AST3-CT-2003-503826

IDEA

Integrated Design and Product Development for the Eco-efficient
Production of Low-weight Aeroplane Equipment

Instrument:
STREP
Thematic Priority 4
Aeronautics and Space

Final Publishable Report

Period covered: 01.01.2004 – 31.03.2007  Date of preparation:   May 2007
Start date of project:  01.01.2004   Duration:  01.01.2004 – 31.03.2007

Project coordinator name: Achim Wendt
Project coordinator organisation name: RWP GmbH

CONTENT

1  SUMMARY AND CONSORTIUM ................................................................. 2
2  MOTIVATION, OBJECTIVES AND APPROACH ............................... 3
3  ACHIEVEMENTS ........................................................................... 4
   3.1  Prototypes ............................................................................ 4
   3.1.1 Evaluation of alloys and parts ........................................... 5
   3.1.2 Full scale tests: ................................................................. 5
   3.1.3 Conclusions and prospects regarding aerospace applications 7
   3.1.4 Outlook of the main achievements .............................. 8
4  EXPLOITATION .......................................................................... 10
1 Summary and Consortium

The IDEA project aimed at substituting aircraft components manufactured from aluminium or other materials by cast magnesium parts. Integration of Mg alloys into the aerospace will lead to breakthroughs, which will reduce the airplane's weight, improve the noise damping and reduce the fuel consumption and air pollution. Nowadays approximately 20 Mg-casting alloys are available, however more than 97% of the castings are made of AZ91, AM50 (or AM60) and WE54 or AS21 (or other sand cast alloys for specific applications). Thus, there is a need to increase the number of Mg-alloys available for aerospace applications with their specific requirements to strength, damping properties, corrosion resistance etc. In general, large aircraft manufacturers like Airbus and Boeing are reluctant to use Magnesium alloys – and especially Magnesium castings - for civil aircrafts. The share of castings in their airplanes is less than 1%. Since there is an obvious lack of knowledge about the characteristics and advantages of magnesium and its alloys and a lack of approved standards for magnesium components another important aim of the project is to inform aviation designers broadly on the usability of Mg-alloys and to contribute to standardisation. Accordingly, the technical objectives of the project were:

1. To develop new lightweight Mg-alloys, which fulfil the requirements for castability, corrosion resistance and mechanical properties of the cast components.
2. To determine corrosion rates, analyse diffusion processes and develop conducting and non-conducting coatings for the new Mg-alloys.
3. To optimise the most appropriate casting processes (investment casting, sand casting, gravity die-casting, but also high pressure die-casting) for Mg alloys.
4. To develop and use specific simulation tools for determination of local mechanical part properties and virtual standard tests of cast components.
5. To prepare a design manual for cast magnesium components in aeronautical applications. The manual is aimed to be a guide for aviation designers to select convenient Mg-alloys and production methods for convenient aircraft components.
6. To produce demonstrator castings for typical thick-walled and thin-walled aerospace applications.

These objectives were achieved by developing 11 new Magnesium alloys for gravity casting and high-pressure die-casting. Prototype castings have been produced to demonstrate the potential of the new alloys. Furthermore the consortium developed new efficient coatings for magnesium parts, an alternative inhibiting substance for investment casting, computer models for prediction of microstructure, defects and mechanical properties of magnesium castings, and a Design Manual for Magnesium Castings in Aircrafts.

Several aircraft parts produced by the consortium won first prizes in different categories at the Magnesium Component Competition 2006 organised by the European Magnesium Research Organisation of European companies.

Project cost: 4,874,189 €
Project duration: 01.01.2004 – 31.03.2007
Participants: The 13 consortium members (6 companies including 5 SME’s, 5 organisations, 3 universities are the simulation software developer RWP GmbH (D), the Israel Institute of Technology Technion (IL), the Magnesium Research Centre MRI (IL), the end user Israel Aircraft Industries IAI (IL), the light-metal foundries Specialvalimo J. Pap SV (FI), Femalk (HU), and Stone (UK), the Technical Research Centre of Finland VTT (FI), the research company INFERTA GmbH (D), TECOS - the Slovenian Tool and Die Development Centre (SI), the LCSM of the University of Nancy (F), MGEP - the University of Mondragon (ES), and the Fraunhofer Institute IST (D).

