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Cost Effective Solutions for Improvement of Acceptance Rate of an Aircraft Mounted Accessory Gear Box Sand Casting of Fixed Wing Aircrafts

T. Ram Prabhu[1], S. S. Kale[1], G. Gouda[1], P. Jayapal[1], B. Reddy[2], M. S. Venkatesha[2]

[1]Centre for Military Airworthiness and Certification, Bangalore, India
[2]Hindustan Aeronautical Ltd (F&F), Bangalore, India

Email address

ramprabhu.t@gmail.com (T. R. Prabhu)

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Abstract

In this paper, we have been trying to find to find a solution to improve the acceptance rate of aircraft mounted accessory gear box main casing Mg alloy (RZ 05) casting for fixed wing military aircraft applications. We have described the functions, features, processing and airworthiness certification details of aircraft mounted accessory gear box casting in detail. The main problems leading to high rejection rate of casting have been brought out using data analysis of the last 6 years manufacturing details. From the analysis, it is found that the integrated as-cast long and curved oil passages in the casting, melting and casting issues of Mg alloys are the principal factors resulting high rejection rate. To improve the acceptance rate and minimize the loss incurred, we propose the following two main solutions based on properties evaluations, yield and cost assessments, (1) the removal of integrated as-cast oil passages from the design and replace them with external oil passage using pipesis expected to improve the acceptance rate to 50%, (2) the change of material from Mg (RZ 05) alloy to Al (A356) alloy is anticipated to enhance the acceptance rate to more than 70%. Further it is also suggested that the incorporation of both solutions in the aircraft mounted accessory gear box casting will significantly benefit the casting acceptance rate, yield rate and most importantly, cost savings.

Keywords

Al Alloy, Mg Alloy, Sand Casting, Aircraft, Casting Properties, Yield and Cost Assessment

1. Introduction

Aircraft Mounted Accessory Gear Box (AMAGB) is a lightweight, high speed single input and multiple output gear box used in fixed wing military aircrafts. The AMAGB is one of the design marvels in the Indian military aircraft program. It is classified as a flight critical component from the airworthiness view point; failure of this during flying endangers the aircraft and pilot safety[1]. It is designed as a two housing splits, namely main casing and cover casing. The casting weight of the main and cover casing before and after machining are 15 kg and 7kg, and 12 kg and 4.2 kg respectively. Castings are developed using Mg alloy and sand casting process. The casting requires fluorescent penetrant surface inspection quality of MIL STD 2175 and radiographic quality of Military Standard (MILSTD) 2175 class B in stress critical regions and Class C in non critical regions. Tolerance levels of all casting defects are stipulated in the MIL STD 2175.

1.1. Functions and Features of AMAGB

The principal function of AMAGB is to transmit maximum power of 250 hp at a rated speed of 16810 rpm from gear drive assembly to the engine accessories and later to the power take off drive. The pressure pump in the main casing transfers oil from the reservoir and delivers it at a flow rate of 20 l/m with an operating pressure of 10 bars. The maximum operating temperature of lubrication is around 100°C. The attractive features of the main casing are that (1) it has its own self lubrication system withintegrated oil tank with 6.5 l capacity, one pressure pump and two scavenge pump modules, (2) the thin cast integrated oil passages of 6-12 mm diameter at strategic location for proper lubrication and cooling of gear meshes and bearings, (3) it provides the mount points to other accessories of engine and gearbox assembly.

1.2. Casting Complexity

The cover casing casting is a plate shaped casting with large surface area with as cast oil passage holes of 3mm to 5mm diameter. It is quite simple to fabricate using sand casting. In contrast, the main casing casting is highly complex in terms of design features. It has as cast complicated curved oil passages of abruptly varying sizes of 6-12 mm. In addition to that, the complexity associated with wall thickness of 6 mm over a length of 450 mm is an another challenge. The photographs of main and cover casing are shown in Figs.1 and 2. These complexities pose the problem of exceptionally high rejection rate. Hence, the foregoing sections focus only main casing casting material and casting features, problems associated with melting, casting defects, causes for superior rejection rate, remedial measures in terms of design and material change, cost and performance benefits due to material change.

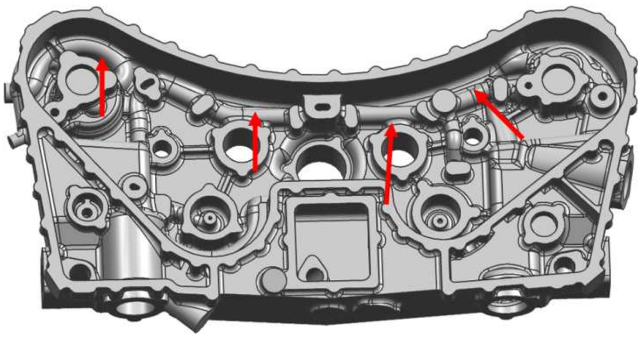

Figure 1. *AMAGB main casing Mg alloy sand casting(Complex geometry) (Red arrows show the curved, lengthy oil passages) (Courtesy: HAL (F&F), Bangalore, India).*

