring and the mould processing conform to the requirements of the titanium alloy casting.

Titanium and oxide ceramic moulds interact and produce reaction products on the casting surface. Electron probe microanalysis has been used to analyse the interface reaction between the different type of ceramic material. This work showed that the content of Ti, O elements was reduced at the interface between metal and the ceramic mould. From the experimental results, the interface reaction between the Y_2O_3 mould or ZrO_2 mould and high temperature molten titanium alloy is not extreme and by pickling and blowing sand and by other surface treatments, the reaction layer can be removed.

Through experimental research, we can draw a method to control the interface reaction.
Wettability comparison of refractory materials: wetting angle is:
Y_2O_3 < ZrO_2 (CaO) < ZrO_2 (MgO) < MgO < Al_2O_3 < zircon powder. Try to select the material of small wetting angle.

b) The enthalpy comparison of refractory:
Y_2O_3 < ZrO_2 (CaO) < ZrO_2 (MgO) < MgO < Al_2O_3 < zircon powder. As far as possible choose the materials with small enthalpy.

c) By adjusting the time of molten titanium alloy contacts the mould.

d) By using the minimum mould preheating temperature to control the interface reaction

In order to study the effect of moulding adhesive on the quality of the mould, design three different kinds of coating adhesive on the back layer, respectively are silica sol, ethyl silicate and the two kinds of coating binder which were used interchangeably.

Yttrium oxide was selected as the surface refractory, zirconium acetate as the bonding agent of face coating, and selects the mullite as the back refractory, silica sol and ethyl silicate as the back layer bonding agent. Forming the mould preparation process:

Face layer is 2 layers, back layer is 10 layers. Mould is dewaxed in the resistance furnace for 200min. Up to 1000min for baking. By this process, there is no crack, drop sand, peeling, ballooning in the mould.

To determine the interface heat transfer coefficient of the titanium alloy precision casting, requires two steps: the first step determines the thermal physical property parameters of the mould material, including heat capacity and thermal conductivity. The second step defines the temperature in the pouring process, for which the coefficient of the interface heat transfer is obtained by inverse calculation. Having established the thermal physical parameter test conditions, the mould was designed for thermal physical property parameters test. With Qinghua university’s help to obtain some of the thermal physical parameters, the pouring temperature used was about 1700°C.

Doorframe and cross connector are thin wall castings, with ribs, large and nonsymmetrical frame structure. It is clear from figure 4.2 that the thin walled area of the casting accounts for more than 90% of the casting. There are many thin-walled ribs, the casting is large and the liquid metal flow distance is very long. These characteristics make casting and mould filling very difficult so that the casting is prone to defects such as misrun and cold shut.

The doorframe uses gravity casting and centrifugal casting pouring, pouring two at a time, to realize symmetrical gating. In order to improve the flowability of the molten titanium alloy, mould preheating was used and the process parameters such as melt temperature, melting current, voltage optimised. Secondly, combined with the results of computer simulation of the filling solidification by Tsinghua University, the pouring system was optimised. It was seen from the simulation and optimisation, that the pouring system allows the molten titanium alloy to fill the mould very quickly under stable pouring conditions.

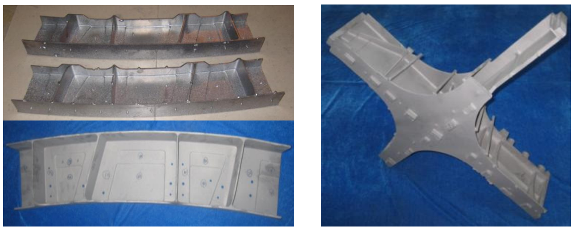


Fig.4.2 Door frame and cross connector Ti6Al4V alloy castings of Airbus

Because the cross connector is asymmetrical it is not possible to use centrifugal casting, casting one at a time. In order to improve the flowability of the molten titanium alloy, mould preheating, process parameters were optimised. Computer simulation was used to optimise the pouring system. By optimisation of all processing parameters accurate shapes were cast with no misruns, few cold cuts, few inclusions, and limited surface reaction layer.

WP4 developed hot isostatic pressing process of the doorframe and cross connector castings. The hot isostatic pressing process (HIP) is as follows: Temperature: 920-920°C, gas pressure: 100-120 MPa, holding time: 2-4 h.

Because casting defects need weld repair, WP4 formed the heat treatment process as follows: Temperature: 710-730°C, vacuum:≤ 0.1Pa, holding time: 2-4h. Doorframes and cross -connector castings are HIPped which effectively eliminates the closed casting defects. Through the heat treatment process design and experiment, the residual stress in castings was reduced, and thus the deformation of the casting reduced. The castings were assessed using NDT. For complicated castings, the use of a 3D coordinates machine and optical scanner, the doorframe and cross connector dimensions, were determined. Measurements of the chemical composition and mechanical properties, in cooperation with the University of Birmingham showed that the ultimate strength and yield strength are in line with the Airbus technical requirements, only the linear shrinkage rate is slightly lower than the technical requirements (5%), the fracture toughness is close to that of forged Ti6Al4V.

WP4 manufactured 4 batch doorframes, cross connector, 10 castings. 2 pieces of doorframe castings were delivered to the University of Birmingham, and 2 pieces of cross connector castings to EADS.

WP5 Production of large wax patterns and development of a strong wax, 3D measurement of cast parts.
The objectives of WP5 defined in the proposal were: (i) To produce wax patterns and to develop waxes which allow improved dimension control of large castings (ii) To assess dimensional accuracy of castings produced in WP3 and 4.

(i) Production of wax patterns and to develop waxes which allow improved dimension control of large castings The wax pattern is used as the part prototype of investment casting, and its cost and quality are the key factors determining manufacturing cost and part performance. This study used additive manufacturing (AM) technology of selective laser sintering (SLS) to fabricate large wax patterns rapidly. The research work is mainly focused on the scanning strategies for large working table, high performance wax material, intelligent pre-heating technique for large powder bed, the shrinkage prediction and intelligent processing plan based on numerical simulation and the 3D measurement. The main research results are summarised below:

In SLS, the scanning strategy affects the internal stress distribution of the parts, resulting in warping deformation and influencing the overall accuracy. To limit the internal stress to a very low level, many scanning strategies were studied. By grouping and reversal scanning strategy, the scanning direction is changed layer by layer which generates stress in multi directions. Compared to the stress when scanning is carried out in a single direction, the warping deformation is limited to a low level. Scanning in block patterns and using reverse scanning, the large scanning area is divided to small blocks of the same size. The internal stress is reduced in the scanning layer, and the warping is well controlled in large parts. By circular scanning, the shrinkage stress in the single layer decreases, but the radial stress increases. After the optimisation of this strategy, the powder outside the scanned area was pre-heated to further reduce warping.

At present, polystyrene (PS) is widely used for SLS to make patterns used in investment casting. However, PS is not suitable for making patterns with thin-walled or delicate structures due to its poor mechanical properties. In this study, a type of high impact polystyrene (HIPS), a polymer blend of PS toughened with polybutadiene rubber, was developed as an SLS material to make the parts with good mechanical properties as well as with good laser sintering properties. The study reveal that the bending strength and modulus of HIPS SLS green parts are 18.9MPa and 62.3MPa, respectively, which are much higher than those of PS SLS green parts. Compared to PS, the particle bonding of HIPS powder is easier because of the viscous flow of rubber in it. This property gives sintered HIPS specimens, which have a more compact microstructure, and results in better mechanical properties than PS specimens and is suitable for making thin-walled and delicate structural parts. When the SLS parts are immersed in the molten wax, the wax infiltrates the SLS parts through capillarity action. After post-processing, most of the voids are filled with wax, and the void fraction is decreased from 52.8% to 8.1%. The SEM images show that most of the HIPS particles are well wrapped by wax. The wax shows good bonding with HIPS because both of them are non-polar materials. Compared with the properties before post-processing, the mechanical properties are significantly improved after post processing. The complete decomposition temperatures for HIPS and PS in inert atmosphere are 412 and 446°C, respectively. This indicates that PS and HIPS can all burn out completely and the decomposition temperature of HIPS is lower than that of PS. In order to determine the ash content, gravimetric determination was employed, and the resulting ash contents of PS and HIPS are both 0.3%. The decomposition of HIPS during the sintering and dewax processes releases an unpleasant odour of butadiene, leading to environmental pollution. Therefore, nowadays, most patterns for investment casting are made by PS. In some cases, HIPS can be used to make large-scale patterns with thin walls.

