MAGNESIUM CASTINGS FOR AIRCRAFTS

A.Wendt*, B.Bronfin, A. Ben-Dov***, J. Townsend****, S. Mahmood******
***RWP GmbH, **Magnesium Research Institute, ***Israel Aircraft Industries LTD,**
******Stone Foundries LTD**

Keywords: *Magnesium alloys, castings, aircraft, mechanical properties, modelling*

Abstract

Magnesium has a large potential to reduce aircraft weight due to low specific weight and good castability. Advanced Magnesium alloys have been developed to address the increased demands on high strength and good corrosion properties. Reference castings and prototype castings for aircrafts were produced to demonstrate the excellent casting properties.

1. Motivation and Objectives

The work described in this article shall demonstrate the applicability of cast magnesium parts for aircrafts. With a density of 1.8 g/cm³ magnesium alloys are more than 50% lighter than aluminium alloys like, for example the A357 alloy with density of nearly 4 g/cm³. Data presented at the Mg 2000 conference revealed that in aeronautics industry the value of a pound in weight saved ranges between 300 and 3000 USD [1]. This is 100 to 1000 times more than in automotive industry. This causes an obvious demand for weight saving in airplane design and manufacture, which could be perfectly achieved by increased use of magnesium. Additional weight saving can be achieved because magnesium allows the casting of thinner walls in unstressed locations than aluminium.

Nevertheless, alloys for aerospace industry must combine high performance regarding mechanical properties (fatigue, strength, vibration properties) and corrosion resistance. Although weight reduction in aircraft is a fundamental matter, yet further research is needed in order to develop Magnesium technology suitable for the aerospace industry.

Thus, the objectives of the present work are

- To develop Magnesium alloys that meet the requirements of aeronautics industry to new materials in terms of low density, improved mechanical properties and corrosion behaviour.
- To evaluate casting processes with respect to their suitability for aeronautics industry.
- To evaluate corrosion properties of magnesium castings and specific coatings.

Since the use of Magnesium in aircrafts would - apart from cost savings - also lead to reduced fuel consumption and air pollution, the important environmental requirements of the 6th Framework Programme (FP6) of the EC are met. Accordingly, the “Aeronautics and Space” programme of the FP6 offers an opportunity to support aerospace industry, Tier1 companies and Foundries in their intention to use more magnesium casting alloys for different applications. Based on the above background a consortium was established, which intends to demonstrate the potential of Magnesium castings for essential weight reduction in aircrafts. This consortium, consisting of partners from eight countries, worked out a corresponding research programme called IDEA. The acronym stands for “Integrated Design and Product Development for the Eco-efficient Production of Low-weight Aeroplane Equipment”.

2. Procedure and results

After set up of the requirements to non-structural and semi-structural parts new Magnesium alloys with improved mechanical properties were developed and further optimised. Reference levels for alloy properties and casting quality were set by producing and testing standard samples (tensile and fatigue bars, corrosion plates, etc.), test parts and reference castings of commercial magnesium alloys as well as by production of the same parts from the newly developed alloys. Reference levels were also set for different casting technologies like sand casting, investment casting, gravity die-casting and high-pressure die-casting.

Based on the results of numerous experiments three gravity-casting alloys and one HPDC-alloy have been selected out of more than ten new alloys for further testing and optimisation. Two of them were finally used for production of Prototypes.

Although four casting technologies were investigated this paper would focus on sand casting technology except for paragraph 2.4, which is also related to investment casting, gravity die-casting and high-pressure die-casting techniques.

2.1 Requirements of Aeronautics Industry to magnesium alloy castings

Aircraft costs are often regarded in terms of price per unit weight. Thus, there is a straight relationship between weight saving and cost. As already mentioned in aeronautics industry the value of a pound in weight saved ranges between 300 and 3000 US Dollars depending on the aircraft. For a business jet like I.A.I.'s – G-200 (Gulfstream) the value is 700 $ per lb, which makes weight saving crucial. However, weight saving has become quite a complicated task since a number of constraints and boundary conditions have to be considered. This includes material properties like corrosion resistance or flammability and properties of the component like stiffness. Production and material costs must also be considered.