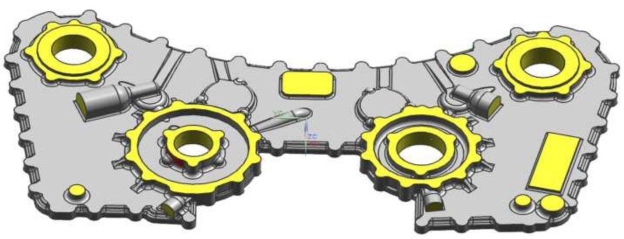

Figure 2. *AMAGB cover casing Mg alloy sand casting (simple geometry) (Courtesy: HAL (F&F), Bangalore, India).*

2. Material and Methods

The attractive properties of low density (ρ ~ 1.738 g/cc), high stiffness, ability to cast complex shapes with intricate passages, excellent damping capacity and machinability, and good electro-magnetic shield make Mg alloys preferable over other light weight alloys such as Al, Ti alloys[2]. For instance, the reduction of aircraft weight by 10 kg helps in 2% saving of the fuel consumption which amounts to the cost saving of USD $ 100 per 100 h flight implying the potential weight saving features of Mg alloys. In spite of these merits, the poor creep strength and corrosion resistance, toughness properties, melting and casting difficulties, poor formability, and high cost deter its application to niche areas in aerospace applications. Recently, it is found that the addition of rare earths (Nd, Gd, Ce) and Zr in Mg improves the elevated temperature strength by precipitation hardening and grain refinement respectively[3, 4]. The precipitation reaction involved in the heat treatment of RZ 05 alloy is as below:

Super saturated solid solution → Coherent GP zones → Plate shape intermediate precipitates (Mg_3Nd, hcp) → Incoherent equilibrium precipitate, $Mg_{12}Nd$ (bct)

Also, the rare earths alter the phase diagram of Mg by shortening the freezing range that helps in minimizing the micro shrinkage porosities in the castings, cracking in the welding[3,4,5]. The addition of Zn in the Mg alloy improves the strength by solid solution strengthening and also enhances the corrosion resistance by acting as a scavenger for cathodic impurities of Ni, Fe, and Cu[4,5,6]. In light of these advantages, Mg alloy based on rare earths, Zn, Zr alloying elements (DIN 3.6104.9/RZ05/BS 2L128 / ASTM ZE41A) is selected for manufacturing AMAGB casting. The composition of the RZ 05 alloy is Mg – 0.8-1.7% R.E – 3.5 - 5% Zn -0.4% Zr. The heat treatment cycle of the RZ 05 is T6 condition, solution treatment at 330°C for 2 h and air cooling followed by artificial ageing at 180°C for 10-16 h and air cooling.

Sand casting is a most preferable process to fabricate casting of high complex shape with concealed integrated oil passages. The gating system used for this casting is unpressurized gating ratio of 1:4:4. The number of sprues, runner bars, ingates, spring cores, sand cores, risers is 2, 2, 12, 2, 5, 7, and 36 respectively. The main casing casting assembled with gating system is shown in Fig. 3. The processing flow chart of AMAGB is illustrated in Fig.4. The airworthiness certification requirements for the AMAGB casting are concisely shown in Fig. 5.

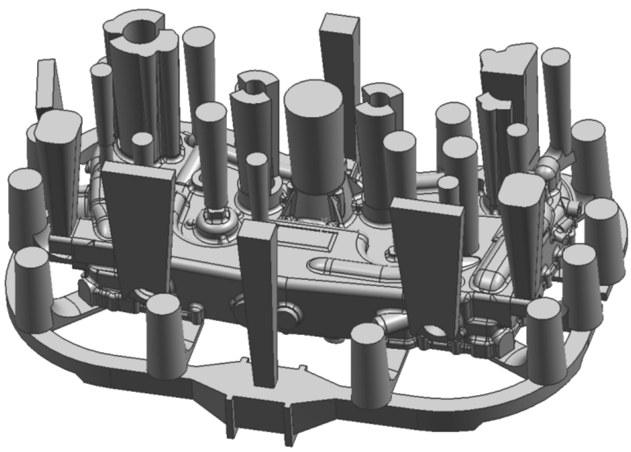

Figure 3. *AMAGB main casing with gating system (Unpressurized gating ratio: 1:4:4).*