When heated by the moving laser during SLS, there are temperature field inhomogeneities in the polymer-sintered layer in the sintering height direction and before and after the scan lines. In addition to the different constraints and cooling conditions in different areas, which result in a different extent of shrinkage in different regions, leading to internal stresses. These stresses cause local warping of the outer boundary of the convex corner boundary region and of the initial layer of the part. Once warping of the workpiece occurs, it seriously affects the precision of the parts.

Therefore, this study uses methods, such as increasing preheat temperature to limit the occurrence of deformation or reduce the degree of deformation. When the preheating temperature exceeds the glass transition temperature of the polymer, which is about 15°C, the powder outside the sintering zone melts and some agglomeration occurs. The agglomerated area acts as a restraint on the workpiece and can suppress to some extent of the extent of deformation. In addition, increase of preheating temperature causes the surface temperature of the sintered layer to increase, which reduces the inconsistency of the temperature, and also reduces the uneven shrinkage and non-uniform stress due to non-uniform temperature field, so leading to improved precision of parts. The deformed layer is defined as a “discontinuity layer” and other layers as “general layers”. When confronted with a discontinuity layer, the system identifies it and appropriately enhances the preheat temperature to achieve intelligent control of the preheat temperature.

(ii) Assessment of dimensional accuracy of castings produced in WP3 and 4. Based on partial test data a neural network and regression model based on vectors have been established, which shows the relationship between the SLS process parameters and part shrinkage. The created models have been applied to research and analyse the rules of the single factor and multiple factor process parameter on the shrinkage rate. Based on vector regression models, the intelligent selection of optimisation of the process parameters when the shrinkage is set before, which provides a numerical simulation method for optimisation of the SLS process.

In our system, four-step phase-shifting method is used to realise fast and accurate 3D shape measurement. Typically, the gamma distortion of projector will produce periodical phase error, which is the major error source. In order to eliminate the phase error, the gamma distortion phenomenon, which considers the defocusing effect is modelled, and a novel gamma correction method proposed for phase error compensation which improves the measurement accuracy significantly. On the other hand, for improving registration accuracy of multiple 3D point clouds from the multi-view scanning directions, a global accuracy optimisation method based on bundle adjustment is proposed, and it is very important for measuring large-scale objects.

Based on the study of the scanning process, high-strength materials, intelligent preheating, numerical simulation and 3D measurement, a large SLS system is used to fabricate multiple batches aircraft door and cross joint casting wax. For nearly 1m dimensions, thin-walled and complex structure of wax: the average size deviation of the aircraft door wax control is 0.3-0.7mm, and the maximum deviation is 1.3-1.8mm. The average size deviation of the cross connector wax is 0.4-0.9mm, and the maximum deviation is 2.0-2.6mm. According to the analysis: the absolute value of the negative deviation is greater than the positive deviation value, and size of workpieces are overall smaller than the CAD model, and presented a trend to "shrink". This is relevant to the shrinkage, when the polymer materials are sintered by the laser during SLS. The maximum deviation appears in the local area wax of the outer edge. After intelligent preheating and the optimisation-based on numerical simulation, the maximum deviation is reduced and the warping is decreased. But the increase in temperature results in powder in non-parts areas becoming sintered and blocked, affecting the overall accuracy of wax, which increases of average deviation. With optimisation of the pre-heating temperature and processing plan, the biggest deviation of the wax pattern is about 1.5mm, and the average deviation is 0.3-0.8mm. Wax patterns made by SLS are successfully applied to the casting production. The average size deviation of castings is 0.7-1.0mm. Compared with the wax pattern, the casting size deviation increased. This is mainly caused by expansion of wax shell, metal solidification contraction, the surface quality and other factors. After three batches of the casting process optimisation, the overall precision of casting is very close to the wax pattern, and the average deviation is controlled to about 1mm.The maximum deviation area of the casting is basically consistent with the wax pattern, the casting overall has no significant deformation. Compared with the metal mould, the forming cycle of large casting wax produced by SLS method is only 1/9 of the conventional method, in a single piece and small batch, it also has a cost advantage.

Dissemination level: public

WP6 Final Report. Development of computer modelling for casting large Ti components

The objectives for WP6 defined in the proposal were to develop computer models of (i) centrifugal castings of engine components (ii) gravity castings of airframe structures (iii) centrifugal castings of airframe components. Calcom ESI focused totally on objective (iii), Tsinghua focused on objectives (ii) and (iii). BIAM focused on objective (i) and all work on the engine casing is reported in WP4.

The first section describes CALC's work on flow, porosity and deformation of a cylinder and of a spaceframe. The second section describes Tsing's work on doorframe and cross connector

1. **Modelling of the flow aspects of centrifugal casting** Figure 6.1 shows an intermediate step of the filling of the two main components provided by ESA. The developed flow solution covers the dynamic of the centrifugal filling process quite well.

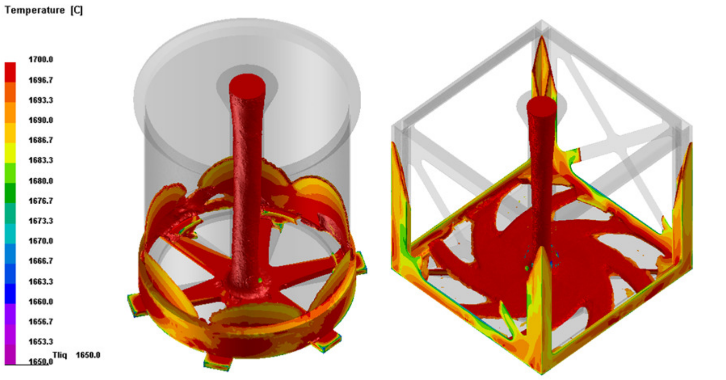


Figure 6.1: Filling simulation results of two ESA parts. The scale covers the range from 50C above the liquidus temperature of 1650C (the actual pouring temperature) to the liquidus.

2.

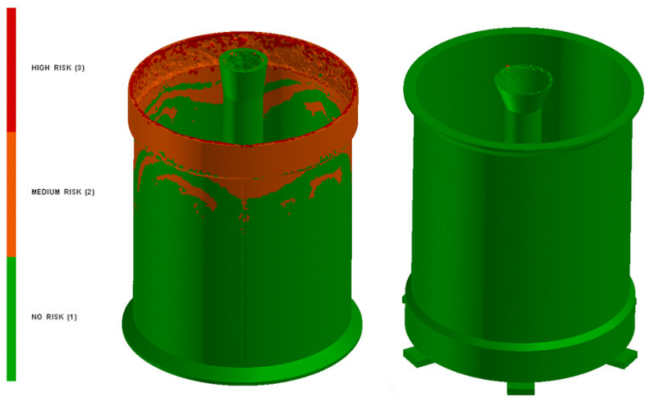


Figure 6.2: Risk of interrupted filling due to too early solidification (left side process version with risk, right side improved filling system with removed risk). High risk of early solidification (brown) is eliminated by improved filling system.

Calcom ESI developed furthermore a new flow criterion, which indicates the risk of intermediate filling due to too early solidification. While the process version on the left side of **Figure 6.2** indicates a risk of too early solidification since melt was not fast enough to the casting part, with the improved filling system this risk could be removed.

Modelling of porosity in centrifugal casting An important aspect of the new casting modeling capabilities integrated in ESI casting solution ProCAST capability of taking into account the centrifugal forces on the porosity formation. **Figure 6.3** shows the influence of the centrifugal forces on the porosity formation using a small demonstrator case.

