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Development of Aircraft Components

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ABSTRACT

When aircraft projects were taken up , new challenges were thrown open for the development of components. A change in culture of making parts for land-based vehicles to high precision aircrafts components was essential. Indigenous technologies were developed and implemented in realising the precision products. The experiences are enumerated below:

I. LCA AIRCRAFT MOUNTED ACCESSORY GEAR BOX (AMAGB)

Introduction

Developing Aircraft Mounted Accessory Gear Box (AMAGB) for Light Combat Aircraft (LCA). AMAGB will be housing Jet Fuel Starter (JFS) unit, Integrated Drive Generator (IDG), Hydraulic pumps etc.

The development of wooden patterns for the cover casing and Main casing for AMAGB and development of castings in Aluminium (LM-25) were carried out at a vendor source. Further development of the castings in Magnesium is being carried out at HAL (Foundry and Forge).

When coordinating with the design group right from the initial design and drawing stages. In the due course suggestions were made to the designers, whenever required, with a view to produce the components as per drawing. At several instances the designers have re-designed the casings based on the manufacturer's suggestions for produce ability of the casings.

Since it was the first time requirement at Workshop to manufacture precision components for Aircraft applications, an exposure to the manufacturing environment of Aircraft components was felt necessary. Hence various divisions of HAL were visited to acquire and transfer the technology of manufacture of Aircraft components.

Initially three pilot castings were made out of Aluminium alloy / AZ 91C Magnesium alloy at local vendor source. Further ten sets were supplied by HAL (F&F). All the sets were successfully machined at CNC machine complex of CVRDE. The experiences gained during the machining of the above casings were utilized to prepare this report.

Machining features of Casings

Cover casing is a slender casting of 5 mm section thickness. Not only the Aircraft quality but also the machining of such a thin casting is the first time requirement at work shop. Added to the above are

(1) The flatness requirement is 0.010 mm over an area of 400 x 750 sq.mm
(2) Tolerance on bore centre distance dimensions is ±0.010 mm over a maximum length of 122 mm
(3) Tolerance on bore dimension should be within –0.002 / - 0.005 over a maximum bore size of Ø68. This tolerance level falls under IT3 grade.
(4) Concentricity of bores between Cover and Main casings should be within 0.010 mm over a depth of 200 mm
(5) Requirement to produce holes either by using extra long series overhanging drills or at angular position.
(6) Machining of tapped holes as per proprietary standards and so on.

The drawings of the casings were thoroughly analyzed and process planning was carried out. Broadly the process flow is as follows

1. Semi finishing of Cover Casing.
2. Semi finishing of Main Casing.
3. Assembling Cover and Main Casings
4. Finish machining of Assembly Casing.
5. Finish machining of Cover Casing
6. Finish machining of Main Casing

The various aspects of machining of AMAGB casings are discussed in the succeeding paragraphs.

Flatness

The designers have proposed to assemble the Cover Casing and Main Casing without using any gasket. Hence it is essential that the mating surfaces of the casings need to be perfectly flat to prevent any leakage through the interface of the mating surfaces. During visits to HAL divisions, it was learnt that there are two different approaches for achieving the flatness.

(1) Machining the surface followed by scraping and blue checking. This is being in practice at HAL Koraput division.
(2) Machining the surfaces repeatedly to achieve the required flatness. This method is followed in HAL Engine Division, Bangalore.

It was decided to adopt the second approach and hence the assistance of HAL divisions was sought through AMAGB design group and Aeronautical development agency (ADA). Though some process sheets were received, the process technology for achieving the flatness through machining alone was not made available. However it was decided to develop the process technology in-house at CVRDE.

As the proposed approach involves repeated reversal of the component and machining of surfaces sufficient tooling pads have been provided in the casting to create plane surfaces parallel to the jointing surfaces of the castings. In addition, tooling pads have been provided for clamping the component, especially externally in the cover casing to enable machining of jointing surface in single setting and in the single pass of the cutter.

For machining the jointing surface on a CNC machine, necessary part program is to be developed. While going through the designer's drawing, one may find sufficient points for cutter movement. Any programmer will naturally be tempted to use those co-ordinate dimensions. But practically, on the machine, when the program is executed the system pauses the tool movement a fraction of second at each changeover of the tool direction. This instantaneous stop/start of the cutter evidently leaves tool marks thereby resulting in poor surface finish. Hence the problem was tackled through a different approach.