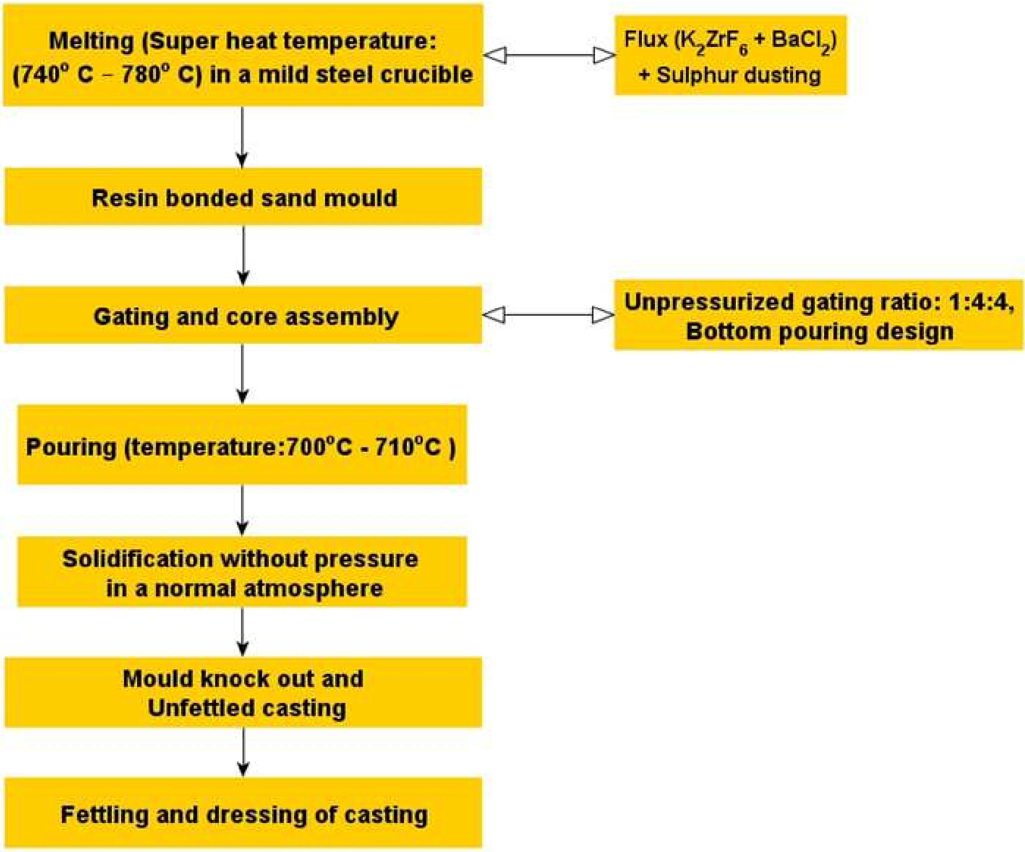

Figure 4. *Sand casting process flow chart of AMAGB casting.*

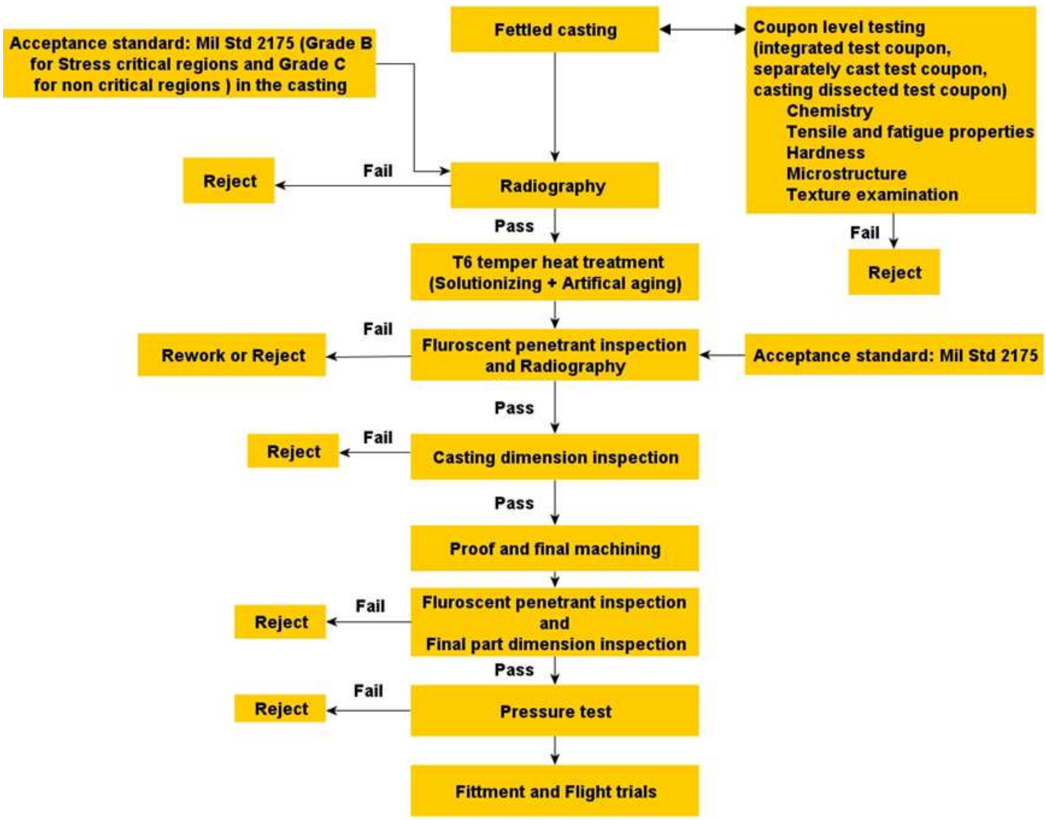

Figure 5. *Flow chart providing the details of airworthiness testing and certification requirements.*

3. Results and Discussion

3.1. Melting Problems

Liquid Mg reacts vigorously with oxygen, if unprotected by an inert gas atmosphere, dusting with sulphur and fluxes resulting fire explosion by oxidization. Currently RZ 05 alloy is melted in mild steel crucible with sulphur and flux. Poor control over oxidation owing to the old practice of dusting with sulphur and flux additionscauses oxide defects in the casting and importantly frequent fire accident resulting huge loss to the foundry properties and in extreme cases, human loss.