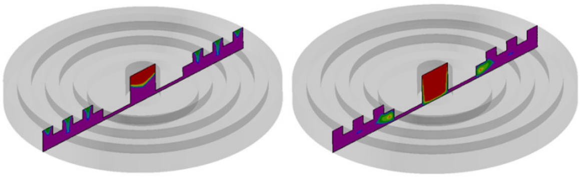


Figure 6.3: influence of centrifugal forces on porosity formation (left side gravity casting, right side centrifugal casting). Red indicates high porosity

While the porosity can be found on the top in the case of gravity casting (**Figure 6.3** left side), the porosity is moved inwards in the case of centrifugal casting (**Figure 6.3** right side).

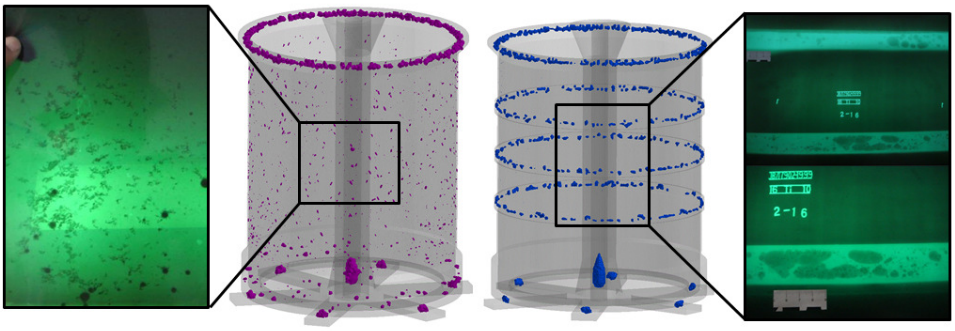


Figure 6.4: Comparison of predicted porosity with experimental results (left, micro porosity, right side use of rings to move the porosity to sections which were machined after casting).

The new porosity approach was applied by IMR in the process development of the casting of the ESA cylindrical geometry. **Figure 6.4** shows that porosity could be concentrated to sections, which were machined after the casting process so that the casting quality could be improved.

Modeling of stress and deformation In the case of the ESA cubic geometry a large deformation was observed in the area of a cross inside the quadratic frame (**Figure 6.5**). The stress modeling results indicated a deformation of similar size coming from the fact, that the inner cross (with a thinner wall thickness) is cooling earlier then the surrounding frame. Being relatively lengthened by plastic deformation the inner cross is moved out of tolerance when the outside frame is shrinking afterwards. The difference in the deformation (inwards experiments versus outwards modeling) might be because the modeling setup and in reality differ from each other.

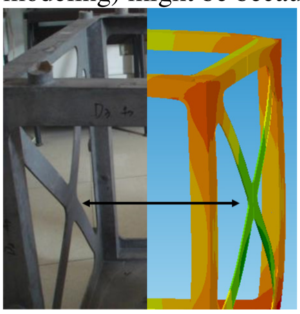
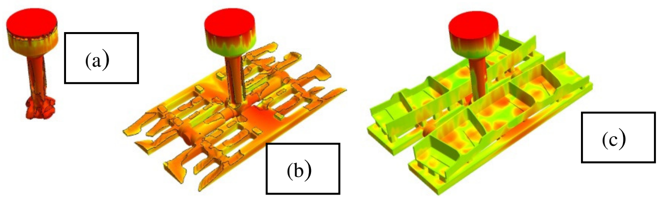


Figure 6.5: Comparison of predicted deformation with the one observed in the cast component. Most heavily distorted regions in green

2 Modelling of casting of door frame and cross connector Using in-house software, TSING, which takes centrifugal and Coriolis force into account, mould filling and solidification of door frame and cross connector were simulated. Gravity and the centrifugal casting were compared.

Simulation of mould filling and solidification process (1) door frame The pouring process lasts for 4.5s in BIAM. The mould filling process in simulation can be seen in Fig 6.6.



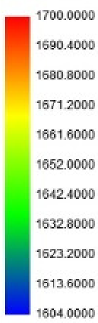


Fig 6.6 Mould filling process of door frame in gravity casting process. The pouring temperature (red) was 1700C which was supplied by BIAM as the temperature used. The liquidus is about 1650C (green).(a)25%, (b) 65%, (c) 100% filled

Smaller Niyama values than 0.2 are marked in Fig 6.7. Porous defects may appear in these areas. This prediction agreed with observations of the localities where pores were observed by BIAM.

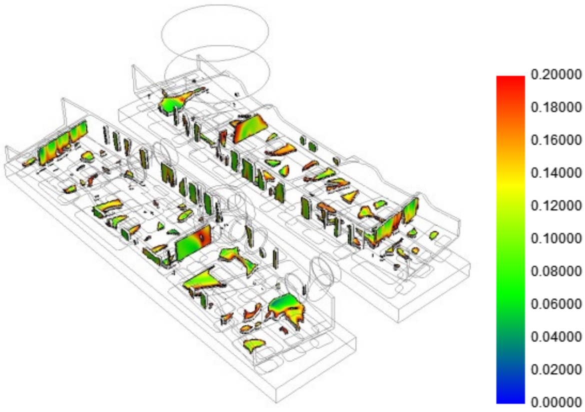
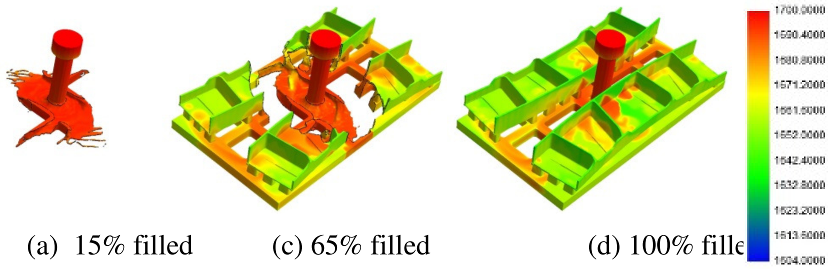


Fig 6.7 Distribution of Niyama value less than 0.2 (red) in gravity casting process for the door frame, which show the potential area to form porosity.

The mould filling process of door frame in centrifugal casting process was simulated as seen in Fig 6.8. The mould filling time is 4.5s and the rotational speed is 200r/min.



(a) 15% filled (c) 65% filled (d) 100% fille

Fig 6.8 Mould filling process of liquid metal of door frame in centrifugal casting. Red is pouring temperature (1700C). Green is liquidus of about 1650C

Positions of door frame where have smaller Niyama values than 0.2 in centrifugal casting are marked in Fig 6.9. Porous defects may take place in these areas. For this casting process, the modeling results were also in agreement with experimental observations made by BIAM.

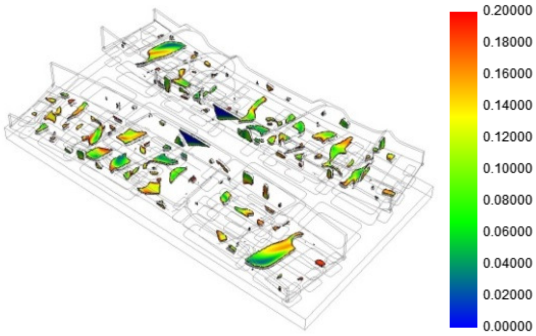
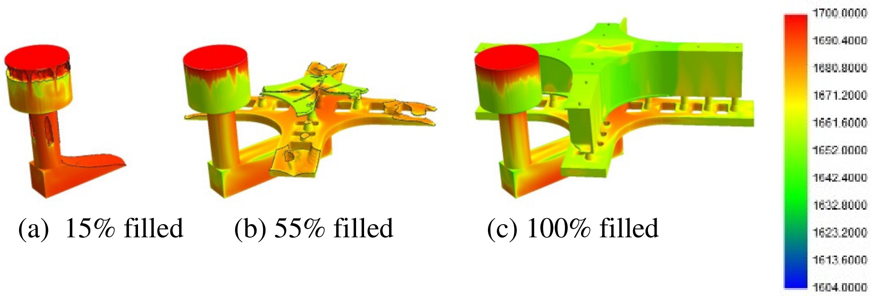


Fig 6.9 Distribution of Niyama value less than 0.2 (red) in centrifugal casting for door frame, which show the potential area easy to form porosity.