The project was co-ordinated by RWP GmbH, Roetgen, Germany
E-mail: rwp@rwp-simtec.de
Internet: www.rwp-simtec.de
2 Motivation, Objectives and Approach

The aerospace industry is currently facing many challenges related to the increase in air-traffic. Regulatory efforts to lower the weight of airplanes, which in turn will decrease air and noise pollution, are forcing commercial companies to constantly search for, and develop new methods and processes to improve aircraft’s performance. Successful integration of Mg alloys into the aerospace industry can lead to breakthroughs, which will reduce the airplane’s weight, improve the noise damping and reduce the fuel consumption and air pollution.

The use of Mg alloys is not widespread in the interior of airplanes or electronic packaging due to “traditional” problems with the corrosion resistance. Although major developments have led to a new generation of Mg alloys with improved corrosion resistance properties, these alloys are mostly designed for automotive industry. Alloys for aerospace industry, however, must combine high performance regarding mechanical properties (fatigue, strength, vibration properties) and corrosion resistance. Weight reduction in aircraft is a fundamental matter, yet further research is needed in order to develop Magnesium technology (alloys, computer aided manufacturing, surface treatments, etc.) suitable for the aerospace industry.

In view of the above the IDEA consortium aimed to achieve the following objectives

1. To develop new Mg-alloys, which meet the end-users requirements regarding corrosion resistance, mechanical properties, strength, fatigue and coatability and to select at most 3 of them for developing prototypes and demonstrators.
2. To develop optimum processes for sand and investment casting, gravity die-casting, high-pressure die-casting enabling the production of non-structural, semi-structural and structural castings for airplanes fulfilling the end-users requirements.
3. To develop specific simulation tools for determination of local mechanical properties of magnesium castings.
4. To prepare a design manual for cast magnesium components. The manual shall be a guide for aviation designers for selecting the convenient Mg-alloys and production methods for convenient aircraft components.
5. To produce demonstrator castings, which are approximately 30% lighter than the same components in their current design.

To achieve the above objective the consortium worked in the following main areas

- Alloy development
- Corrosion protection and surface technology
- Casting technology and simulation
- Exploitation
- End use and prototyping

End Use and Prototyping

The clamp keeping the whole project together was given by the end user, I.A.I. and supported by the Advisory Group of experts from aviation industry, supply industry and research. In the beginning of the project components were selected, which finally should be cast with the new magnesium alloys, see Figure 2.1. The requirements to the properties of these parts allowed defining the requirements to the new alloys. At the end of the project the prototypes were produced and evaluated by the end user.

![Figure 2.1. Selected prototype castings a) Housing for motion transfer, b) foot pedal for transmits pilot control inputs to yaw and brake control](image-url)
Alloy Development
Once the requirements were known new alloys for gravity casting and high-pressure die-casting were developed. High-pressure die-casting was included although the process is not appropriate for production of high performance small series parts. Nevertheless it should be pointed out that not only aircraft parts are in the focus of weight reduction but also movable equipment like trolleys that do not need to fulfil high requirements and may be produced in larger series.
New alloys were first developed and after thorough testing on laboratory scale four alloys were selected for further tests in industrial environment. Two of them were finally chosen for prototype production.

Corrosion protection and surface technology
Part of the tests and developments was dedicated to corrosion protection. Corrosion properties of the new alloys were determined and compared to those of commercial magnesium alloys.
In parallel, new coatings were developed and compared to commercial coatings.

Casting Technology and Simulation
Sand casting, investment casting, gravity die-casting and high-pressure die-casting (HPDC) processes were considered in IDEA. The overall goal was to improve these processes to enable production of thin-walled components with commercial and new magnesium alloys. Since numerical simulation should play a major role in the design of running and feeding systems a substantial amount of effort was allocated to measurements and experiments, which allowed determining material properties and casting properties as well as development and verification of simulation models.
Further efforts were allocated to
- Development of new non-reactive shell mould material for investment casting of magnesium.
- Determination of a minimum amount of SF6 gas for flushing of the investment moulds.
- Development of alternative inhibiting substance for investment casting and determination of its optimum use.

