NEW MAGNESIUM ALLOYS

APPLICATIONS ON HELICOPTERS

by Jean-Michel ARLHAC
Jean-Claude CHAIZE

EUROCOPTER FRANCE

ABSTRACT

The on going improvement of operational capacities of helicopters, whether civil or military, together with the decrease of operating and manufacturing costs, are still the prevailing factors, guiding the manufacturers in their technical choices.

These choices are all the more important when they concern sophisticated dynamics components such as Gear Boxes, whose vital function, level of reliability to be maintained and use under extremely severe conditions, have a significant influence on the operating costs.

As regards this subject, significant research efforts have been made over the past 5 years, to improve resistance to corrosion of Gear Box housings.

Within this scope, a new yttrium-based magnesium alloy called WE43, associated to a protective treatment of the anodize type (HAE), has led to a significant breakthrough which is the best weight / performance / cost trade off.

Validating this technology by applying it on " full size " parts and studying its characteristics on them, with the help of several partnerslike founders, cooperating firms and sub-contractors, makes possible its application on the reduction housing of Gear Boxes on the new in-development helicopters. This technology could also be retrofitted, should there be an opportunity, to commercialized helicopters.

Associating the new WE43 alloy with HAE protective treatment will allow the following :

- notably increase the TBO (Time Between Overhaul) of Gear Box housings,
- significant cutting down of the operating and reiconditioning costs of such assemblies ,
- optimizing the design concepts.

INTRODUCTION

The need to reduce weight has generally led Eurocopter designers to select magnesium alloys to manufacture gear box casings from foundry blanks for the in service helicopters (from 2 to 13 tons).

The long operational experience acquired over thirty years, thanks to a very extensive and systematic analysis of data obtained through the connections with our customers and the practice of helicopter gear box overhaul and reconditioning, helped to analyse the behaviour of this magnesium technology.

As regards the new generation of helicopters: Tiger (5 t), NH90 (10 t) and EC120 (1.5 t), the decision to select those materials rather than aluminium alloys which are also foundry made was a significant one.

This is why the search for more efficient solutions as regards corrosion resistance as well as the improvement of mechanical characteristics has led to the evaluation, characterisation and validation, compared with new aluminium technologies, of :

- protections based on the anodic oxydizing principle offering thicker and tighter layers ,

- the new alloys (WE43, AZ91HP) that were developed over the last few years compared to the basic alloys RZ5 (or ZE41) ,

This paper shall present :

- the applications and analysis of the design choices made for parts in magnesium alloys ,

- Eurocopter experience of operational behaviour ,

- a summary of the studies undertaken on the new alloys and protections ,

- the applications planned on new helicopters being developed ,

- conclusions and perspectives for the future .

1. MAGNESIUM ALLOYS ON HELICOPTERS

A status of the existing applications, technological characteristics and magnesium solution, and then a comparison related to the design choices, form the subject of the present chapter.

1.1 Applications:

In most cases, they involve casings, housings and covers of main, tail, intermediate and accessory gear boxes (cf. Fig. 1).

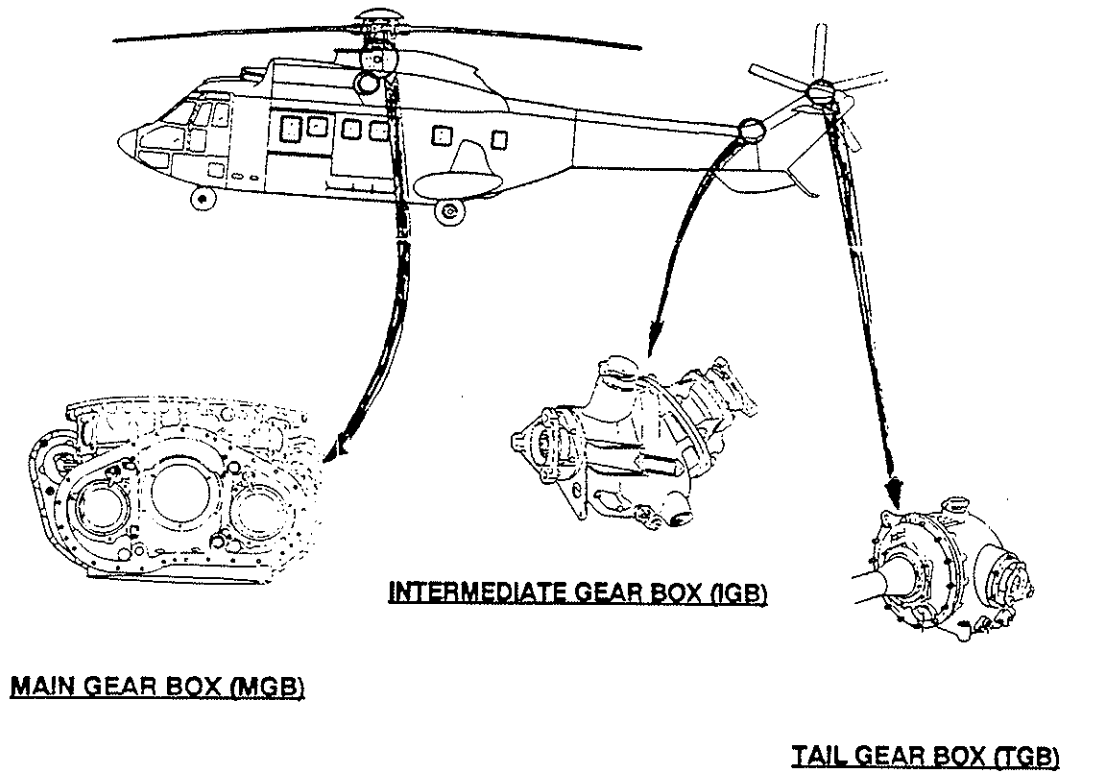

Fig. 1 - Localization of housings in Magnesium alloy on an helicopter

They are valid for commercialized EUROCOPTER helicopters :

1.5 to 2.5 t category :	Alouette and Gazelle family Ecureuil and BO 105 family
4 to 6 t category :	Dauphin, Lynx family
8 to 10 t category :	Puma and Super Puma Mk 1 & 2
12 to 13 t category :	Super-Frelon

Whatever the version may be : civil, military or marine.