(2) Cross connector The mould filling process of cross connector in gravity casting process can be seen in Fig 6.10. The pouring process lasted for about 4.5 seconds.



(a) 15% filled (b) 55% filled (c) 100% filled

Fig 6.10 Mould filling process of liquid metal of cross connector in gravity casting. Pouring temperature (red) is 1700C and liquidus temperature (green) about 1650C

Positions of cross connector where have smaller Niyama values than 0.2 in gravity casting process are marked in Fig 6.11. Porous defects may take place in these areas, which are in good agreement with the experiments done by BIAM.

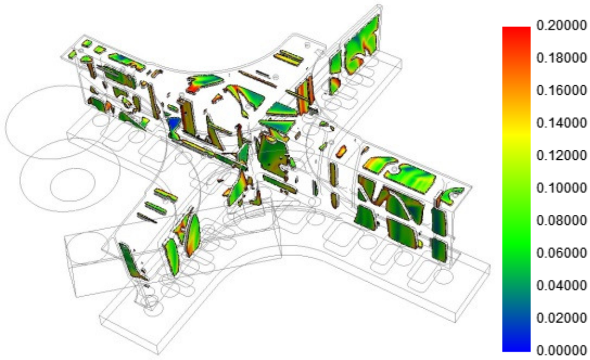


Fig 6.11 Distribution of Niyama value less than 0.2 (red) in gravity casting process for cross connector, which show the potential area to form porosity.

Conclusions WP 6 activity in COLTS was able to build and apply state of art casting modeling techniques to predict flow, thermal, porosity and stress aspects of the casting process for gravity and centrifugal castings. Numerous casting simulations were performed by the partners in WP6 (only a part of them is shown in the text above) and thereby a good agreement between modeling and experimental investigation was found. By indicating the consequences of the selected technical process parameters the modeling activity supported the process development and helped to make it possible to cast the highly complex components (very large and thin walled) that were selected for the project. The modelling capabilities developed in COLTS were integrated in the commercial software package ProCAST. By this the aeronautic and space industry is provided with a professional software solution to further produce such complex titanium parts with a well-controlled casting process.

WP7 Welding of Ti airframe and modelling of welding The objectives of WP7 defined in the proposal were: (i) To develop all aspects of welding procedures including post welding heat treatments for air frame components cast in WP4, which was addressed by Bamtri. (ii) To model welding and post weld treatments, which ING and CIMNE performed.

The work carried out covered the following:

1) Research on welding process of EB welding of cast Ti6Al4V plates (CAE-BAMTRI) supplied by BIAM, which involved quality control of EB welding.

2) Development of welding process of EB welding of wedge-shaped samples to simulate welding of airframe components cast Ti airframe as agreed with Airbus. (CAE-BAMTRI)
Residual stress measurements and distortion control technique of welding of cast Ti airframe (CAE-BAMTRI)

3) Numerical simulation to predict residual stresses and distortion in welding and in response to post-weld heat treatment (CIMNE) using experimental conditions supplied by Bamtri.

1. Research on welding process of EB welding of cast plates The influence of welding speed and welding current on different thickness samples were investigated in order to find the optimum processing conditions. Typical results are shown in Figure 7.1, and assessment of the microstructure and properties on samples supplied by Bamtri, measured in WP8, showed that the optimum conditions met the A-class acceptance conditions provided by Airbus.

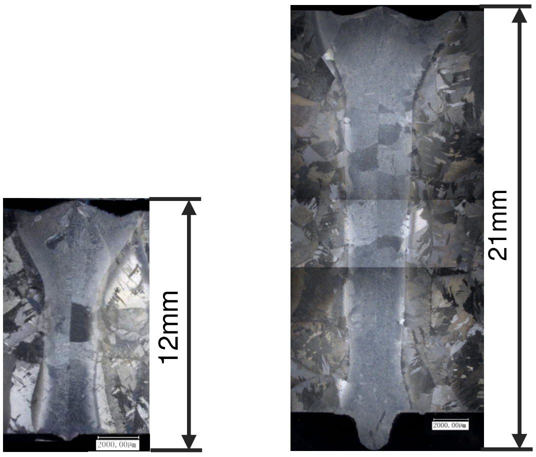
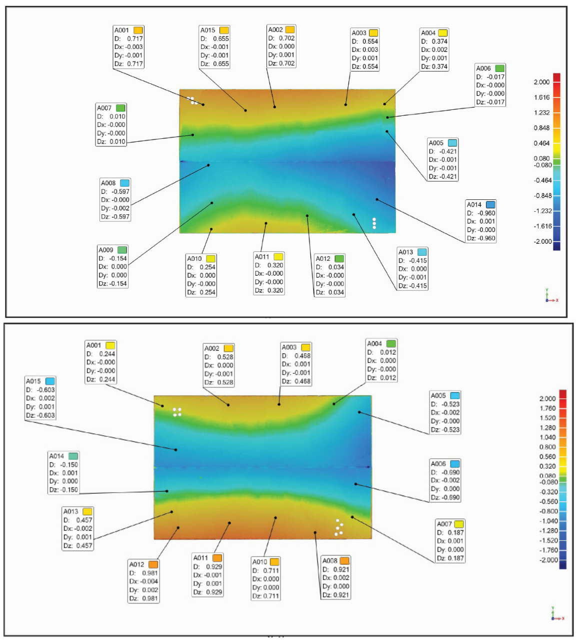


Figure 7.1 Photographs of welded plates of Ti6Al4V (a)12mm thick (b) 21mm thick.

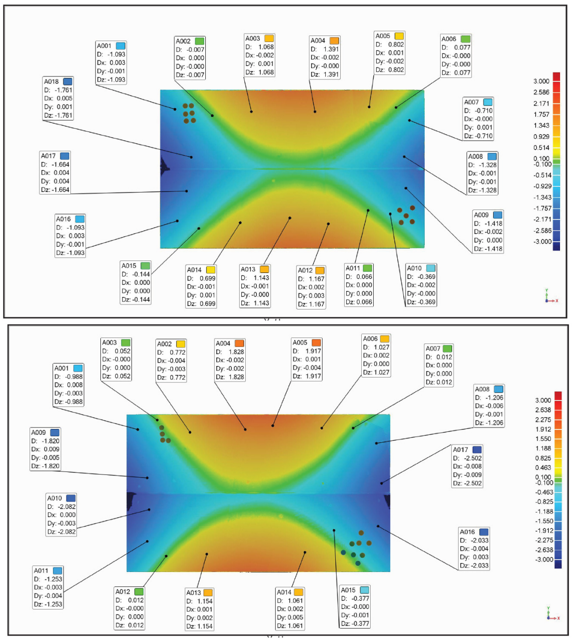
Measurement of the distribution of deformation of electron beam welding 3D Scanner (VTOP200) was used to measure the distribution of deformation of electron beam welded plates of thickness 5 mm and 10 mm. The results (shown in Figure 7.2) show, for a plate thickness 10mm, the maximum angular distortion is 0.74°-0.85° and the maximum deflection is 2.85mm. For the 5mm thick plate, the maximum angular distortion is 1.14°-1.37° and the maximum deflection is 3.803mm.

Measurement of the residual stress in electron beam welded plates The residual stress generated in 5mm thick and 10mm thick electron beam welded plates was measured by strip method. As shown in figures 3 and 4 the longitudinal residual stresses are all large tensile stresses, between 400MPa and 600 MPa, and the maximum value is close to 700MPa. The transverse residual stress is smaller. For the 10mm plate it is between -200MPa and 300 MPa, and for the 5mm plate is between 50MPa and 350 MPa. These stresses can be relieved by post weld heat treatments, see figures 7.3 and 7.4.



1#
(10mm)

2#
(10mm)



3#
(5mm)

4#
(5mm)

Figure 7.2 Distortion result of plates 1, 2, 3 & 4. (Unit: mm)

EB welding of wedge samples Wedge samples (figure 7.5) with variable cross-section based on the A350 XWB door frames were designed, and the matching of welding parameters for the changes of section was solved. Defects such as burn through and lack of penetration were avoided although undercuts were sometimes observed. EB welds which met A grade of Airbus standards (AIPS01-04-011) were achieved.