Exploitation
Project achievements and knowledge gained during the project were gathered, organised and made available in form of a Design Manual for Aviation engineers.

3 Achievements

3.1 Prototypes
Two demonstrator castings were developed: the housing and the pedal. The housing is a semi structural part. A box in which motion transfer mechanism from the cockpit to tail through pressure bulkhead is located. It is attached to the pressure bulkhead and is part of the flight control system. The rudder pedal transmits pilot control inputs to yaw and brake control.

Several objectives were defined for the evaluation of the prototypes:
- Evaluation of prototypes: Quality requirements and product soundness.
- Evaluation of mechanical test results on specimens extracted from castings.
- Performance of full scale fatigue tests simulating flight conditions.
- Analysis of test results.
- Environmental tests on coated specimens.
- Conclusions and recommendations.
3.1.1 Evaluation of alloys and parts

Product quality evaluation: Demonstrators were evaluated by I.A.I as if they were aircraft parts passing quality assurance tests. The tests are as follows:

- Visual inspection for surface defects
- Radiography per AMS – STD – 2175 Class 2 Grade B
- Penetrate inspection per AMS 2644 and ASTM – E – 1417 Type 1 Acceptance class L, Sensitivity level 2.

Test results are summarized in the following table:

<table>
<thead>
<tr>
<th>Test</th>
<th>Housings MRI 207 – T6 Sand Casting</th>
<th>Pedals Investment Casting and HPDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual Inspection</td>
<td>Not acceptable (1)</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Radiography</td>
<td>Not acceptable (2)</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Penetrate Inspection</td>
<td>Acceptable</td>
<td>Acceptable</td>
</tr>
</tbody>
</table>

Notes:

1. Usually parts that are not accepted by this inspection need to be finished by means of surface polishing or need improving surface quality by foundry. They could have been repaired to pass the visual inspection but due to time and budget constrained their repair was given up.

2. Castings meet requirements of Grade C. There were areas of Grade B but the total grade is determined by the lowest level of part. The failure was due to minor areas of micro porosity, without structural importance.

Tensile and fatigue results for castings: Tests were carried out by MGEP and MRI. Results are summarized in the following tables:

<table>
<thead>
<tr>
<th>Requirements</th>
<th>UTS=290 MPa</th>
<th>YS=220 MPa</th>
<th>Elongation= 3%</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRI 207-T6 Sand cast tensile bars</td>
<td>304±6</td>
<td>220±8</td>
<td>4±1</td>
</tr>
<tr>
<td>MRI 207-T6 Sand cast housing</td>
<td>295±6</td>
<td>210±6</td>
<td>3±1</td>
</tr>
<tr>
<td>MRI 207-T6 Investment cast tensile bars</td>
<td>285±3</td>
<td>215±3</td>
<td>3±0</td>
</tr>
<tr>
<td>MRI 207-T6 Investment cast pedal</td>
<td>249±5</td>
<td>205±10</td>
<td>1±0.5</td>
</tr>
<tr>
<td>MRI 207-T6 Gravity die cast tensile bars</td>
<td>265±15</td>
<td>203±12</td>
<td>3±1</td>
</tr>
<tr>
<td>MRI 207-T6 Gravity die cast pedal</td>
<td>292±2</td>
<td>213±2</td>
<td>5±1</td>
</tr>
<tr>
<td>MRI 219 HPDC tensile bars</td>
<td>275±8</td>
<td>184±3</td>
<td>5±1</td>
</tr>
<tr>
<td>MRI 219 HPDC pedal</td>
<td>204±15</td>
<td>137±10</td>
<td>2.7±1</td>
</tr>
</tbody>
</table>

According to the tensile test results, sand castings have the best properties and conform to requirements. Investment castings and gravity die castings exhibit lower properties especially in the elongation. The 5% reduction of properties for samples taken from sand castings is accepted. For the investment castings the reduction is 6 – 15%, a little bit beyond expected values, but it is still acceptable. Fatigue results for smooth specimens were presented by MRI for the MRI 207 and accepted. All requirements were fulfilled.