3.2. Casting Material and Design Problems

The inherent property of low volumetric heat capacity of the RZ 05 alloy demands faster filling of the mold cavity resulting in heavy turbulence of the molten metal in the runner and ingates. This causes mold gas pick up, dross formation and mold erosion resulting casting defects such as oxide and sand inclusions and blow and gas holes. Also, the requirement of fast filling needs more gating elements which affect the casting yield. The AMAGB casting design has two integrated oil passages running parallel to each other with in-between wall thickness of 6 mm over a length of approximately 450 mm. These passages are fabricated using spring cores. It is observed that the overlapping of passages after solidification due to the sagging of springs by the impact of liquid metal reduces the wall thickness between oil passages and causes cold shut defects that result in the rejection of the casting. Other inherent disadvantages of relatively large freezing range, eutectic formation and high shrinkage ratio of the RZ 05 alloy make the casting prone to micro shrinkage or sponginess particularly feathery type, and segregations.

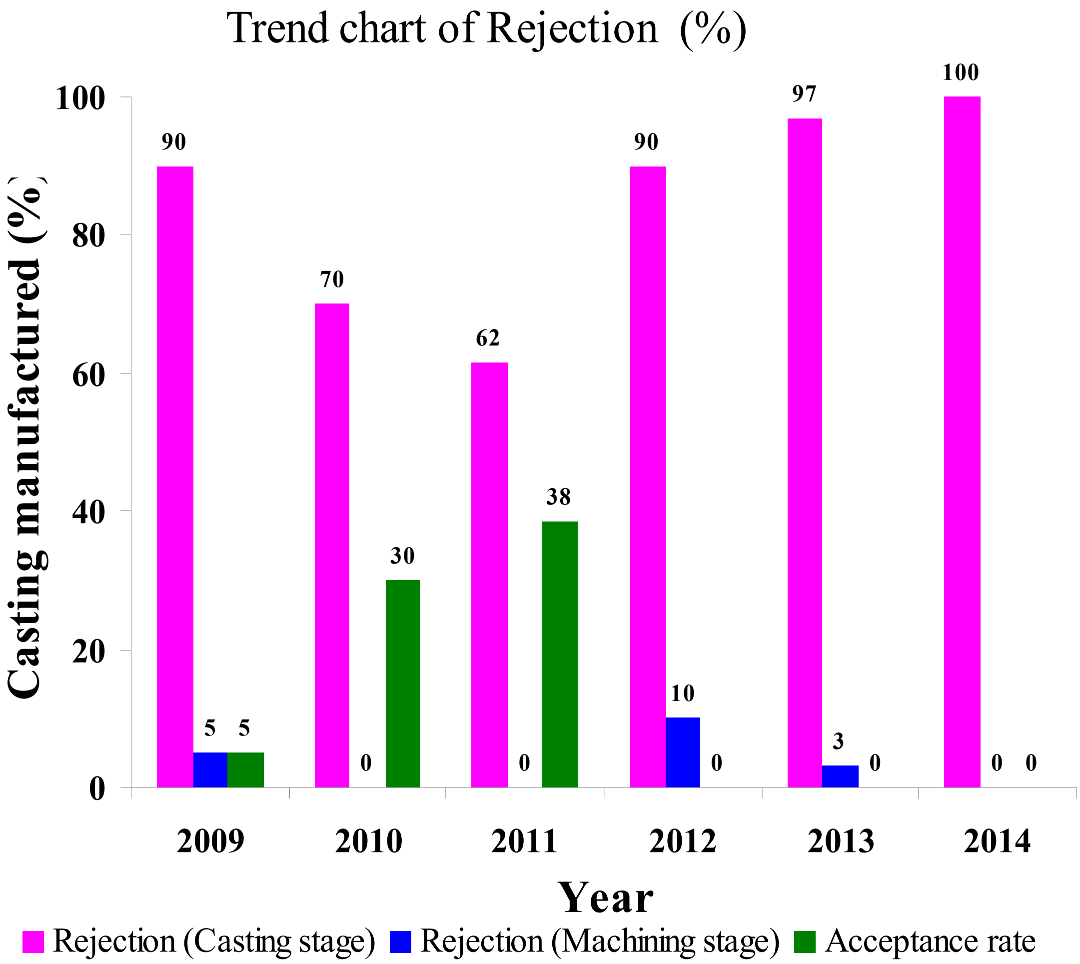

Figure 6. Trend chart showing statistics of acceptance (%) and rejection (%) of AMAGB main casing casting manufactured for the years 2009-2014. (Source: HAL (F&F), Bangalore).

3.3. Inspection Problems

The in accessibility to some regions of AMAGB casting such as oil passages, intricate sections and core holes makes 100% radiography inspection impossible. Further, it adds difficulty in cleaning that results in blockage of oil passages noticed during pressure testing. Other problems of super imposition of walls due to the complex shape of AMAGB casting, very less difference in contrast between defects (slag, shrinkage, gas holes) and defect-free region due to the low density of Mg alloy in the radiography films poses challenge radiography inspection.

3.4. Rejection Rate Analysis

Fig. 6 shows the trend of rejected casting in the casting and machining stages for the years 2009-14. As can be seen in Fig. 5, the rejection rate of AMAGB casting in the casting stage is miserably very high (~86%) incurring a huge loss as reported in the cost assessment section. The rejection in the machining stage (~ 3%) is negligible compare to that in the casting stage. Even the rejections in the machining stage are mostly not due to the machining faults, it is because of the unexamined intricate oil passage regions by radiography due to inaccessibility during the casting stage resulted pressure leakage in the pressure testing. The high rejection rate leads to a significant cost penalty and delays the program exceedingly.