1.2 Technological characteristics

- The basic grade selected was zirconium alloy RZ5 (or ZE41) because it offered the best compromise between casting, health, mechanical characteristics and cost.

- Gravity casting in sand moulds (cf. Fig. 2) was the only method practised for the development of blanks by the different foundries retained (mainly in Europe), whether the origin of the manufactures was internal, cooperations, licences or sub-contracts.

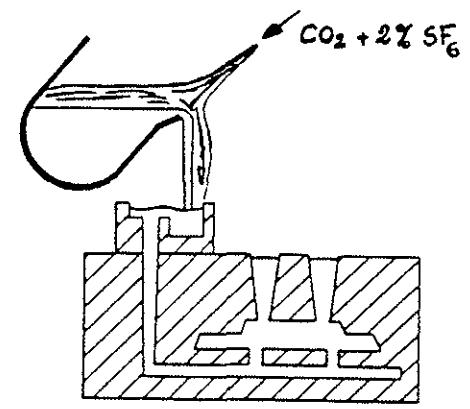

Fig. 2 - Conventional Gravity Pouring

The protection was adapted, according to the zones, from a "standard" nomenclature :

- chromatation ,
- sealing with an epoxy-phenolic varnish ,
- chromate primer ,
- finish paint .

1.3. Comparison between magnesium and aluminium technologies

As far as Eurocopter is concerned, the design of a casing is associated to the consideration of different constraints (cf. Table 1) :

- Weight constraint ,

- Rigidity constraint to retain an excellent meshing quality as a function of the torque transmitted ,

- Resistance constraint in vibration and low cycle fatigue mode in those areas subjected to high dynamic stresses (MGB struts and servo-control attachment; loads applied at MGB input and output as well as attachment pick-up on transmission deck) ,

- Dynamic constraints at the accessory gear box attachments; optimization of shapes to avoid local eigen frequencies related to gear box operation ,

- Environmental constraints associated to atmospheric and galvanic corrosion effects,

- Operating constraints at high temperature upon loss of lubrication ,

- Implementation constraints :

    - Minimum wall thickness upon casting
    - Machining and suface treatment

Of all those constraints, weight is paramount in most applications and magnesium density is, without any doubt, an advantage in this case.

As an example, selecting magnesium for TIGER IGB and TGB casings helped save approximately 3 kg (30%) while improving the helicopter's center of .gravity.

Furthermore, a study undertaken with the main MGB casing in 332 Mk2, which is more complex and voluminous, demonstrated that selecting magnesium saved approximately 10% i.e. 8 kg max.

As a consequence, Eurocopter attempted to retain this advantage over aluminium alloys while alleviating those well known drawbacks of conventional magnesium alloys and their protections.

Parameters	Mg (RZ5 or ZE41)	Al (AS7G0.6 or A357)	Remarks
Casting (gravity, sand mould)	good	good	lost wax casting possible with Al
Health	medium	medium	depends on foundry (Al more sensitive)
Minimum thickness (web)	4 to 5 mm	3 to 4 mm	greater thickness reduction capability with Al
Machining	easy	easy	limited precautions with Mg (fire risk)
Protection	Chemical + varnish sealing +paint	electrolytic (chromic anodizing) + paint	basic protection more efficient on Al, but with pitting risk
Physical characteristics d (g/cm^3) α (10^{6}/K)	 1.8 27.0	 2.7 23.0	
Mechanical characteristics U.T.S. (MPa) Y.T.S. (MPa) A% (%) E (GPa) σf bare metal (MPa) σf protected (MPa)	 200 135 2.5 44 ± 70 ± 65	 280 220 3 75 ± 86 ± 75	
Material cost	ZE41 is 10% more expensive than A357		

Table 1 - Comparison between Mg and Al technologies

2. EUROCOPTER OPERATIONAL EXPERIENCE

More than thirty years of in-service experience in more than 120 countries all around the world and very diverse operating conditions allowed a realistic analysis of the behaviour of magnesium alloy casings and the improvements that need to be made.

2.1. Results of the analysis of data in use

Should one take the operator place and consider scheduled maintenance operations, it can be stated that the corrosion sensitivity of magnesium alloys

- only generates a very low percentage of premature removals, "Marine" applications included (analysis performed with French Navy Super-Frelon and Lynx helicopters)

- does not increase, compared to aluminium parts, the number of maintenance operations i.e. periodic inspections, touch-ups and repairs defined in the Standard Practices Manual.

On the other hand and as far as scheduled revisions are concerned, corrosion damage is more extensive and localised in sensitive areas defined above, in particular in those assemblies where the protection and sealing operations have not been properly carried out by the user. This accounts for the need of specific precautions in every junction area, such as mating plane, housings, water retention areas and dissimilar material contacts.

A corroded area example is shown in the photograph below (cf. Fig. 3) in a cover locating area.