3.1.2 Full scale tests:

3.1.2.2 Pedal

The requirements for the pedals are as follows:

Limit load Test
The pedal shall withstand a limit load of 300 Lbs in forward direction applied at an arm of 6.5" above the pivot point to simulate brake operation. The pedal is held to the shaft with taper pins and the shaft is held rigidly while application of load (See Figure 3.1).

**Endurance Test**
The endurance test is composed of three stages as follows:

- 100 cycles at limit load. (300 lbs).
- 50,000 cycles at 50% of limit load. (150 lbs).
- 200,000 cycles at 10% of limit load (30 lbs).

All tested pedals, investment, gravity die and high pressure die casting passed limit load and endurance tests.

![Figure 3.1 – Testing facility for the endurance test of the pedal.]

### 3.1.2.3 HOUSING

The housing is attached to the pressure bulkhead and is subjected to cabin pressurization. The full scale test of the housing was planned to be carried out simultaneously versus original aluminium housings. Fatigue and DT test system was used for functional tests in the housings, where specimens were attached simultaneously to plenum.

**Discussion:** After Stone Foundry declared that no housings according to X-ray Grade C requirements were produced, the following decisions were adopted:

- Stone produced housings with reduced radiographic quality: instead of Grade B housings were Grade C. Grade C is not used for structural / semi structural parts due to its inferior fatigue properties. Since only this quality was achieved, it was decided to perform the full scale test on these parts.
- In order to reduce testing time, the internal pressure of the cyclic loading was raised to 72 PSI. This induces destructive stress of 22.6 kg/mm² (220 MPa)
- MRI 207 Housing cracked after 8100 cycles. The crack propagated through wall thickness and gained length of 40 mm. The AZ91E housing cracked after 21400 cycles.

![Figure 3.2 – Fatigue and DT test system; specimens attached simultaneously to plenum.]

- Investigation of crack and fracture surfaces as well as crack surroundings did not reveal any significant finding.
- Second full scale test was planned to be according to initial test plan, meaning, 36 PSI cyclic loading.
The second full scale test could not be commenced due to severe sealing problems. The pressurization system could not build internal pressure to begin the tests. Other tests were carried out meanwhile. The regular NDT tests – radiography and penetrate inspection – did not reveal any problem, but after more failures in building internal pressure and after consulting experts in these tests, a special penetrate inspection was performed while trying to build internal pressure. After some more tests and using leakage detection facilities, very thin cracks were found in the housing. The cracks prevented pressure building. These thin cracks can not be detected using usual NDT tests because they are tightly closed. When internal pressure increases they open slightly, releasing the pressure and close again, disappearing from all the usual detection systems. Thus the second full scale test could not be commenced using the MRI 207 Housing. The test began later with AZ91E Housing and is reaching now 55,000 cycles with no cracks detected. I.A.I decided to continue this full scale test after completion of the IDEA program.

Fatigue in general is very sensitive to micro-cracks and hence must be treated statistically. In addition, fatigue and damage tolerance behaviour of the newly developed MRI 207 is not fully known. Therefore, much more full-scale tests are required in order to have a good statistics and reliable failure analysis. However, the results can also be correlated to high sensitivity to crack initiation and even by the possibility of thin cracks resulted from not yet fully optimized casting procedure. This point is very important and further development of casting technologies adjusted to casting of MRI207 in a grade acceptable by the aerospace industry must be carried out.

Flammability Test:
Although not included in the research program I.A.I conducted this test for AZ91E and for MRI 207. Test was carried out at I.A.I laboratories per FAR 25.853. The AZ91E and the MRI 207 passed the test.

3.1.3 Conclusions and prospects regarding aerospace applications

- The new gravity Mg-alloy (MRI207S) fulfils aerospace requirements, which are those of commonly used aluminium A357 alloy.
- The pedals were successfully produced by investment casting and gravity die casting. All the pedals passed load limit and endurance tests.
- MRI 207S casting technology for the housing did not succeed to produce sound castings according to aircraft requirements as defined by I.A.I. However, it looks like the gap for achieving the goal is very close and reachable.
- Considering the current state of the art, sand casting is the preferred potential technology for the housing. However, further process development is required in order to obtain sound castings.
- MRI 207S investment casting process requires significant improvement in order to realize the potential of the process for the production of the housing, but this technology has a high potential due to the achieved surface quality.
- HPDC is not suitable for structural aircraft parts due to low mechanical properties, porosity, and tooling costs.
- Corrosion tests for the various coatings and alloys revealed that AZ91E with phosphate conversion coating and epoxy primer is the most corrosion resistant. No corrosion signs were detected after 1000 hours in salt spray.
- MRI 207S anodized and primed with epoxy primer showed corrosion signs in the scratch region after 672 hours in salt spray. Other areas were attacked after 840 hours.
- All tested Mg-alloys passed the flammability test.
- MRI207S exhibits higher mechanical properties than AZ91E. However, it failed in full-fatigue test due to micro-cracks, which can be overcome with appropriate casting technology.
3.1.4 Outlook of the main achievements