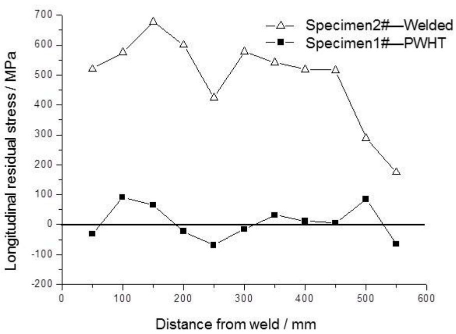


Fig.7.3 Longitudinal residual stress distribution in 10mm thick sample

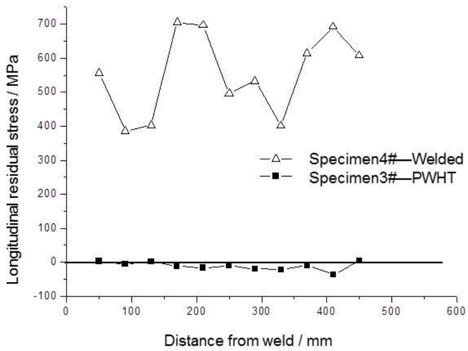


Fig.7.4 Longitudinal residual stress distribution in 5mm thick samples

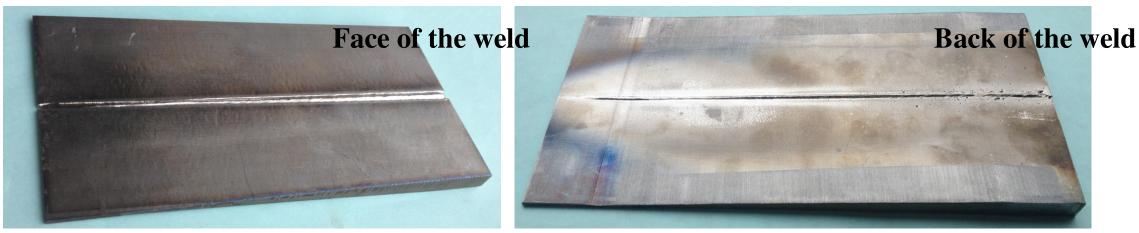


Figure 7.5 Wedge sample welding by electron beam

Dissemination level: public

Measurement of the thermal cycle curve during EB welding Temperature measurements during EB welding were performed and the data provided to CIMNE for their numerical simulation. These are shown in Figure 7.6 and Figure 7.7

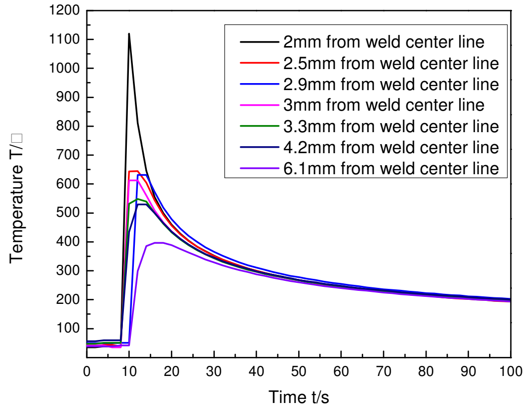


Figure 7.6 Temperature measurement during EB welding during first traverse

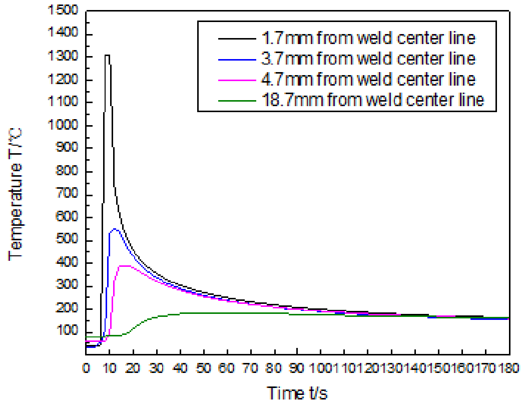


Figure 7.7 Temperature measurement during EB welding during second traverse

2. **Numerical simulation** The numerical modeling of the EBW process is a powerful tool to better understand the physics of the process and its sensitivity to the process parameters (welding speed, electron beam power, work-piece thickness, etc.) for design and production engineering. However this kind of simulation is not an easy task since it involves the interaction of thermal, mechanical and metallurgical phenomena. This is the reason why the numerical framework proposed has been formulated coupling heat transfer phenomena to the mechanical analysis to achieve the highest accuracy simulation results. The material behavior has been characterised by a thermo-elasto-viscoplastic constitutive model.

The work carried out during the project can be divided into the following parts:

State-of-the-art survey **on EB welding simulation covering:**

The FE technology currently used for the EBW simulation

Most common definition of moving heat source to represent the key-hole in EBW.

2.1 **Implementation of a Pre-processing module** where the final user can:

(i) Read/modify the geometry to be welded (ii) Generate the FE mesh to be used for the discretization. (iii) Define the welding path. (iv) Define the industrial parameters characteristic of the EB-welding process (e.g. welding power, efficiency, welding speed, key-hole shape, etc.)

(v) Specify the material (e.g. titanium alloy) and the corresponding parameters of the constitutive equation implemented (e.g. Young modulus, Poisson ratio, yield stress, conductivity, specific heat, density). (vi) Launch the simulation

2.3 **Implementation of the Solver kernel** for the solution of the **thermo-mechanical** problem defined by the EBW process:

(i) Diffusion/convection equation-solver, based on enthalpy format made ready for complex phase-change problems.. (ii) Temperature-dependent material properties (conductivity, specific heat, density). (iii) Phase change phenomena (latent heat, solid fraction function) according to Sheil's rule. (iv) Moving heat source representing the EB power distribution during welding process.(v) Heat convection, heat conduction and heat radiation law at the surface boundaries of the geometry for the heat loss.

2.2 **Implementation of a Post-processing module** where it is possible to:

(i) Visualize the temperature evolution during the welding process and cooling phase,(ii)Visualize the solid-fraction evolution during phase-change process.. (iii) Draw the temperature evolution graphs at different thermo-couple locations.(iv) Study the distortion of the final part after welding and the residual stresses induced by the process.

2.4 **Benchmarking procedure**:
In accordance with BAMTRI have been defined different benchmarks to firstly verify and secondly calibrate the software module.
The experimental evidence recorded in terms of thermocouple plots and distortion measurements have been compared with numerical data achieved using the brand-new software developed within the COLTS project.

The proposed formulation has been implemented into a **multi-physic environment** able to run coupled thermo-mechanical analysis. This is the so-called, software **kernel**. The original software platform to deal with coupled thermo-mechanical analysis was COMET (COupled Mechanical and Thermal software). COMET is a research-purpose software property of the International Center for Numerical Methods in Engineering (CIMNE). All the necessary implementations to deal with the EB welding process have been added to such platform.

The **software-interface** to let the user introduce both the material and the process data has been developed, starting from the original pre-post processing platform is GiD. GiD is a powerful commercial tool property of CIMNE. Using this pre-post processing tool is possible to read geometries from the most common CAD format. It is also possible to generate geometries from scratch using different CAD tool available. The mesh generator is also integrated in GiD offering a powerful tool for FE analysis. Starting from such graphical environment, a collection of software windows to interact with the solver-kernel, have been developed. The content of such windows as well as the geometry and mesh data are collected in an input file for the solver kernel.

The **numerical assessment** of the software developed for the numerical simulation of the EBW process has been carried out checking both thermal and mechanical responses. Firstly the calibration and, latter, the validation procedure have been made possible thanks to the experimental work carried out at BAMTRI.

The correct definition of the EBW heat source resulted in excellent agreement between numerical results and experimental measurements at the different thermo-couple locations. The comparison between the temperature evolution computed by the software and the experimental data available show a very good agreement.