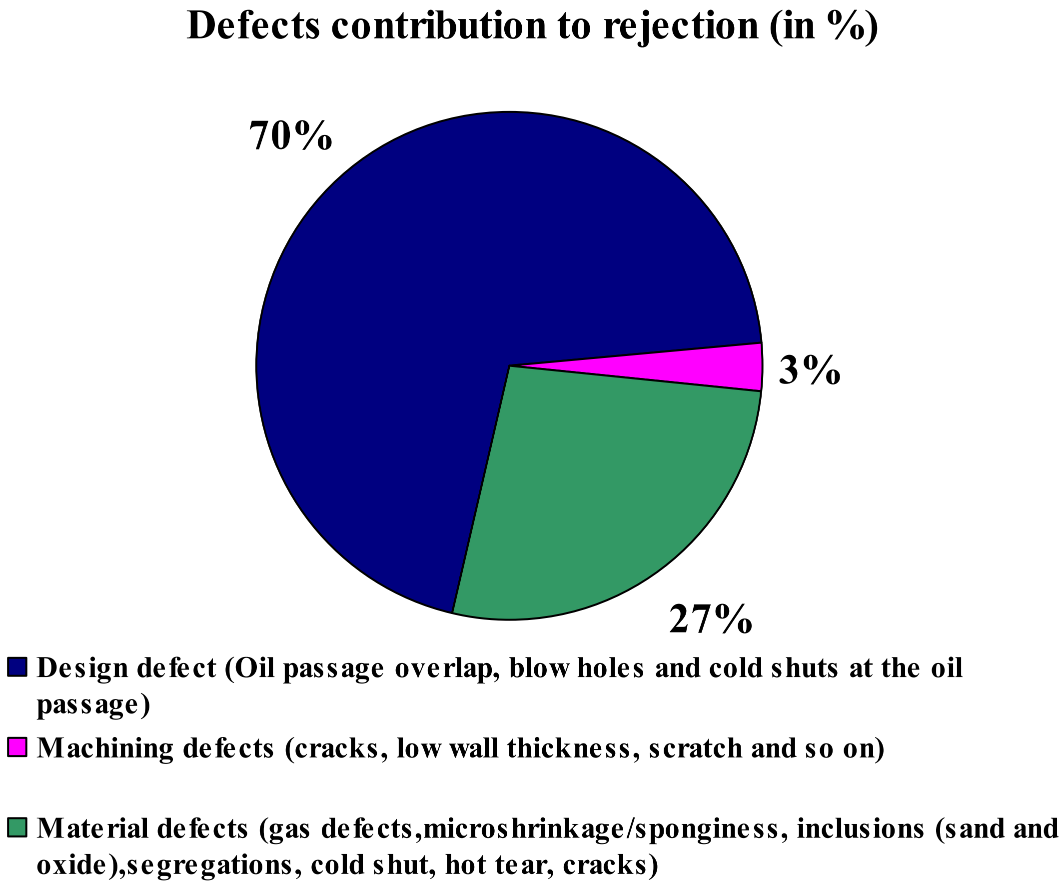

Figure 7. *Contributions of different defects to rejection (%) of AMAGB main casing casting (Shown data are taken from 2009 to 2014 manufacturing details) (Source: HAL (F&F), Bangalore).*

The pie charts in Figs. 7 and 8represent rejection percent based on the process cause wise and casting material defect wise for the years 2009-14. It is clear from Fig. 6 that design and casting material defects are mainly responsible for the rejection of AMAGB main casing castings. Particularly, the gases escape near the lengthy, curved oil passages through spring core leaving the blow holes around oil passages. This casting material defect due to the internal oil passage design is the major reason for the rejection of almost 60% AMAGB main casing casting.

As seen from Fig.8, the followings casting material defects are mainly responsible for rejection of the component, (1) blow holes and wall thickness variation in the two adjacent lengthy and curved oil passages, (2) micro shrinkage or spongінessand porosity, (3) low density inclusions (sand and oxide), (4) segregation, and (5) cold shut. Particularly, blow holes around the oil passage and cold shuts are the principal casting material defects causes for the rejection contributing to 85% rejection, as represented in Fig. 8.

From the data analysis of rejection rate of the casting, we understand that the overlapping of curved, lengthy two adjacent oil passages, and blow holes and cold shut Mg alloy casting defect characteristics are the principal reasons for the high rejection rate. Former problem may be solved by a redesign of the as cast oil passages to external oil passage in the casting, and the latter requires the change of Mg alloy to other lightweight, easy castable, less defect prone alloys. It is also envisaged that the change of alloy and redesign of oil passages may substantially improve the acceptance rate of the casting. The following section elaborates the solutions to improve the acceptability of the casting.

3.5. Solution Methods

3.5.1. Casting Design Change

It is clear from the rejection rate that the overlap of the two curved, lengthy oil passages and the casting defects surrounding those regions are a major factor for rejections. One of the possible solutions is to change the design involving the replacement of internal, integrated oil passages with external oil passages similar to other designs such as the main gear box (MGB) housing Mg casting of SU-30. In the case of SU-30, the acceptance rate of the MGB housing is 60-70%. The proposed design change will dramatically improve the acceptance rate to 55%. Additionally, it helps in significant weight reduction from the current weight of 14 kg to 10 kg.