Although the weight saving potential of magnesium is well known, and although Magnesium is already been used in aircrafts since the Forties and Fifties of the 20th Century, it does not play an important role in current aeronautics industry. The main arguments against magnesium are

- Magnesium has poor corrosion properties.
- Magnesium has poor mechanical properties.
- Magnesium has a high flammability.
- The availability of Magnesium is too low for mass production.

In addition, there is a strong resistance against the use of castings in aircrafts. Probably, this is caused by the general preconception that castings are in general of poor quality and always need a safety factor, which in turn increases the weight of cast components. In the Boeing 757 and Airbus 320, for example, castings make only a share of 1% of all product forms.

In order to overcome these obstacles new Magnesium casting alloys should meet the requirements listed in *Table 1*

Table 1. Requirements to magnesium alloy castings.

Property	**Requirement**
UTS	290 MPa
TYS	220 MPa
Elongation	3%
Radiography	Classification and inspection of castings per AMS-STD-2175 Class 2 (former: 1B). Radiography inspection Grade B per ASTM E155. Minimum detectable porosity is 2% of wall thickness
Salt spray test	Per ASTM B 117. Coated specimens will be tested with Copper accelerated acetic acid salt spray per ASTM B 368. Periods: 2 and 4 weeks
SCC test	ASTM G 38, G 44, G 49
Galvanic corrosion test	Testing per ASTM G-71-81 against Aluminium fasteners and steel fasteners

For materials to be used for production of secondary structural parts the fatigue properties required are shown in Table 2.

Table 2. Required Fatigue properties (Axial fatigue tests)

Cycles to fracture	Percent of UTS (R=0.2)	Percent of UTS (R = -1)
10^4	88	61
10^5	66	44
10^6	50	28

In addition, to the above requirements, the castings should pass all standard tests that are usually performed by the aircraft manufacturer.

2.2 Development of new Magnesium Alloys

Under development of new gravity casting alloys it was taken into account that the major mechanisms affecting properties of gravity casting alloys are precipitation hardening, solid solution strengthening and grain boundary strengthening. In general, alloying principles for the development of high strength magnesium alloys for gravity casting applications after T6 heat treatment can be reduced to the following rules [2,3].

Grain refinement is considered as a very important tool at the development of gravity casting alloys. It is well known and documented that Zr has a grain refining effect when added to magnesium leading to the greater casting integrity and improved mechanical properties [4].

The most practical elements compatible with Zr are Zn, Y, Ag and rare earth elements (La, Ce, Pr, Nd, and Gd).

Based on the strict requirements listed in *T*ables 1 and 2 and taken into consideration the availability and commercial attractiveness of the alloying elements, some of them such as Nd, Y, Gd and Ag seem to be most promising for the development of new alloys.

Heat treatment is a very important factor for obtaining a required combination of service properties. It should be selected based on a compromise between mechanical properties, requirements and commercially acceptable holding time at solid solution treatment and particularly at aging. Solid solution treatment should be performed at the highest practicable temperature to dissolve coarse eutectic intermetallic phases formed during casting process. Practically the solid solution treatment is conducted at the temperatures about 20-30°C below the solidus temperature of the alloy. The most challenge is usually associated with selection of the temperature and time of aging because these parameters significantly affect the final properties.

In addition to their influence on mechanical properties, alloying elements should provide good castability (increased fluidity, low susceptibility to cracking, reduced porosity and greater casting integrity) combined with improved corrosion resistance and affordable cost. With regard to the last factor it is believed that for the aircraft industry it is not so critical as for the automotive industry because, for example, in the civil aircraft the value of a pound in weight saved is equal to or greater than $300 US.