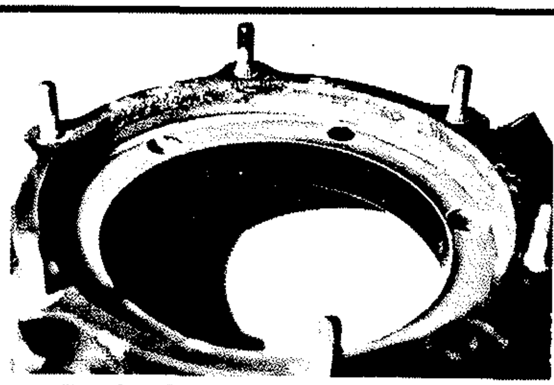

Fig. 3 - Corroded area example
in a cover locating area

The damage noted per helicopter and area concerned is summarised in the following table (cf. Table 2) .

In the next table is given an example of corroded areas on an I.G.B. / Super-Puma 332 MKI (cf. Fig. 4).

This analysis shows the impact this type of damage may have on overhaul and reconditioning costs.

Helicopter	Part (housing)	% Repaired and/or Scrapped	Corroded areas
Ecureuil 355	Combiner gearbox	70% Rep. or Scrap.	External positioning planes bushed areas
Dolphin	M.G.B. housing	50% Rep.	External positioning planes
	M.G.B. input housing	100% Rep. or 80% Scrap.	Guimbal joint fitting (bushes
	Bevel gear housing	10 to 90% Rep.	Boring next to positioning plane
	M.G.B. Output housing		
	Upper cover		
	T.G.B. housing	60% Rep.	Oil sight level boring
		25% Rep.	Machined faces
		100% Rep.	Spirolox thread root draft
Puma and Super-Puma	Bottom M.G.B. housing	80% Rep.	External positioning planes
	I.G.B. housing	90% Rep.	Oil sight level boring
		25% Rep.	Attach tab fitting + internal face
		75% Rep.	Clamp attachment hole

Table 2 - Damage noted per helicopter and area concerned

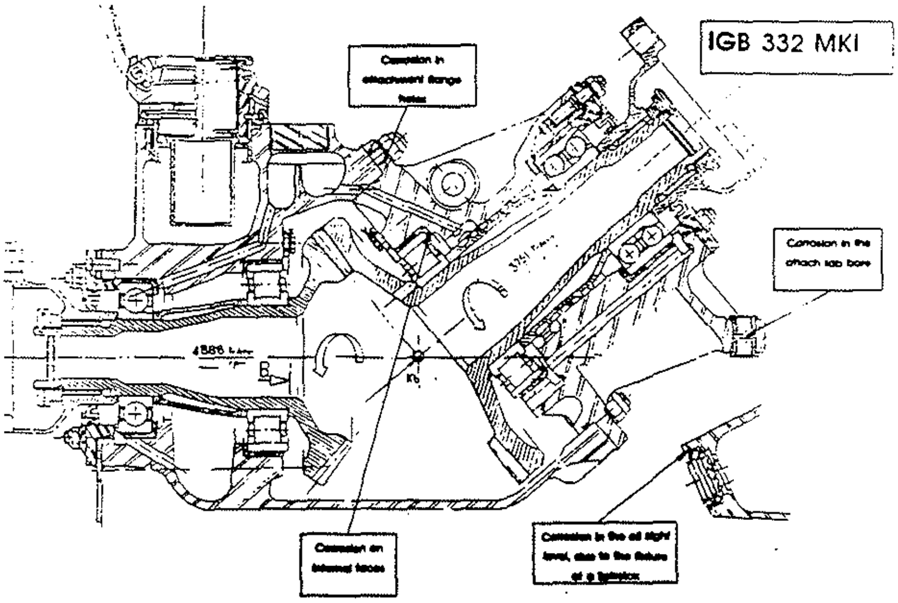

Fig. 4 - Example of corroded areas on an IGB/Super Puma MkI

2.2. Analysis of improvements

The above analysis has led Eurocopter to make a number of improvements between the first and second helicopter generations (Super Puma Mk2, Tiger) based on a better definition/design approach, that is improvements (cf. Fig. 5 & 6) in accordance with drawings (suppression of water retention areas), the selection of materials and protections in contact for bushes and attachments, a reinforced protection in sensitive areas summarised in the following chart (cf. Table 3).

Those improvements were initiated in the current helicopter range and the most recent generation, in particular, from Dolphin 365 N and 366 G to Super Puma Mk 1 and 2.

		Alouette / Puma	Ecureuil	Dolphin / Super-Puma	Tiger
As cast areas	Surface treatment	chromatation			
	Paint cooked in furnace		Pyrolac (3 layers)		
	Finishing (Top coat)	Epoxy primer with strontium chromat (1 layer)			
		Nitrovinylic (1 layer)			Polyurethane "NBC"
Machined areas	Surface treatment	chromatation			
	Epoxy primer with strontium chromate		on mating surfaces	1 coat of paint (non systematic) upon faces	1 layer ou 1 coat on faces and borings
	Sealing compound applying			on bolts, screw heads, studs, mating surfaces	