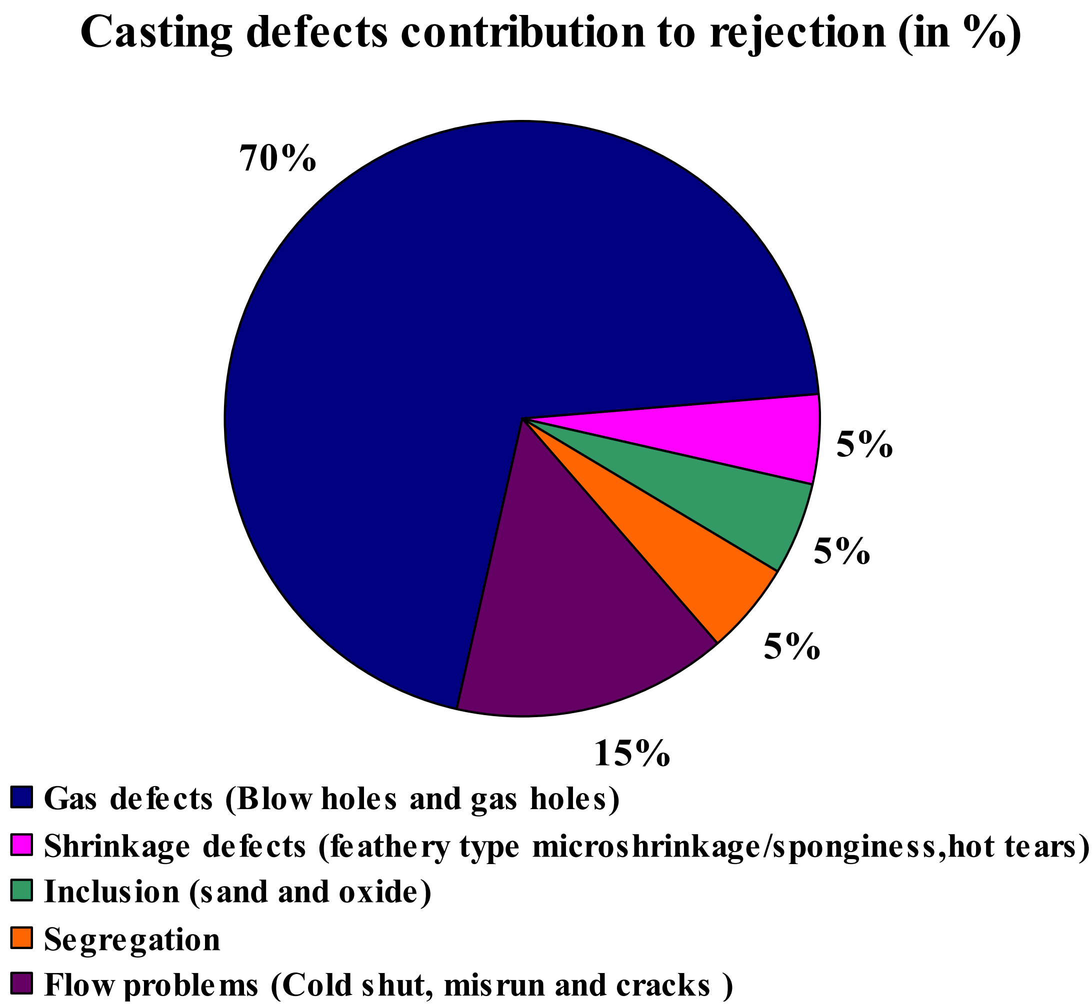

Figure 8. *Contributions of casting defects to casting stage rejection (%) of AMAGB main casing casting (Shown data are taken from 2009 to 2014 manufacturing details) (Source: HAL (F&F), Bangalore).*

3.5.2. Weld Salvaging

Welding of casting is universally allowed in the aircraft industries. Arc welding (Gas tungsten or Gas metal arc welding) are more popular in melting Mg alloys [5]. It is reported that the joint efficiency of Mg and Al alloys welded using arc welding is 80% and 90% respectively. In light of the above facts, it is proposed that the salvaging of the non-critical regions in the AMAGB casting using arc welding may further enhance the acceptance rate in the casting and machining stage.

3.5.3. Fluxless Melting Technology (FMT)

In FMT, the melting is carried out in a closed mild steel crucible furnace system under CO_2 or inert gas (Ar) atmosphere. The advantages of FMT is that (1) it avoids the use of expensive, imported proprietary solid flux additions and their associated problems of pollution and crucible life, (2) it makes clean molten metal free from slag entrapment, (3) it has better control over burning and oxidation of Mg alloys and (4) Very importantly, it avoids gas defects (blow hole and gas porosity) and inclusion in the casting. As seen earlier, the blow hole is a major problem for 70% rejection of the casting; this can be very well solved by implementing FMT for Mg alloy melting. Nair et al.[10] reported that the FMT processed RZ 05 alloy shows improved tensile properties with free from inclusions. They have predicted the whopping foreign exchange savings of 95% if FMT implemented instead of importing flux from foreign countries.