The mechanical results obtained in terms of final distortion of the metal sheets and residual stresses at the end of the welding process also compare very favourably with those of the experiments.

Concluding comments. The objectives listed at the beginning of this report have all been met. The interaction between Bamtri and CIMNE enabled the modelling to reflect accurately the optimised welding conditions identified by Bamtri. Samples were supplied to other WPs for assessment and are reported in WP8.

WP8 Comprehensive assessment of microstructure & properties of cast and welded components. The objectives of WP8 defined in the proposal were: (i) To assess the relevant mechanical properties and microstructures of samples cut from the cast components produced by CAE -BIAM and IMR in order to assess the success of the casting process in producing castings fit-for-purpose. (ii) To assess the relevant properties and microstructures of welded components produced by CAE(BIAM and BAMTRI). (iii) To improve casting and welding of Ti64

ESA components The assessment of ESA components was started on four large pieces cut from an initial cylinder casting (pattern B), which were provided by IMR. One piece was further HIPped at the IRC. Large cavities were found along the top collar perimeter and small shrinkage porosity at other areas. HIPping can remove the cavities. Y_2O_3 inclusions were found in the thick section (top collar). The microstructure of the component consists of alpha and beta lamellar colony structure. No alpha case was found at the surface. Tensile tests show fracture initiates at casting defects (shrinkage porosity and inclusions). Prior beta grain boundary is the preferred path for crack propagation, due to the thick alpha film formed at the boundary. Following discussions of these observations with CALC and IMR, the following changes were introduced: (a) improving the filling system to remove the large cavities found in top collar by putting the mould upside down, (b) HIPping the components before delivery to remove porosity and improve ductility, (c) adjusting alloy composition to increase strength, (d) refining beta grain size to improve ductility and (e) considering further heat treatment to optimise properties.

Following the initial casting, a total of four components were produced by IMR for ESA, from which three were cylindrical structures denoted as Pattern B and one was a cubic structure designated as Pattern C. Extensive assessment, including dimensional accuracy, NDT, tensile testing and metallographic analysis has been carried out at ESA and the IRC. Geometry measurement shows that dimensional tolerance is generally in line with requirement with some significant improvements in Cylinder 3. The top-to-bottom distance of the Cylinder 3 is slightly undersized by 1.22 mm. The top and bottom collars are undersized while the mid-section is oversized. The roundness of the top and bottom collars are 0.77 mm and 3.68 mm. The thickness of thin section is larger than the nominal specification, but desirable to allow for surface finishing in the case that a requirement on the surface roughness has been set.

Radiographs were used to identify the presence of internal defects in the cylinders. Casting defects such as blow hole, shrinkage porosity, hot tear and inclusion have been found. In contrast to Cylinder 1 and 2, Cylinder 3 did not carry hot tears. Only four blow holes could be identified in the Cylinder 3, which is a significant improvement from Cylinder 2. The number of inclusions found in Cylinder 3 has also been significantly decreased. Approximately 10 inclusions were counted in the whole of the structure, which is significantly less than the 104 inclusions counted in Cylinder 2. It was noticed that the beta grain size and lamellar thickness (Fig. 8.1), varies in the components, especially when comparing the thick top collar and the thin middle section. Efforts have been made to reduce the grain size and homogenise the microstructure by micro-alloying (boron addition) at IMR. The average grain size in Cylinder 3 (with the addition of boron) has been reduced by almost three times comparing to Cylinder 1 (Table 8.1). As shown later, the significant refining of grain size results in improvement of both strength and ductility.

Tensile tests have been carried on both the thin and thick sections, and results are listed in Table 8.2 together with ESA expectation and Airbus specifications. As expected, generally the thin section has higher strength than that of thick section. The initial casting and Cylinder 1 have yield stress (YS) slightly below 800 MPa and further lower to about 750 MPa after HIPping. However, the ductility is increased from about 1-4% to 6-9% by HIPping in both thin and thick sections, which shows the effectiveness of HIPping to remove porosities and improve ductility. Although the tensile property of the cylinders is close to the Airbus specification for Ti64 casting, it is below the ESA expectation. In the following casting, IMR has modified the alloy chemistry to bring the Al and V contents higher but within specification to increase strength. With the modified alloy chemistry coupled with minor boron addition, both cylinder 2 and 3 have YS above 800 MPa and UTS around 900 MPa. While the elongation of thick section is around 8.4%, the thin section in Cylinder 2 and 3 has an elongation less than 2%. Fractographic analysis shows the samples contain micro-porosity, which cause the significant reduction of ductility. Furthermore, X-ray image also shows that the thin section has larger porosities. It suggests that surface-connected porosity on the inner surface of the large thin-wall region of cylinders formed during casting could not be removed by HIPping. It was realised that the use of ribbon-shaped feeders (were added in the initial casting and Cylinder 1 but removed in Cylinder 2 and 3) is necessary for eliminating such porosity in thin sections. IMR has shown that, by removing the porosity in thin section and adding a heat treatment after HIPping, the thin section has tensile properties which meet the ESA expectation, which is a very challenge target for casting.

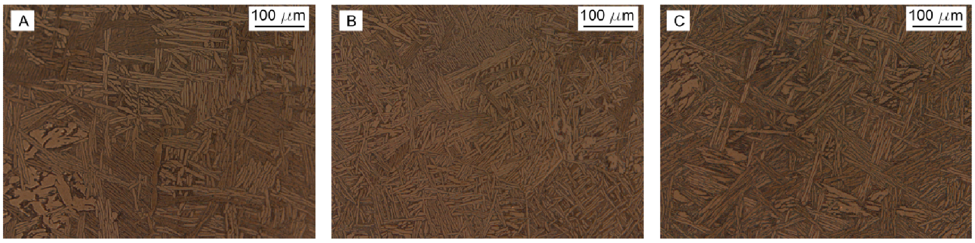


Fig. 8.1: Micrographs of etched samples of (A) top collar, (B) middle section, and (C) bottom collar.

Table 8.1: Average grain size (in mm) for cylinder 1, 2, and 3.

Location	Cylinder 1	Cylinder 2	**Cylinder 3**
Top collar	1.5	0.8	**0.5**
Thin section	0.8	0.4	**0.3**
Bottom collar	1.9	N/A	**0.5**

Table 8.2. Tensile properties of ESA cylinders at thin (middle) and thick (top collar) sections.

Specimens	**YS, MPa**	**UTS, MPa**	**Elongation, %**
Cylinder 1 thin	784	840	4
Cylinder 1 thick	796	861	3
Cylinder 1 thin HIP	779	861	7.1
Cylinder 1 thick HIP	743	812	8
Cylinder 2 thin HIP	863	912	1.2
Cylinder 2 thick HIP	817	895	8.4
Cylinder 3 thin HIP	823	877	1.7
IMR 2012-7 thin HIP+ HT	**820**	**901**	**12**
ESA expectation	800	900	10
Airbus specification (casting)	780	860	5
Airbus specification (b forging)	830	900	6

The fracture toughness K_Q values of the thick section are in the range of 68 to 96 MPa$\sqrt{m}$. HIPping reduced the scatter of K_Q values to 72 – 89 MPa$\sqrt{m}$. Although ESA did not specify fracture toughness requirement, the obtained fracture toughness values are well above Airbus specification for casting (40 MPa$\sqrt{m}$) and close to that of forging (80 MPa$\sqrt{m}$).

Limited work on a pattern C component has shown that the erosion from the filling leads to a large concentration of defects, mostly inclusions. This problem mirrors the challenges encountered with the casting of the cylindrical structure. It is expected that experience gained while producing additional cube structures may minimize and eventually eliminate the presence of face coat inclusions in the future.

In summary, The ESA components produced by IMR have shown great improvement between batches. ESA is satisfied with the component quality produced in the project in view of the great challenges to produce large 3-D thin wall castings, even though improvement such as further reducing inclusions and porosity is needed before the components can be put into production.