Table 3 - Evolution of protection on magnesium parts on helicopters

Fig.5 - Optimization of the protection

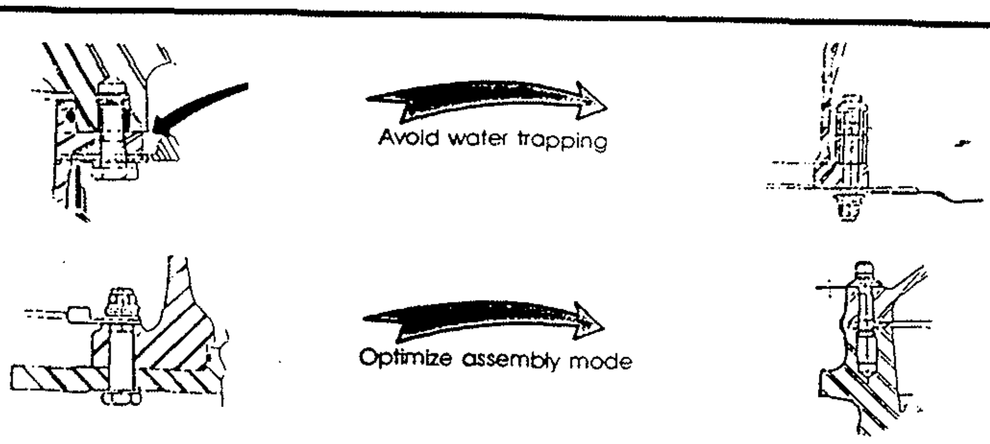

Fig. 6 - Optimization and reinforcement of the design/definition

3. SEARCH FOR NEW SOLUTIONS

Since magnesium alloys are also of interest for weight saving reasons which are increasingly taking priority, enhanced corrosion protection solutions had to be found for the new generation helicopters.
New materials and protections had first to be evaluated and the two technologies then had to work in association.
Validation was first performed with specimens and then with probatory parts.

Furthermore, the bibliography, the contacts made with MEL as well as European and US foundries indicated that most helicopter manufacturers have also studied and manufactured parts associating new alloys and protections of the anodic oxidizing type. This comforts our choice and anticipation for future applications in this field.

3.1 New alloys

Based on the studies and developments undertaken over the last few years, two alloys (AZ91HP, WE43) were selected for specific tests (characterisation tests on specimens), and the yttrium-based magnesium alloy WE43 (cf. chemical composition chart in Table 4) was rapidly selected because it offered the best compromise for its properties and characteristics as a whole :

- a metallurgical health equivalent to that of reference alloy RZ5 but much better than that of alloy AZ91HP (porosity and micro-cavity sensitivity)

- static mechanical characteristics higher at ambient temperature, and especially around > 120°C (no T.U.S., T.Y.S. characteristic drop up to 250°C approximately) ,

- satisfactory welding repairability provided appropriate heat treatment is adopted ,

- improved fatigue behaviour (+20% approximately) compared to alloy RZ5 and AZ91HP for a same foundry quality (cf. Table 5),

- atmospheric corrosion resistance equivalent to that of alloy AZ91HP and much higher than that of alloy RZ5 (or ZE41) as shown in Table 6 ,

- galvanic corrosion sensitivity in the presence of dissimilar materials, lower than that of alloy RZ5 (or ZE41) .

	Y	R.E.	Zr	Zn	Fe	Cu	Mn	Si	Ni	Ti Pb Si Be	Mg	Al
RZ5 (ZE41)	-	0.75 - 1.75	0.4 - 1	3.5 - 5	≤ 0.01	≤ 0.03	≤ 0.15	-	-	-	base	≤ 0.01
AZ91 HP	-	-	-	0.4 - 1.0	≤ 0.005	≤ 0.03	0.17 - 0.35	≤ 0.3	≤ 0.001	-	base	8.1 - 9.3
WE43	3.7 - 4.3	2.4 - 4.4	≥ 0.04	-	-	-	-	-	-	-	base	-
AS7G 0.6 (A357)	-	-	-	≤ 0.1	≤ 0.2	≤ 0.1	≤ 0.1	6.5 - 7.5	≤ 0.05	≤ 0.05 for each	0.45 - 0.7	base

Table 4 - Chemical Composition of cast magnesium and aluminium alloys

	U.T.S. (MPa)	Y.T.S. (MPa)	A % (%)	E (GPa)	Fatigue limit R = -1 (MPa) Kt = 1
RZ5 T5 (or ZE41)	200	135	2.5	44	± 60 to ± 105 (*)
AZ91 HP T6	215	115	3	43	± 85
WE43 T6	220	172	3	45	± 120
AS7G 0.6 T6 (or A 357)	280	220	3	75	± 86

(*) Scattering function of foundry

Table 5 - Minima Mechanical Properties of bare cast magnesium and aluminium alloys