3.5.4. Material Change - A356 Al Alloy

Another best solution is to change of material from Mg alloy and Al alloy. Among the Al alloy, A356 is the best alternative to RZ 05 because of numerous casting characteristics and better mechanical properties. The tensile and fatigue properties of A356 Al alloy outperform the RZ 05 Mg alloy. Particularly strength to weight ratio is a little lower than the RZ 05 Mg alloy. Another important design parameter is the Young's modulus (E) of the material. The significantly higher E of A356 Al alloy is beneficial in the view point of structural design. Mg alloy suffers corrosion especially galvanic corrosion. The strong corrosion protection scheme (anodized layer, seal coat, two or three coats (primer coat, top coats)) and frequent maintenance are required to ensure the proper functioning of the component[5,6,8,9,11]. In contrast, Al alloys are inherently possesses high corrosion resistance because of non porous, thin and strong oxide (Al_2O_3) layer. The low cost corrosion protection schemes (anodizing, resin impregnations) are quite sufficient to ensure corrosion resistance of the component. Other benefits of Al alloys in the component service and maintenance are lower replacement cost, easier repair schemes, and less inspection burden. The fatigue properties of Al alloys are usually higher than Mg alloys.

(i) Properties Comparison

The comparative study of properties of RZ 05 Mg alloy and A356 Al alloy is presented in Table 1.

Table 1. *Properties comparison between Mg (RZ 05) alloy and Al (A356) alloys (Note: Properties are given for T6 temper condition)* [5,7,10,12,13,14].

Properties	Alloy currently in use	Proposed substitution
Composition	Mg alloy: RZ 05 (Mg – 0.8-1.7% R.E – 3.5 -5% Zn -0.4% Zr) T6 condition	Al alloy: A356 (Al – (6.5-7.5%) Si - (0.2-0.45%) Mg) T6 condition
Density	1.74 g/cc	2.68 g/cc
Tensile Properties (Min)	Yield strength: 135 MPa Tensile strength (UTS): 200 MPa Elongation: 3% Young's modulus: 45 GPa	Yield strength: 200 MPa Tensile strength: 280 MPa Elongation: 3% Young's modulus: 71 GPa
Strength to weight ratio (N.mm/kg)	115 x 10^6	104 x 10^6
Fracture toughness (MPa √m)	15.49 (experimental value)	38 (estimated value)
Fatigue strength (R=-1, unnotched, completely reversal loading case) for a life of 10^6 cycles	90 MPa	124 MPa
Specific heat (J/kg*°C)	960	963
Castability	Relatively poor	Excellent and proven alloy
Corrosion rate (Salt spray test)	> 500 mils/year	< 30 mils/year
Corrosion resistance in salt water environment	Very poor, require extensive corrosion protection schemes to protect from galvanic and atmospheric corrosion	Relatively good.
Melting practice	Requirements of inert gas atmosphere or flux and sulphur addition to prevent oxidation	Conventional air melting is sufficient
Minimumcastable wall thickness	5 - 6 mm	3 - 4 mm
Defects	Highly prone to micro shrinkage/sponginess, blow holes and dross formation	Least prone to shrinkage and gas defects.
Weldability	Moderate	Excellent
Pressure tightness of the casting	Relatively poor due to micro shrinkage defects	Excellant
Loss of strength	Alloy is stable upto 100°C	Alloy is stable upto 150°C
Notch UTS/ unnotched UTS	-	0.97
Stress corrosion problem	No service failure noticed	No service failure noticed

(ii) Casting Yield and Weight Penalty

The calculation of casting yield for both Mg and Al alloy for the AMAGB main casing casting is given in Table 2 as below:

Table 2. *Comparisons on casting yield and weight penalty between Mg (RZ 05) alloy and Al (A356) alloy.*

Parameters	Mg alloy RZ 05	Al alloy A356 (without wall thickness reduction or current design)	Al alloy A356 (with wall thickness reduction design)
Melt loss (kg)	16	10	9
Unfettled weight (kg) (with gating system)	40	56	52
Casting weight (kg)	15	21	19
Casting yield = casting weight / (Unfettled weight + melt loss)	26.7%	32%	31%
Weight penalty (kg) in the casting stage	-	6	4
Machined component weight (kg)	12	16.4	14.4
Weight penalty (kg) in the final component	-	4.4	2.4

From the above table, it is clear that the change of material from RZ 05 to A356 imposes the weight increment of 4.4 kg and 2.4 kg for the cases of the same design and design change with wall thickness reduction from 6 mm to 4 mm. On the other hand, A356 Al alloy provides better casting yield improvement of 4-5% over RZ 05 Mg alloy.