Airbus components The doorframe and cross connector were cast by BIAM. Two doorframe and two cross connector components were delivered to EADS and IRC for assessment. Defects, such as porosity and inclusions, have been revealed by X-ray tomography. The number density of defects is low and defect size is generally small. The chemical composition of the doorframe is within the Airbus Material Specification (AIMS-03-21-002). The microstructure of the doorframe is similar to that of ESA cylinders (Fig 8.2). The surface is clean and no alpha case was found. The average beta grain size varies with wall thickness, ranging from 0.5 to 1mm.

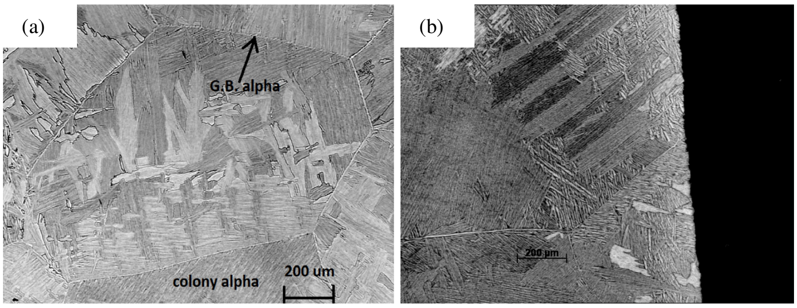


Figure 8.2. Microsturture of the door frame at inner (left) and surface (right).

The tensile properties of the doorframe at different locations are shown in Fig. 8.3. Clearly, all samples have tensile properties above the Airbus specification (AIMS-03-21-002) for casting. However, the strength of some samples (at bottom of the doorframe, denoted as S in Fig. 3) just missed the challenge target set by Airbus for forged and β annealed product (YS > 830 MPa, UTS > 900 MPa). Tests on samples with unmachined surface shows the rough surface significantly reduces ductility.

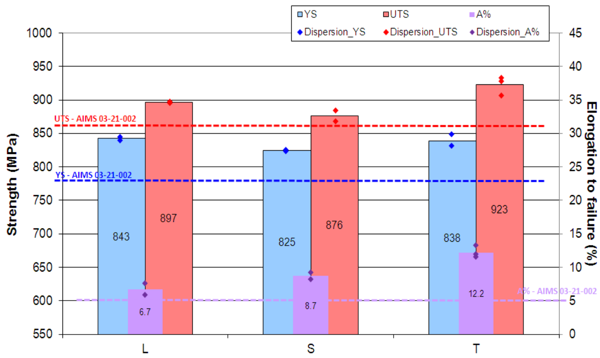


Figure 3. Tensile properties of the doorframe.

Fatigue crack growth rate is one of the most important parameter for designing and maintenance scheduling of large aerospace component. Figure 8.4 shows the fatigue crack growth rate (da/dN) of the door frame at different locations as a function of stress intensity range (ΔK) with comparison to Airbus specifications for casting and forging. Due to large beta grain size and colony size produced during casting, the component has very low fatigue crack growth rate, and meets both the Airbus specifications for casting and forging.

The first cross connector was delivered in as cast condition. Numerous defects were found. After HIPping, the porosity was greatly reduced but the surface became irregular. The second cross connector was produced with improved filling system and it is expected to reduce porosity.

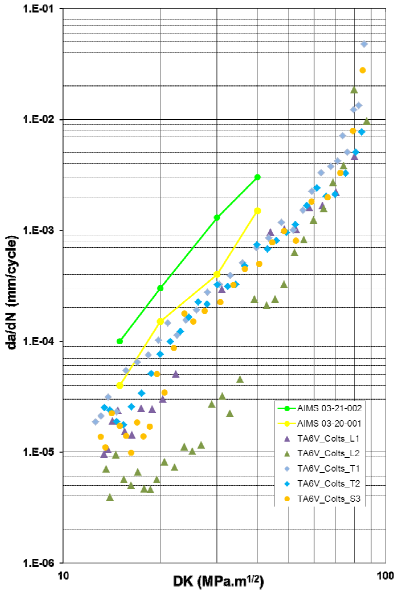


Figure 4. Fatigue crack growth rate of doorframe

In summary, the doorframe has a generally clean chemistry and relatively uniform microstructure and mechanical properties. The mechanical properties, in terms tensile and fatigue crack growth rate, meet the Airbus specification for casting and even the Airbus challenge target (specification for forging), although the tensile properties of some samples just miss the target. Some irregularities of microstructure and properties have been found in the component which suggest further attention should be made to the effect of defects, weld repair and stress relief on properties. Other properties, such as fatigue also need to be investigated to satisfy all Airbus requirements. It is expected the cross connector has similar microstructure and properties to that of doorframe.

Welding of casting plates BAMTRI has provided 3 batches of welded casting plates to IRC, including 3 thick (23mm) plates, 6 thin (5mm) plates and one plate with varying thickness from 2mm to 10 mm. The optimised EB welding processes employed in welding both the 5mm and 23mm thick cast plates changed the microstructure from lamellar colony structure in the base metal into martensite in the fusion zone (Fig. 8.5); Gas pores within the weld as large as 50μm in diameter were found.

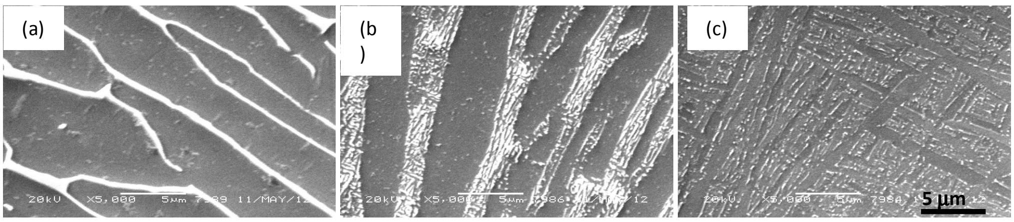


Figure 8.5. Microstructure around weld: (a) base metal, (b) HAZ and (c) fusion zone.

The weld joint has higher strength than that of the base metal. All specimens failed in the base metal during tensile testing. The overall tensile properties largely depend on those of the base metal. Stress relief at 650°C for 2 hours does not have a significant effect on tensile properties. Fracture toughness of the weld on 23mm thick plates was improved from 51.9MP$a\sqrt{m}$ to 66.3MP$a\sqrt{m}$ after HIPping. This is attributed to the softening and coarsening of the fusion zone structure such that the fracture is more ductile and the crack tortuosity is higher.

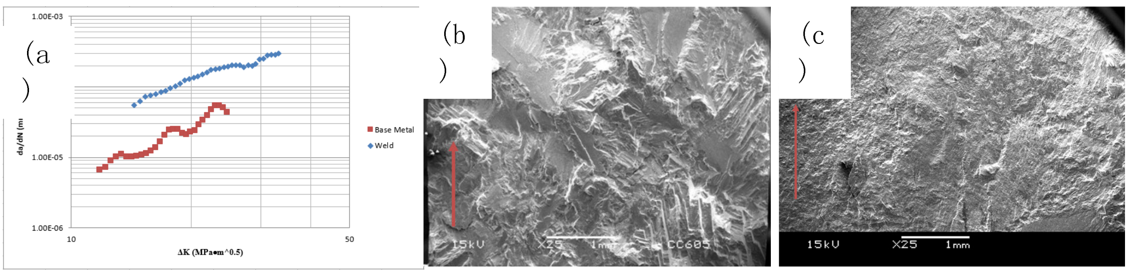


Figure 8.6. Comparison of fatigue crack growth (FCG) rate in between base metal and weld (a) together with fracture morphology of base metal (b) and welds (c).

After stress relief, the weld on 5mm thick welded plates has FCG rates almost 5 times larger than that of base metal (red line in Fig. 8.6a) due to its much finer martensitic microstructure and therefore less crack deviation (Fig. 8.6b,c). The residual stress in the weld has significant effect on FCG rate. The complexity of residual stress induced during welding and its re-distribution during specimen machining and testing make the FCG rate unpredictable.

In summary, EB welding is a viable process to form clean and sound joints of cast Ti64 components. The weld joint has higher strength but lower fatigue crack growth resistance and fracture toughness than the base metal. Post welding heat treatment (PWHT) is necessary to reduce residual stress and make the fatigue crack growth rate predicable. The feasibility on welding varying thickness components has been confirmed. Further optimising PWHT and reducing gas pores have been suggested.