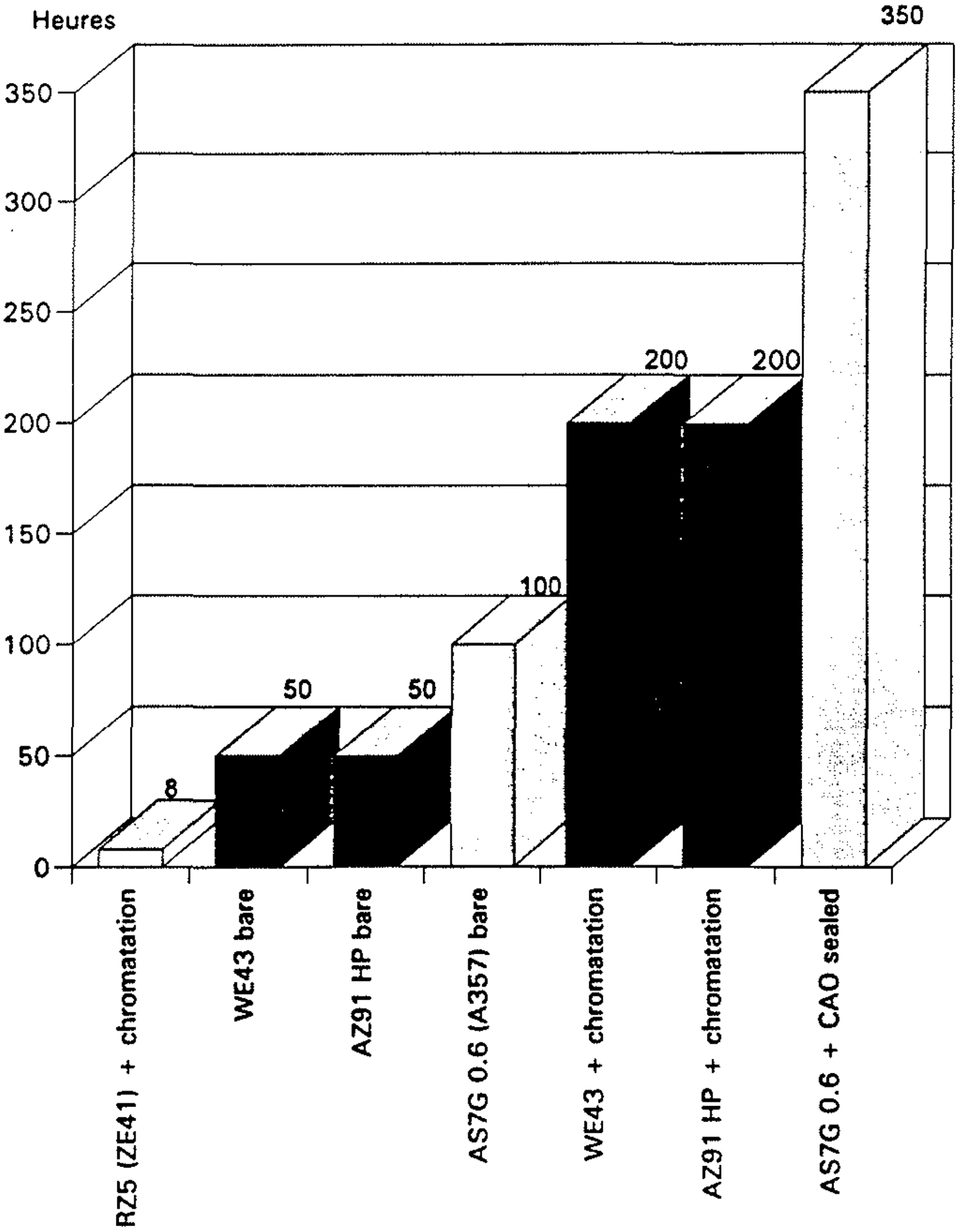

Table 6 - Corrosion behaviour of cast Mg and Al alloys, machined and exposed in salt spray (NFX 41-002)

In a second phase, feasibility was demonstrated with parts from different foundries and two casting processes (gravity and low pressure); this helped :

- check the satisfactory casting of this alloy with a same process and tooling (mould designed for RZ5), as well as a limited modification of the industrial process (inerting, power supply and cooling devices) ,

- confirm its metallurgical health and mechanical characteristics compared to RZ5 after cut-out ,

- glimpse the capabilities of the low pressure process (cf. Table 7) :

    - enhanced material health ,
    - enhanced level and homogeneity of characteristics ,
    - improved control and reproducibility (automation) .

Below is an illustration of the new low pressure casting processes as well as images of the parts manufactured (cf. Fig. 7 to 10) .

	WE43 T6			AS7G 0.6 T6 (or A357)		
	U.T.S. (MPa)	**Y.T.S. (MPa)**	A% (%)	**U.T.S. (MPa)**	**Y.T.S. (MPa)**	A% (%)
Samples/ gravity	250	190	7.4	-	-	-
Part/gravity	260	200	5	320	270	7
Part/low pressure	290	220	7	-	-	-

Table 7 - Comparison gravity / low pressure process - Typical values

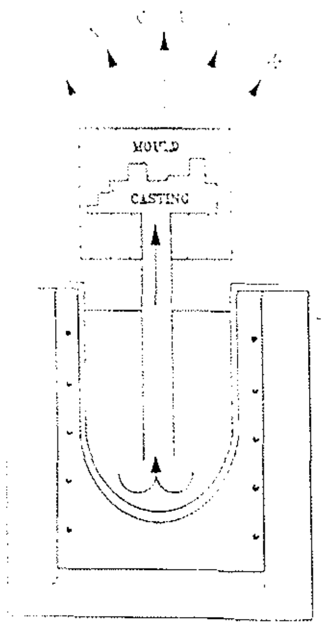

Fig. 7 - MEL Casting Process (DPSC)

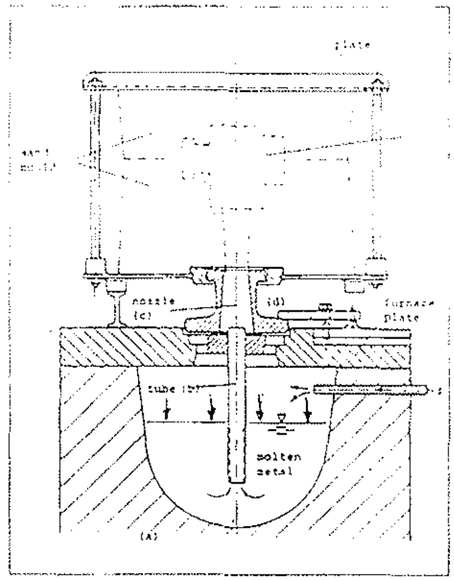

Fig. 8 - MESSIER Casting Process (REDEM)