(iii) Cost Saving

The calculation of cost saving benefited by substituting Mg alloy with Al alloy for the AMAGB main casing casting is given in Table 3 as below:

Table 3. *Cost analysis of Mg (RZ 05) alloy and Al (A356) alloys (Note: Cost considered are rough one, not exact value).*

Parameters	Mg alloy RZ 05	Al alloy A356 (without wall thickness reduction or current design)	Al alloy A356 (with wall thickness reduction design)
Cost (INR) of alloy per kg	1000	250	250
Component weight (kg)	12	16.4	14.4
Material cost of the component (INR)	12000	4100	3600
Recycle potential in (%)	0%	40%	40%
Scrap (kg) = gating material + melt loss + machining waste	44	50.6	46.6
Recycling (kg)	0	20.2	18.6
Scrap after recycling (kg)	44	30.4	28
Loss (INR) due to scrap	44000	7600	7000
Manufacturing cost of the component (INR)(exclusive of other costs such as tools, transport, packaging, man-hour and so on)	56000	11700	10600
Cost savings over Mg alloy (INR)	-	44300	45400
Acceptance rate of the AMAGB casting	10%	70%	70%
Cost savings over Mg alloy considering acceptance rate of the casting for 10 castings (INR) (+ indicates savings, - indicates loss)	- 504000	+ 513200	+ 482900

From the above table, it is clear that the change of material from RZ 05 to A356 shows the whopping saving of INR 44300 and INR 45400 for the cases of the same design and design change with wall thickness reduction from 6 mm to 4 mm. Also, the saving from acceptance of the casting amounts to more than INR 500000. The saving is mainly attributed to low cost, excellent cast ability, and high recycling potential of A356 Al alloy.

3.6. Merits and Demerits

The significantly high cost saving from acceptance rate and manufacturing cost, high recycling potential of gating material scrap, low melt loss, excellent cast ability, better mechanical properties (fatigue and tensile strength, fracture toughness), high corrosion resistance, high casting yield, low material cost, better high thermal strength stability and superior quality casting are the merits of replacement of Mg alloy (RZ 05) with Al alloy (A356) alloy. On the other hand, the weight penalty of 4-5 kg and relatively poor damping properties are drawbacks of replacement. The former (weight penalty) may be offset by reducing the wall thickness of the casting by casting redesign and optimization process whereas the latter (damping properties) may be still a concern especially rotorcraft applications due to high vibration and noise.

4. Conclusions

In this paper, we have briefed the complexity of casting, processing and airworthiness certification details and causes for the high rejection rate of Mg alloy (RZ 05) AMAGB main casings and casting. The following solutions were proposed to improve the acceptance rate of the casting:

- The sole change of alloy from Mg (RZ 05) to Al alloy (A356) will significantly enhance the acceptance rate to 70% from 14% and also, reduce the product cost substantially (~ 500%)by higher casting yield, low material cost, and high recycle potential. The disadvantage of weight penalty arising from this solution can be very well mitigated by designing the casting with reduced wall thickness.
- The sole modification of design involving the removal of as cast integrated, lengthy oil passages from the casting and making it to external oil passages similar to MGB casting in SU-30 aircraft will increase the acceptance rate to 50% from 14%.
- The change of both alloy and oil passage redesign of the casting will have a potential of increasing acceptance rate to more than 85%.
- Other solutions such as flux less melting technology and weld repair may help in improving the acceptance rate however, not so significant as the change of material or oil passage redesign.

Acknowledgements

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References

[1] Procedure for Design, Development and Production of Military Aircraft and Airborne Stores (DDPMOS 2001). CEMILAC, Department of Defence Research and Development, Ministry of Defence, India, 6003 (1), 2002.

[2] Edgar, R.L. Magnesium alloys and their application. K.U. Kainer Pub., France, 2000. 3 p.

[3] Rokhlin, L.L. Magnesium alloys containing rare earth metals-structure and properties. Taylor & Francis Pub., Moscow, 2003. 197 p.

[4] Apps, P.J.; Karimzadeh, H.; King, J.F. & Lorimer, G.W. Phase compositions in magnesium-rare earth alloys containing yttrium, gadolinium or dysprosium. *Scr. Mater.*, 2003, 48 (5), 475-481.

[5] Avedesian, M. M. & Baker, H. (Eds.). Magnesium and magnesium alloys. Materials Park, OH: ASM International (The Materials Information Society), USA, 1999.

[6] Griffin, R.B.; Bollfrass, C.A.; Zuniga, D. ; Ijaz, M. ; Ayala, J.F. &Dibua, O. Evaluation of coatings on mg alloy ZE41A used in helicopter rotor gearboxes, 2005.

[7] Gwynne, B. & Lyon, B. Magnesium alloys in aerospace applications, past concerns, current solutions. *In* Proceedings of the Triennial International Aircraft Fire & Cabin Safety Research Conference, UK, 2007.

[8] Craig, B. For its rotorcraft, navy is switching to aluminum gearboxes. *Corrdefense*, 2008, 5(2), 1-2.

[9] Gallaccio, A & Ebihara, W.T. corrosion susceptibilities of magnesium alloys, AZ91, EZ33 and ZE41. US Army Armament Research and Development Command, Technical Report. ARSCD-TR-83007, June 1983.

[10] Nair, C.G.K, Gopalkrishna, V. &Dwarakadasa, E.S. Source Book: Magnesium alloys technology, production, properties and applications. Non Ferrous Metals Division and Indian Institute of Metals, Bangalore, India.

[11] Craig, B.Services Workto reduce maintenance costs and raise helicopter readiness. *Corrdefense*, 2007, 3(2), 1-2.

[12] Magnesium Casting Alloys, Datasheet: 440, Magnesium Elektron, Manchester, UK.

[13] Aluminium Casting Alloy, A356.0 data sheet, Hadleighcastings Aluminium Technology.

[14] Kaufman, J. G. & Rooy, E.L., 2004 (Eds). Aluminimalloy castings – Properties, processes and applications. Materials Park, OH: ASM International (The Materials Information Society), USA.