Based on the above principles three new alloys designated MRI 204, MRI 205 and MRI 207 were developed in the framework of the IDEA project. The alloys MRI 204 and MRI 207 are based on Mg-Zn-Zr-Nd-Y (Gd) alloying systems and are in fact also creep resistant alloys. Precipitation hardening and grain boundary strengthening are major mechanisms contributing to the strength of the above alloys. On the other hand, solid solution and grain boundary strengthening underlying unique properties of MRI 207, which is designated for room temperature applications that require high strength, combined with increased ductility.

The results of tensile and compression tests of new sand casting alloys are summarised in *Table 3* in comparison with the benchmark commercial alloys AZ91E-T6, ZE41-T5 and A357-T6.

It is evident that the new alloys significantly outperform commercial magnesium alloys and have tensile and compressive properties similar to those of aluminium alloy A357-T6. In addition, the unique combination of strength and ductility that was obtained on MRI 207-T6 alloy should be noted. One of the most important requirements to new alloys set by the end user is improved fatigue behaviour

Table 3. Mechanical properties of MRI sand casting alloys in T6 condition compared to Aluminium alloy A357 and Mg-alloys typically used in aeronautics.

Alloy	TYS [MPa]	UTS [MPa]	E [%]
MRI 204-T6	210±5	305±7	3 ±1
MRI 205-T6	220±6	320±8	10 ±1
MRI 207-T6	215±9	290±12	4±1
AZ91E-T6**	138±8	287±9	6±2
ZE41-T5*	140	220	5
WE43-T6*	180	260	6
A357-T6*	240	290	5

*Metals Handbook Data. **Measured in IDEA.

The results of first axial fatigue tests (R=-1) performed on the alloy MRI 205-T6 are given in *Fig. 1* in comparison with mean value and minimum border previously obtained for aluminium alloy A357-T6. As can be distinctly seen MRI 207-T6 is superior to A357-T6 in axial fatigue behaviour both at high and low stresses.

Finally, it should be noted that the results obtained so far are very promising and can serve as a background for further research. It is evident that more data including corrosion behaviour should be obtained prior to some decisions can be made.

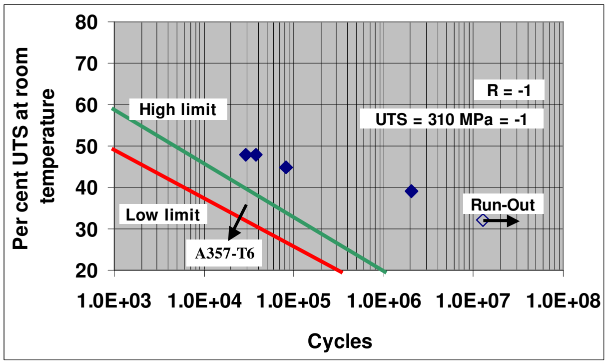


Fig. 1. Axial fatigue behaviour of MRI 205 -T6 in comparison with aluminium alloy A357 - T6.

2.3 Corrosion and Coating

The basic idea regarding the coating and corrosion behaviour is that Magnesium alloys should successfully compete with their counterparts – Aluminium alloys.

Therefore basically aircraft manufacturers and authorities prefer to test the coatings on magnesium alloys versus coated aluminium alloys using the same procedures. This means, for example, that anodised magnesium alloys should withstand for 336 hours in salt spray, exactly as anodised aluminium alloys. The corresponding test are part of the IDEA work plan, but will not be discussed here.

2.4 Appropriate Magnesium Casting Processes

In spite of the above-mentioned reluctance against the use of magnesium alloy in modern aircraft design, some magnesium castings that have been used in the past are still being manufactured. Traditionally, the above parts are manufactured by sand casting. The most striking advantage of sand casting is its ability to produce small series of large castings with excellent and repeatable quality. Other casting techniques are not frequently used but also could be considered.

For example, investment casting, provides near net shape production with excellent surface quality. Problems of this casting process are occasionally found in chemical reactions of the ceramic shell mould with the magnesium melt. In addition, the production of the shell mould is usually more laborious and complicated than making a sand mould.

Gravity die-casting can also be regarded as an alternative for small series production of castings with good surface properties. However, the tool manufacturing costs, which can reach up to several thousands of Euros for complex castings set an economical limit to small series casting.