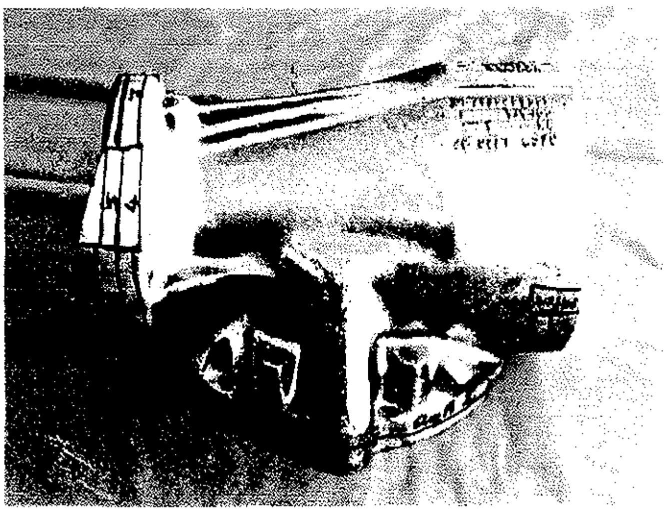

Fig. 9 - First reduction housing
of the MGB/Dauphin

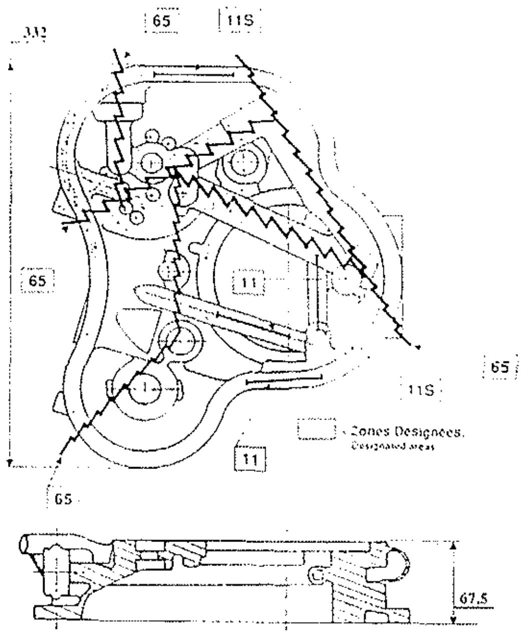

Fig. 10 - Upper cover and housing/
accessory reduction box (TURBOMECA)

3.2 New protections

Since in-service experience has demonstrated the limitations of the conventional dichromate treatment some microns thick vis à vis corrosion resistance, a search was undertaken for processes based on anodic oxydizing (comparable to chromic and sulphuric anodizing for aluminium alloys) that would ensure relatively high thickness layers (10 to 30 microns) as well as a significant increase in superficial hardness ; both characteristics being favorable for resistance to wear by micro-friction or fretting corrosion.

Three different processes were retained for a first evaluation and characterisation on specimens (feasibility, dimensions, corrosion and fatigue) :

- **the DOW17 process (acid bath) used for several years on magnesium casings among others in U.S. helicopters (Sikorsky, Boeing, etc.) ,**

- **the HAE process (alkaline bath) mainly used in the automotive industry (clutch casings and gear boxes) ,**

- **the MAGOXID process (alkaline bath) developed and patented by AHC in Stuttgart.**

A synthesis of the trade-off analysis for these anodic treatments on cast magnesium alloys is given in table 8.

Anodic coating	Bath Constituents	Thickness	Coating	Touch-up	Installation Make-ability
DOW 17	Ammonium hydrogen fluoride, sodium dichromate phosphoric acid	8μ to 40μ	Porous	No	Easy
HAE	Potassium hydroxide, aluminium Potassium Fluoride, Sodium Phosphate, Potassium Permanganate	5μ to 40μ	Very porous	Yes	Not so easy
Advanced Magoxid	Mineral Acids, phosphoric/boric acid, organic substances	$\approx 20\ \mu$	porous	Yes	Not so easy but patented

Table 8 - Comparison of some promising treatments for cast magnesium alloys

Above mentioned characteristics associated to mechanical tests on RZ5 alloy allowed :

- to check the significant corrosion resistance improvement offered by this type of treatment (anodic oxydizing), when the porosities inherent to formed layers are sealed with resin (cf. Fig. 11 & 12),

- to check that there is little influence on the fatigue resistance of the material,

- to select the HAE process offering the best compromise regarding performance vis à vis corrosion and ease of implementation, with the capability to repeat the treatment several times or to proceed with a local treatment without complex application procedures.

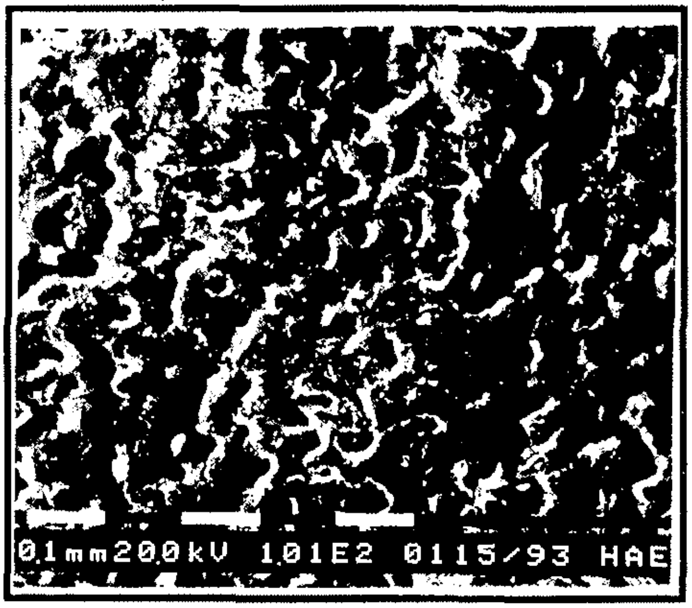

Fig. 11 - Porosity of the HAE Layer on machined part (observed with SEM)

Fig. 12 - Cross-section of an HAE layer + surface sealing (varnish)

Once the HAE process was selected, this study was completed with feasibility tests on parts (Dauphin MGB input casing and Tiger MGB upper cover). These additional tests helped check that this type of treatment is easy to apply but will impose however, for each new application, a preliminary study of the feasibility part to define exactly the machining process lay-out and the dimensions area by area. This is to take into account the swelling resulting from layer formation estimated to represent approximately 2/3rd of this layer's thickness.