In addition to the assessment, the WP8 has provided support for modelling in WP6 in the form of supplying thermal and thermo-mechanical data.

WP9: Industrial assessment of demonstrator components and cost/environment benefits
The objectives of WP9 defined in the proposal were: (i)To assess cast and welded components with respect to dimensional tolerance and property requirements (ii) To assess the cost reduction (iii) To assess the environmental benefits.

(i)Assessment of dimensional accuracy and property requirements This part of the report covers the assessment of the properties by the industrial partner, EADS, who focussed their attention on Airbus components- the doorframe and the cross connectors. These were cast by BIAM.
Door frame. The tensile properties and fatigue crack growth (FCG) properties were within or in the case of the FCG measurements exceeded the Airbus specifications for TA6V cast part requirements. However properties, such as fatigue tests would have to be investigated in order to meet all Airbus requirements.
Cross connector The first cross connector delivered had not been HIPped and tomography showed a high density of pores. A second cross connector has been received, but tomography has yet to be performed.

The properties and geometries of welded cast plates have also been assessed and these were found to meet all of AIRBUS's specifications. In addition to the mechanical property data reported in WP8, which showed that the specifications had been met, ESA carried out dimensional assessment of the cylinders and space-frames cast by IMR. It was found that the cylinders were undersized by about 5mm at the two collars positioned at the ends. On the other hand, the mid-section were oversize by about 6mm. The wall thickness of this this section is only ~0.5 mm away from the nominal. Further iterations would be required to eliminate these small discrepancies. The surface roughness of the COLTS cast Ti components is in the range of typical investment castings and final sand-blasting and polishing have been used on the final demonstrators, which obviously reduced the roughness.
(ii) Assessment of cost reduction It has been confirmed during COLTS that manufacturers are unwilling to make public their detailed manufacturing costs and for that reason it has not been possible to make a realistic comparison of the costs of the casting technologies developed during costs either with current castings produced by PCC or by similar components made by other process routes. Only very general analyses have therefore been carried out but these suggest that there should be a significant reduction, both through the fly-to-buy ratios, which strongly favour casting, and through the energy consumption during processing. If near net shape HIPping (NNSHIP) is further developed then it appears from these analyses that the costs of casting and

NNSHIP may become comparable and with the superior properties of NNSHIP components this technology could be preferred to casting for components such as engine casings, but not for the other components assessed in COLTS.

(iii) Assessment of the environmental benefits The production of raw Ti6Al4V requires a large amount of energy and results in high CO_2-emission, so that any reduction in the scrap generated during component manufacture will result in a significant reduction in the environmental impact. On that basis alone casting would be expected to be a more environmentally friendly process-route than forging and machining where typically 90% of an ingot is reduced to machining swarf. The analysis of the actual environmental impact is very difficult because varying amounts (up to 40% in electron beam melting, to produce aerospace quality ingots) of the machining swarf are recycled. If as an extreme assumption it is assumed that no scrap is recycled and that a billet is simply machined to shape (rather than ring-rolled) then calculations based on the total energy consumption and the CO_2-emission suggest that the impact on the environment of manufacturing Ti components by casting rather than machining would be reduced by a factor of about 7. The assumptions made in these calculations are extreme, but the very different fly-to-buy ratios of these two process-routes strongly suggests that a reduction of the environmental impact of at least 3 times would be expected for the manufacture of large components.

Conclusions from WP9. The objectives listed for WP9 were known to raise some issues, such as confidentiality of manufacturing costs, which would make it not easy to draw firm conclusions. Nevertheless the objectives have largely been achieved, although further work would be required by end-users before the components produced during COLTS could be accepted as fit-for-purpose. This further work, such as fatigue measurements could be done by the end-users and there is every reason to believe that the components produced during COLTS could provide the foundations for the efficient manufacture of lower cost, more environmentally acceptable castings that could replace thermo-mechanically processed components

WP10 Dissemination and exploitation The objectives of WP10 defined in the proposal were:

(i)To disseminate the results to the partners outside the consortium (ii) To make scientific, professional, industrial and general public aware of the COLTS project and its plan, results and potential benefits that can be derived from science and technology achievements (iii) To attract additional RTD funds in order to make the COLTS Consortium operational and prosperous after the end of the project (iv) To ensure that the technologies and processes developed in COLTS are marketed through the partners to all potential end-users and supplier chains– if necessary by interacting with other approved suppliers.

Objective (i) and (ii) have been achieved through multiple channels that include a website, attending conferences and publishing in peer-reviewed journals, showcasing hardware at public events, interacting with other projects, and exploiting its results. The COLTS website was set-up within the first six month of the project at: *http://www.colts-project.eu*. The site contains a layman's description of the project, its objectives, the Chinese and European partners involved and lists publications from the projects.

Nine conference presentations were given over the course of the project, from which five provided a general overview of COLTS to the general public (D.J. Jarvis (ESA), le Bourget Airshow, 2011; J. Pons i Prats (CIMNE), Festa del Cesta, 2013) and the aerospace and titanium communities (X. Wu (Monash), Aerodays, 2011; X. Hao (IRC), Titanium Information Group, 2013; M. H. Loretto (IRC), 3rd Int. EASN Workshop, 2013). Modelling activities were presented for the centrifugal and gravity castings (O. Koeser (CALC), 3rd Int. EASN Workshop, 2013) and for electron beam welding (M. Chiumenti (CIMNE), Coupled, 2013). The physical and mechanical properties of centrifugal castings were the topic of two presentations that focused on the fatigue crack propagation and fracture toughness (X. Feng (IMR), 13th Int. Conf. Fract., 2013) and on the microstructure, tensile strength, and the geometrical assessment of the component (X. Hao (IRC), 3rd Int. EASN Workshop, 2013).

Two peer-reviewed papers were submitted by Z. Li and Y. Zi (HUST) to Optics Letters and Measurement Science and Technology. The first article describes a profilometry method using fringe image modelling and gamma correction [1]. The second presents a three-dimensional microstructural measurement technique using optical microscopy and variation of illumination [2]. In addition to journal publications, a patent was also submitted by HUST for a process to measure complex three-dimensional surfaces using surface structured light and light pen [3]. The work by HUST led to copyrights of the PowerMetric 3D software used for three-dimensional coordinate measurements and photogrammetry. In addition to conference and journal publications, cast components produced by BIAM and IMR have been displayed publicly at the GRAIN meeting in Beijing held between March 26-29th, 2012. This event was attended by several EC and CAE officials. Several components are also expected to be permanently displayed at the European Space Agency - ESTEC in Noordwijk, in the Erasmus High Bay, which is home to numerous space artefacts and has attracted more than 25,000 visitors during 2012.

Objective (iii) has been addressed through three draft proposals for future European/Chinese funding which have been submitted by the COLTS partnership to the EC in order to gain future funding; these will be considered later this year and if one of the topics is approved, a full proposal will be submitted.

Objective (iv) is with ESA and Airbus for the specific components produced during COLTS but those partners (BIAM, BAMTRI and IMR who developed generic technologies will no doubt be able to benefit from the quality improvements in their products as aerospace demands grow.

CONCLUSIONS

COLTS has been a successful programme as can be judged from this report. The success was achieved because the interaction between those developing casting and welding, with those carrying out modelling of the processes and the detailed assessment of the cast and welded components, was very productive. It is apparent that most of the objectives defined in the proposal have been realised, and that the foundations for those few that were not achieved have been laid.

If the end-users need the work to be taken further, it would be efficient for the appropriate partners to complete these objectives, because the optimised conditions are based on experimental expertise developed during COLTS which is backed up by modelling data, as indicated in the report. Some areas, such as removing buckling of the cross members should be straightforward, but others, such as eliminating yttria inclusions will be more difficult. Proposals have been submitted for consideration by the EC and by CAE and if these are funded it is hoped that many of the partners involved in COLTS can work together in the future, so that we are able to take full advantage of the excellent productive relationship between many of the partners.