This relates even more to the high-pressure die-casting process (HPDC), which is a typical process for mass production. In addition, HPDC products contain an intrinsically high level of porosity that deteriorates mechanical properties.

Nevertheless, HPDC could be an interesting process for components like trolleys that are not subjected to high mechanical loads and needed in greater quantities.

For these reasons all indicated casting processes are considered in the IDEA project. Due to the important role of sand casting, only this process will be further discussed in details.

2.5 Test Castings and Evaluation

On the first stage the new alloys and the casting methods were evaluated using different standard test specimens (tensile, fatigue, corrosion, etc). In order to set a reference level the same tests are also performed on specimens cast in the commercial alloys AZ91 and AM50 (HPDC). Then a test plate with an inherently difficult for casting geometry was selected for further investigations (*Fig.e 2.*) The plate consists of thin-walled and thick-walled sections and a number of junctions, which make the plate prone to formation of shrinkage porosity and cracks.

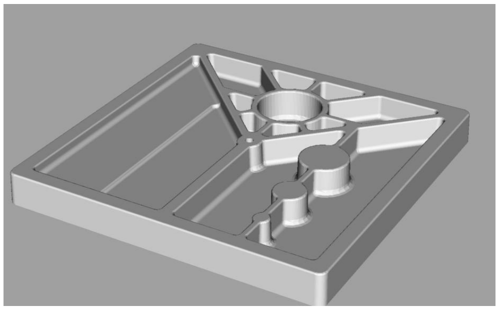


Fig.e 2. Test plate for Magnesium castings comprising difficult changes of wall thickness.

The test plates were cast in all new alloys and commercial AZ91E alloy. Runners and feeders were designed using computer simulation. Temperatures were measured at different locations of the plate and in the mould (*Figure 4*).

Good matching of measured and simulated temperatures confirms the correctness of the thermo-physical material properties used in the simulations, which is a necessary condition for correct prediction of microstructure, defects and mechanical properties. Simulation as well as radiographic investigation revealed the shrinkage distribution shown in *Fig. 7* for the plate cast in AZ91E. *Fig. 8* shows the shrinkage appearing detected in plates cast in MRI207. The shrinkage detected by X-raying was confirmed and locally quantified by measurement of pore sizes and pore shapes in samples, which were excised from the plate.

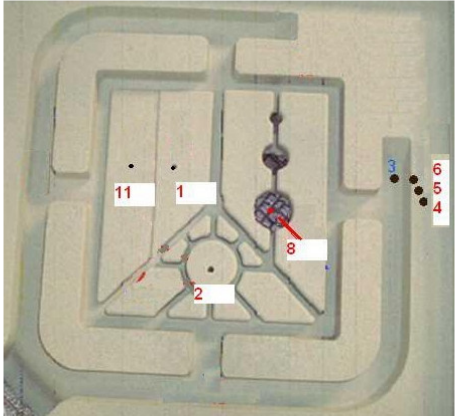


Fig. 3. Pattern of the test plate with runner. The numbers mark positions of thermocouples.

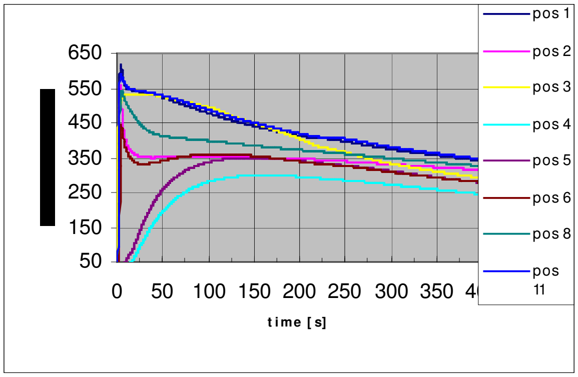


Fig. 4. Measured temperatures in test plate, cf. Fig. 3.