The HAE protection is today applied in production in the first reduction casing of the Dolphin Main Gear Box made of RZ5 (or ZE41 alloy).

3.3 New WE43 alloy / HAE protection association

Judging from the results and conclusions of the preliminary tests performed on materials and protections, the selection of WE 43 alloy + HAE protection was evident and is covered in the last phase of this study where its optimum behaviour is confirmed:

- corrosion resistance higher than or equal to that of foundry made *aluminium alloys (AS7G0.6) protected with chromic anodizing (specimen) as* shown in Table 9 ,

- feasibility (machining, protection) equivalent to that demonstrated with alloy RZ5 in the Dolphin MGB input casing ,

However, one notes a slight fatigue resistance reduction of alloy WE43 caused by HAE protection, which remains nevertheless equivalent to that of alloy RZ5 (cf. Table 10).

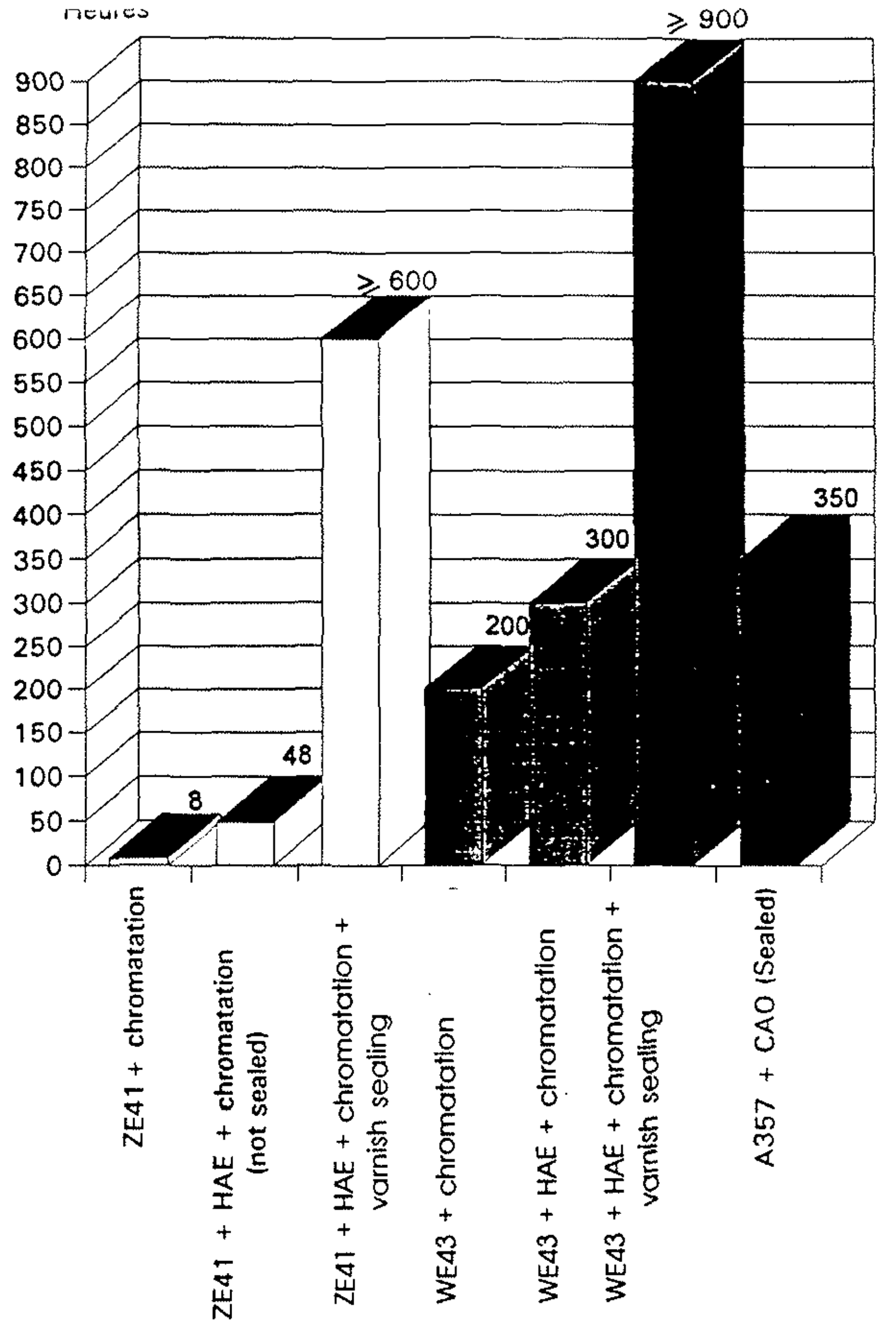

Table 9 - Corrosion behaviour of cast Mg and Al alloys, machined and protected, then exposed in salt spray (NFX 41-002)

	Protection	Type of Test	σ_∞ (MPa)
RZ5 T5 (or ZE41)	Chromatation	Flat Bending	100 ± 69
	Chromatation	Rotative Bending	± 60 to ± 105 (*)
	HAE (30 µm)	Rotative Bending	± 96
AZ91 HP T6	Chromatation	Flat Bending	100 ± 68
	HAE (30 µm)	Flat Bending	100 ± 50
WE43 T6	Chromatation	Rotative Bending	± 110
	HAE (30 µm)	Rotative Bending	± 94
	Chromatation	Flat Bending	120 ± 80
AS7G 0.6 T6 (or A357)	CAO sealed	Rotative Bending	± 75

(*) Depends on foundry quality

Table 10 - Fatigue behaviour of cast Mg and Al alloys on samples (without overstress : Kt = 1.035)

4. APPLICATIONS TO PARTS BEING DEVELOPED

The file composed from the different studies and investigations helped EUROCOPTER to select magnesium WE43 + HAE protection as the best compromise for most of the gear boxes installed in the new generation helicopters from the development phase.