Exploitation and End Use

State-of-the-art: Until now it is generally believed that the potential increase of Mg alloys application is in the automotive industry and to be more specific, merely in components subjected to elevated temperature like gear box, oil panel and engine. In general, large aircraft manufacturers like Airbus and Boeing are reluctant to use Magnesium alloys – and especially Magnesium castings - for civil aircrafts. Currently, large manufacturers like Airbus and Boeing don’t use magnesium at all in structural parts of their aircrafts. The share of castings in their airplanes is less than 1%.

Progress: In the reporting period the progress in alloy development and magnesium casting of aircraft parts has been clearly demonstrated. The prototype castings - housing and foot pedal - have been produced with commercial and new alloys as well as by various casting methods. The parts were exhibited at the Aeronautics Days 2006 in Vienna. In addition, the sand cast housing as well as the foot pedal produced by investment casting, gravity die-casting and high-pressure die-casting all won the first prizes in different categories of the Magnesium Component Competition 2006.

Alloy Development

State-of-the-art: For the aforementioned applications the alloys AZ91, ZE41 and WE43 are the best alternative out of the commercially available alloys. However, the castability, corrosion resistance and strength of these alloys do not fully comply with the requirements for applications in modern helicopters and aircrafts.

Progress: In the course of the project activities five gravity casting and six HPDC alloys were developed and evaluated. It was found that new alloys significantly outperform existing alloys with respect to tensile, compressive and fatigue properties. One gravity casting alloy and one HPDC alloy were selected for casting demonstrative components namely the pedal and the motion transfer housing.

New alloys were manufactured in industrial scale. The properties of new alloys meet End-User (IAI) requirements. The castability is reasonable – thin walled components were cast in gravity die-casting, HPDC, sand casting and investment casting. The corrosion behaviour is acceptable.

Thermodynamic data base was developed and used in alloy design and analysis of the microstructure evolution during solidification and exposure to elevated temperatures.

In depth characterisation of components in as-cast state and solution and precipitation heat treatment state were performed.

The data regarding physical and mechanical properties of new alloys were obtained and reported in Deliverable D23 and Milestone M12.

Corrosion and Surface Treatments

State-of-the-art: Due to its reactivity, corrosion resistance of commercial Mg-alloys is still a concern that has to be fully addressed. The level of understanding the corrosion mechanism is lacking even for the most studied alloy AZ91. Moreover, not much is known concerning the conductivity of the film formed on these alloys, their porosity, and the electrical, dielectric and semi-conductive properties.

Progress: In this working period, the corrosion properties of the new alloys (MRI204, MRI207 and MRI219, in previous reports called MRI 219) were characterised in comparison to commercial alloys, and two kinds of coatings were tested and developed on new alloys. The first one is chemical conversion coating which thin anticorrosion barriers are made by a simple dipping process in a chemical bath. Phosphate-permanganate and chromate based coatings were tested as references. New cerium and carboxylate based coatings were developed and
tested to find green alternatives to toxic reference coatings. The results show that these new coatings are efficient solutions to replace the chromate and phosphate-permanganate coatings.

The second kind of coating is the electrochemical conversion coating made by oxidation at high voltage named plasma electrolytic coating or micro-arc anodisation. A study of the anodisation characteristics allows us to choose the best conditions to stabilize the micro-arc formation on the metal surface during the process which is necessary to form dry ceramic oxide. Aluminate, silicate or stannate were added as additives in the bath to form the best protective layer in moderate corrosive media.