Similarly, the actual microstructure and its prediction by simulation were confirmed by means of grain size measurements. Grain sizes varied between 110 µm in the thin and 150 µm in the thick sections of the plate. Simulation results are shown in *Fig. 5*. Information on grain size and porosity distribution is used to model local mechanical properties as described in [5] and [6]. The predicted mechanical properties (TYS, UTS and elongation) were verified using specimens excised from the thicker sections of the plates, cf. *Fig.e 6*.

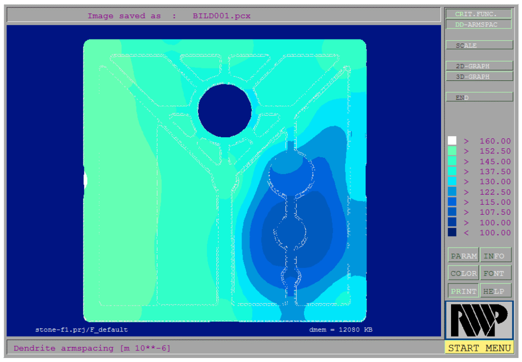


Fig. 5. The picture shows the simulated grain size distribution through the sand cast test plate (AZ91E). The simulated values vary from 110 to 160 µm and match well with measurements.

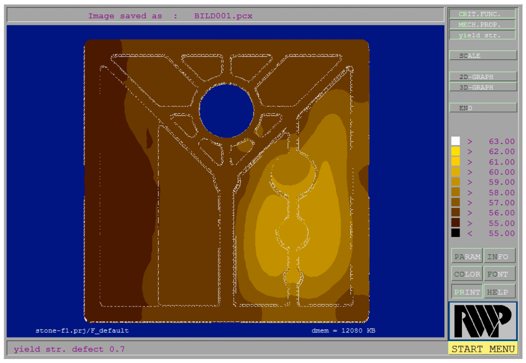


Fig.e 6. Simulated yield strength. The values in the flat sections on the left part of the castings show values between 56 and 58 MPa, little below the measured values of 59 MPa.

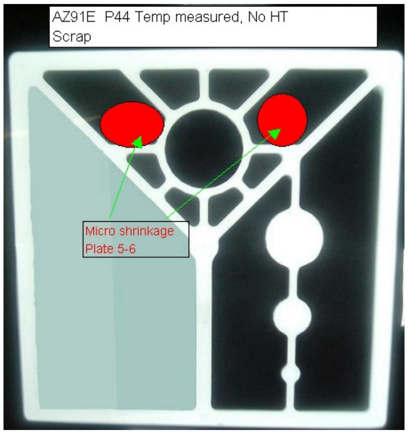


Fig. 7. Defect map of AZ91E test plate. The red areas mark micro shrinkage per ASTM STD 2175 E155 of levels 5-6. The plate quality is not acceptable.

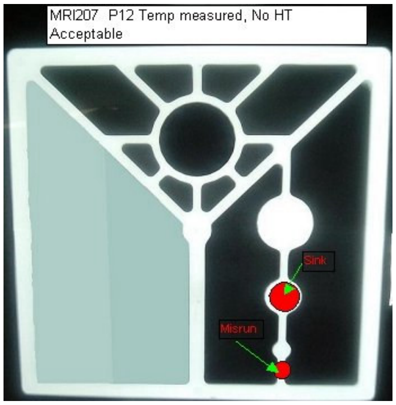


Fig. 8. Defect map of MRI207 test plate. No porosity was found, however misrun and surface shrink were revealed. The plate quality is acceptable.

2.6 Production of Prototype Castings

For the sand casting process, the so-called “housing” was selected as a prototype casting (*Fig. 9*)

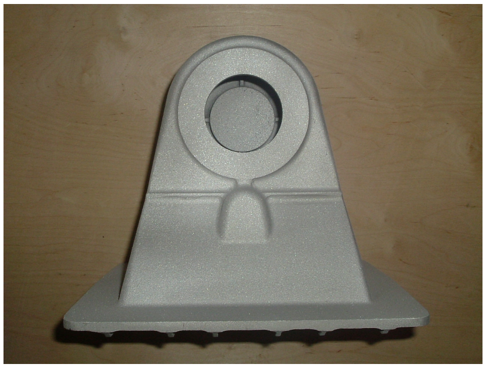


Fig. 9.Prototype casting “housing”. Cast in AZ91E with 2 mm minimum wall thickness.