Thus, a small cost penalty is apparent on the production cost, it is acceptable because of :

- weight savings compared to aluminium and equivalent corrosion resistance,

- attractive economic fallouts for users with :

    - Noticeable reduction of revision costs with limitation of repairs and discards from the first revision (the objective is - 80%)

    - Significant reduction of maintenance costs (the objective is - 50% of casing DMC).

Thus, several applications are already planned for new helicopters being developed :

- Casing and cover for NH90's TGB (cf. Fig. 13)
- Main casing, sump and input cover for EC120's MGB (cf. Fig. 14)

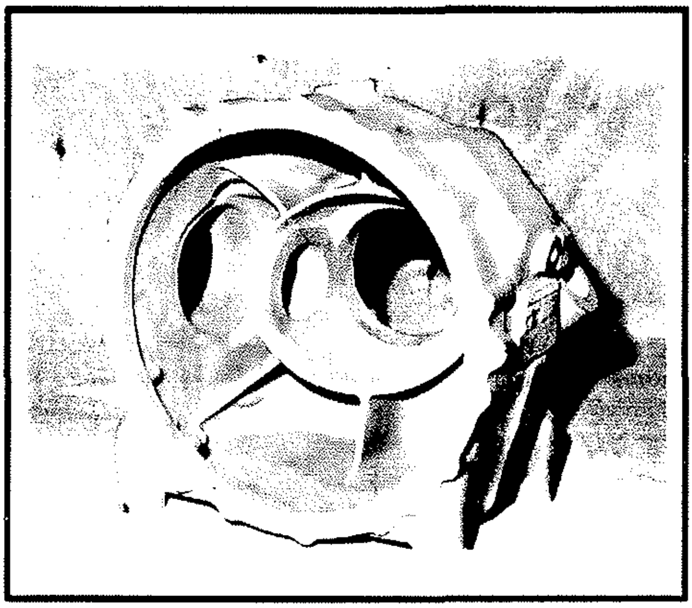

Fig. 13 - TGB housing/NH90 :
WE43 + HAE casted by REDEM Process

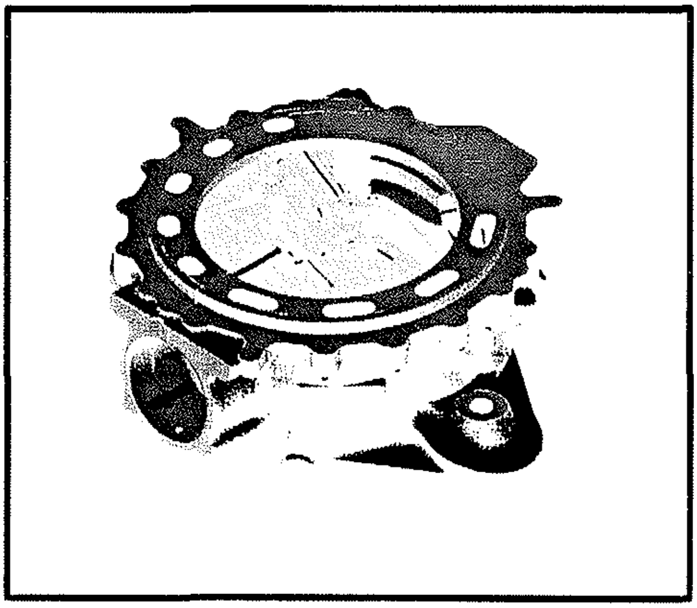

Fig. 14 - MGB housings/EC 120 :
WE43 + HAE casted by DPSC process

CONCLUSION

The studies and work undertaken with magnesium technology for gear box casings helped with a progressive approach ...

- Evaluation of part behaviour in operation
- Evaluation and characterization on parts of new and more efficient alloys associated to recent evolutions in foundry processes ,
- Development and validation of new surface treatment concepts resistant to both corrosion and wear

... to find a solution meeting future needs to a same extent as the aluminium technology while saving weight.

As far as Eurocopter is concerned, there is no doubt that the research and development results comfort the magnesium technology selection for most future gear box applications. However, efforts shall continue in this expanding field with improvements that can already be envisaged as regards:

- Low pressure casting process ;
- Metal Matrix Composites (particle reinforcements and long fibers) ;
- Surface treatments (TAGNITE process recently developed in the U.S., in particular) .

SYMBOLS

C.A.O.	Chromic Anodic Oxydation
D.M.C.	Direct Maintenance Cost
I.G.B.	Intermediate Gear Box
M.G.B.	Main Gear Box
S.E.M.	Scan Electronic Microscope
T.B.O.	Time Between Overhaul
T.G.B.	Tail Gear Box

REFERENCES

1) P. Lyon , Use of light weight magnesium for high strength high temperature corrosion resistant helicopter application , Magnesium Elektron , 1993.

2) A. Yates and P. Jones , Interim report on the evaluation of magoxid anodic treatments, MR10 / DATA / 235 , Magnesium Elektron , Aug. 1992.

3) J. Hawkins , Assessment of protective finishing systems for magnesium , MDHC , 1993.

4) Dr D. Bartak , A protective anodic coating for magnesium alloys , Technology Applications Group , Inc. , March 1992.