**Casting technology and simulation**

**State-of-the-art:** Cast housings as well as other cast components for the aircraft interiors are two of the applications ideally suited for the use of cast magnesium parts. The applications require development of new alloys with improved mechanical properties and the manufacturing processes to be able to successfully make the parts.

Components for these applications vary in their size and wall thickness weighing up to a few kilograms and hence several processes may be considered for their manufacture. Components of wall thickness down to 4mm are currently the state-of-the-art in sand and investment casting methods.

High Pressure Die Casting (HPDC) is a leading process for mass and high volume production of components in a variety of shapes and sizes typically with thin to medium wall thickness sections. For lower production rates, gravity die casting, sand casting and investment casting methods are more suitable producing complex components of thin to medium wall thickness sections. Surface finish and dimensional tolerances in each of these processes vary with investment casting process producing the finest surface finish and best dimensional accuracy possible. This method is capable producing thinner wall sections and tighter tolerances.

Casting filling and solidification simulations are often used nowadays to support die and gating design. However, these currently play a minor role for magnesium castings due to the lack of reliable thermo-physical data and knowledge of heat transfer characteristics. Correlation among solidification behaviour, microstructure and properties of magnesium alloys is also lacking. This project, therefore, also aims at the research and understanding of all of these topics.

**Casting Technology Progress:** A huge progress was made regarding the achievement of some key milestones of the project. The in the IDEA Project addressed casting processes are the Sand Casting, Investment Casting, Gravity Die Casting and the High Pressure Die Casting (HPDC). Some of the achievements of the project are summarised below:

- Determination of minimum amount of SF$_6$ gas for flushing of the investment moulds
- Development of alternative inhibiting substance for investment casting and determination of its optimum use
- Production of small to medium sized components of minimum wall thickness of 2mm in sand, investment and gravity die casting methods in commercial and new alloys thus pushing the limits from 4mm to 2mm
- Achievement of AMS-STD 2175 Class 2 Grade B quality standard in parts produced in AZ91E alloy using sand casting method thus enabling the full-scale testing to be carried out
- Part produced by using sand casting method won first prize for “Degree of Innovation – Sand Casting” and investment cast component was awarded the first prize in the “Degree of Difficulty – Investment Casting” in the Aeronautics category at the Magnesium Component Competition. Also high-pressure die-cast and gravity die-cast components won first prizes for “Degree of Difficulty – High-Pressure Die-Casting” and “Degree of Difficulty – Gravity Die-Casting”, respectively.

**Progress simulation:** The capabilities of process simulation have been improved by determination of thermo-physical material properties of the new magnesium alloys. Realistic simulation of mould filling, solidification as well as prediction of microstructure and mechanical
properties of magnesium castings produced with new alloys has been made possible. In the consortium the progress is demonstrated by the fact that all three participating foundries now regularly use simulation.

4 Exploitation

Aircraft components are subjected to high requirements regarding low-weight, mechanical properties, fatigue and corrosion resistance. The IDEA project developed new high-performance magnesium alloys, new coatings and improved casting processes to produce magnesium prototype castings for aviation applications.

To bring new alloys and techniques into use in aircrafts several actions have been undertaken.

First an Advisory Board of experts from aviation industry, supply industry and research was established. The Advisory Board was regularly informed on the developments of the IDEA project and guaranteed dissemination of results to aviation industry including major players like EADS and Agusta Westland, to supplying industry and to the research community. The contacts established through the Board are still kept beyond the project life time and intensified in order to utilise Magnesium alloys in aviation industry.

Since it is well known that many aviation designers are reluctant to use magnesium in aircrafts - often simply due to a lack of information - the IDEA-project developed a Design Manual for aviation engineers. Purpose of the Design Manual (DM) is to provide valuable information on magnesium alloys and magnesium castings to aviation engineers.

Figure 4.1 shows the opening window of the DM and one of the file cards on material properties. As shown in Figure 4.2 the DM does not only carry material information but also process descriptions and measures to process optimisation.

In conclusion it can be said that the potential of magnesium as light-metal even for structural and semi-structural components in aerospace is large and has been enhanced by the development of new alloys. Outcome of this project is the real use of the two Magnesium castings, foot pedal and housing, in passenger’s aircrafts.