The housing is a semi-structural part, which serves as casing for motion transfer from cockpit to tail through pressure bulkhead. At present it is produced by investment casting in aluminium alloy A356 with a minimum wall thickness of 2 mm. The development of the magnesium casting was started with a minimum wall thickness of 4 mm, which was stepwise reduced to 2 mm. The first parts were designed for the AZ91E alloy although its properties do not meet the requirements defined in *Table 1*. In order to set a reference level for Magnesium castings specimens will be extracted from the flat areas of the AZ91E housing for determination of UTS and TYS. The casting shown in *Fig. 9* meets the radiographic requirements as per AMS-STD-2175 Class 2. *Fig. 10* shows the distribution of tensile yield strength through the housing simulated with WinCast®.

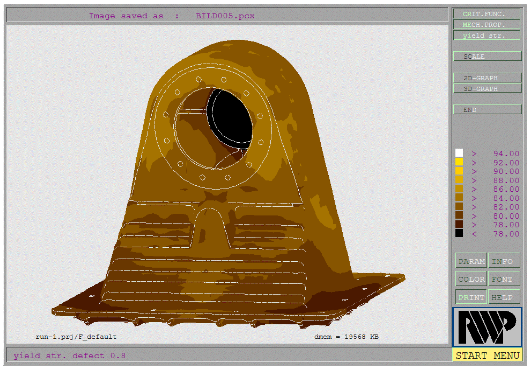


Fig. 10. Simulated distribution of TYS through the 2mm AZ91E housing. Expected values are in the range from 80 to 90 MPa.

After successful casting of the housing in AZ91E alloy, it will be cast in the newly developed aircraft alloy MRI207S, which exhibits improved mechanical properties. It is expected that the housing cast in the new magnesium alloy will outperform even the aluminium housing. All tests indicated in Tables 1 and 2 will be carried out. Samples extracted from the flat areas of the housing will be subjected to tensile and fatigue testing.

In addition, the prototype casting will be subjected to flammability tests (According to clause a (1) of standard: FAA Pt. 25 App. F Part 1 and MIL-HDBK-454A Guideline 3.), fungus tests (MIL-STD-810 method 508) and scratch tests.

3 Discussion and prospects

The previous paragraphs described intermediate results of the ongoing RTD-project IDEA. New magnesium casting alloys with improved mechanical properties have been developed for applications in aircrafts. It has been shown that complex and thin-walled castings like the “housing” can be produced by magnesium sand casting fulfilling the radiographic requirements. After the successful trials with the commercial alloy AZ91E first and the promising test results of MRI207S it is expected that a new generation of magnesium alloys will open the door for increasing use in aeronautics industry.

3.1 Future Role of Magnesium in Aircrafts

Thus, it is believed that magnesium alloys, which combine the advantages of low density and excellent mechanical properties can be introduced into the aircraft world after more than a generation of negligence. In order to land safely in the conservative and suspicious aircraft world significant improvements must be achieved with respect to the following problems:

- Corrosion,
- Poor mechanical properties,
- Flammability,
- Availability and price.

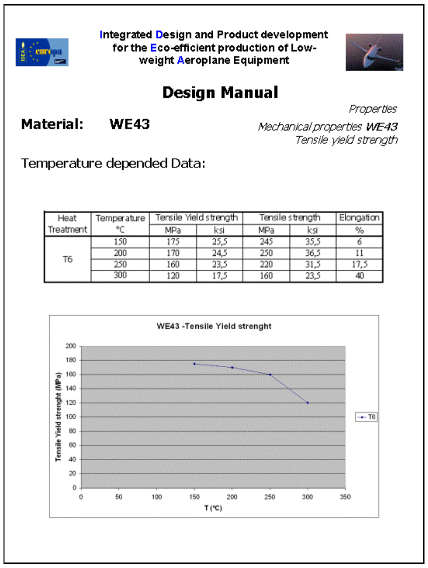
If Magnesium will successfully pass these four tests it will have a very wide range of applications: interiors, secondary structural parts as well as non-structural parts. The weight saving, which also stands for energy saving and pollution prevention are going to be of great environmental benefit.

As appropriate manufacturing process sand casting and investment casting (good surface prop). Even HPDC, where large series of non-structural parts are needed.

For the design of structural and semi-structural parts the role of modelling the manufacturing process in combination with prediction of mechanical properties and load case simulation will help to design parts of sufficient strength.

3.2 Measures for increasing the acceptance of Mg-castings (Design Manual)

All the above mentioned technical reasons will, however, not suffice to increase the share of magnesium castings in aircrafts if not also the widespread – rather emotional than scientifically based – reluctance [1] against magnesium can be overcome. In order to make the use of magnesium castings more popular the IDEA consortium is developing a Design Manual (DM) especially designated for magnesium castings for aeronautic applications. The manual should serve as a guide for the aviation design engineer and help him to select the appropriate magnesium alloys and casting methods for certain applications. It will contain comprehensive information on material properties, standards, manufacturing methods, requirements and a number of examples for the use of magnesium castings in aircrafts. An example page is shown in *Fig. 11*. All the information is presented in a concise and easily accessible way. The manual will be distributed on CD-ROM.



Integrated **D**esign and Product development
for the **E**co-efficient production of Low-
weight **A**eroplane Equipment

Design Manual

Properties

Material: WE43

Mechanical properties ***WE43***
Tensile yield strength

Temperature depended Data:

Heat Treatment	Temperature °C	Tensile Yield strength MPa	Tensile Yield strength ksi	Tensile strength MPa	Tensile strength ksi	Elongation %
T6	150	175	25,5	245	35,5	6
	200	170	24,5	250	36,5	11
	250	160	23,5	220	31,5	17,5
	300	120	17,5	160	23,5	40

Fig. 11. An example page from the Design Manual showing mechanical properties of the WE43 alloy.

Acknowledgements

The work described in this paper was performed by the consortium members of IDEA (*Integrated Design and Product Development for the Eco-efficient Production of Low-weight Aeroplane Equipment*), which is an RTD project of the Sixth EC Framework Programme. The authors thank all IDEA-members (RWP (DE), TECHNION (IL), Magnesium Research Institute (IL), Israel Aircraft Industries Ltd. (IL), SpecialValimo (FI), VTT (FI), INFERTA (DE), TECOS (SI), FemAlk (HU), UHP (FR), MGEP (SP), FhG (DE), STONE Foundries (UK)) for their contributions. We also thank the EC for financial support.

References

[1] Froes F H, Eliezer D and Aghion E. How to increase the use of Mg in aerospace applications. *Magnesium 2000 Proceedings of the Second Israeli International Conference on Mg Science and Technology*, Dead Sea Israel, pp 43-49, 2001.

[2] B.Bronfin et al. High temperature resistant magnesium alloys. *EP Patent 1,329,530.* Aug.11, 2004.

[3] B.Bronfin et al. Metallurgical background to the development of creep resistant gravity casting magnesium alloys. *Magnesium Technology 2005*, ed. H.I. Kaplan. Warrendale, PA. TMS, 2005, 395-401.

[4] E.F. Emley**.** *Principles of Magnesium Technology*. 1st edition. Pergamon, Oxford, 1966.

[5] M. Todte**.** *Prognose der mechanischen Eigenschaften von Aluminium-Gussteilen durch numerische Simulation des Erstarrungsprozesses*. Ph.D. thesis, Otto-von-Guericke - University Magdeburg, 2002.

[6] A.Wendt et al. Modelling Mechanical Properties of Magnesium Castings for Aircrafts. *Modeling of Casting Welding, and Advanced Solidification Processes - XI*, ed. C-A. Gandin and M. Bellet, Opio France, pp 717-724, 2006.