The profile of the jointing surface consists of circular arcs and line segments. As the design drawing was created in AutoCAD, the points for the tool path have been extracted from the AutoCAD. Using the above points a part program was generated and the machining was carried out.

Tooling

Initially a four fluted HSS end mill of Ø 20 mm was used for machining the surface. The surface finish achieved was not satisfactory. The cutter leaves tool marks due to back cut. The problem was analyzed and it was concluded that as the number of cutting edges are more, the axial pressure on the component is more. Then an off-hand ground single point fly tool was tried. The result was most satisfactory. However controlling the cutting geometry on the fly tool is difficult and hence finally it was resorted to use a twin insert T-MAX end mill, by removing one insert or to use a single point end mill with throw away inserts.

Fixturing

Necessary fixtures were made and used. However the job can be very well mounted directly on the bed using block tooling's to get better flatness results. It was experienced that the clamping torque should be even on all the clamping bolts and should be minimal, otherwise the casing deflects due to the tightening torque of the clamping bolts.

Inspection on the machine bed

After machining the surface, the clamps are released. A dial indicator (0.001 mm least count) was mounted on the spindle head and the readings on the machined surface in the clamp free condition were checked. When the error obtained is within permissible limits the component is taken up for further machining. The components were also inspected on CMM and then the mating components (Cover casing and Main casing) were blue checked and found that they match as per the designer's requirements.

Linear Dimensions

The tolerance on liner dimensions is controlled by selection of right machine tool, cutting tools and correct part program.

Bore Dimension

The stringent tolerances on bores are to IT3 Grade. (eg. the tolerance on Ø68 mm is -0.002 /-0.015). However the requirement was met by using imported SWISS precision CO boring bars and boring cutters having accuracy of 0.005 mm on diameters.

Concentricity

Concentricity is achieved by finish machining Cover and Main Casings in assembled condition.

Extra Long Series Drills

Extra long series drills with more over hang is unavoidable, to drill tapped holes for mounting temperature and pressure sensors on Cover Casing outer side. However it was suggested to designer to relocate the pads to obviate manufacturing problem.

Cross Hole Drilling and Cross Hole Boring

It is general practice to use jigs and / or guide bushes to locate the tool for angular drilling. But methods have been devised without using any jig or guide bush to drill angular holes. Necessary special tools are procured to drill Ø1 holes at hydraulic pump stations in the Main Casing inner side.

The primary requirement for drilling cross holes is that either the component should be aligned at the proper angle or the tool axis should be moved along the required hole axis.

Machining of Tapped Holes as Per Proprietary Standards

Assembly of Cover Casing and Main Casing and also mounting of bearings are by using special screws with locking arrangements. The tapped hole is as per "ROSHAN" a proprietary standard. The hole to be drilled is a stepped hole. Hence necessary step drills (special) have been procured and used. Alternatively two different drills (specials) can also be used but resulting in more operation time.

II. DEVELOPMENT OF FLEXIBLE DIAPHRAGM FOR PTO SHAFT ASSY

Introduction

Power Take Off shaft assembly is an important sub-assembly in the aircraft that connects Aircraft Mounted Accessory Gear Box (AMAGB) with Gas turbine engine through Engine Mounted Accessory Gear Box (EMAGB). The primary function of PTO shaft assembly is to transmit power between EMAGB and AMAGB. AMAGB functions in two modes, namely starter mode and accessory mode. In starter mode it transmits power from a gas turbine starter unit or Jet Fuel Starter (JFS) unit mounted in the AMAGB to the Gas Turbine. Once the engine attains its self sustaining speed, the JFS drive is cut off by an Over Running Clutch (ORC) assembly and the power flows from gas turbine to the AMAGB through PTO shaft assembly to drive the accessories such as Hydraulic pumps and Integrated Drive Generator (IDG) mounted in the AMAGB.

PTO shaft also has to absorb axial and angular misalignments. Axial misalignments occur to the extent of ± 5 mm due to thermal variations and angular misalignments occur to the extent of 1.5° due to errors in EMAGB and AMAGB mountings in the aircraft.

PTO shaft transmits 185 kW (250 HP) in the aircraft whereas the total weight of PTO shaft assembly is 1.6 kg. PTO shaft assembly is shown in fig.1.

Flexible diaphragms are the important elements in the PTO shaft assy. There are eight diaphragms, four on either side of PTO shaft. These four diaphragms are stacked together by electron beam welding and then welded with the central tube.

These diaphragms together absorb the misalignments mentioned above.

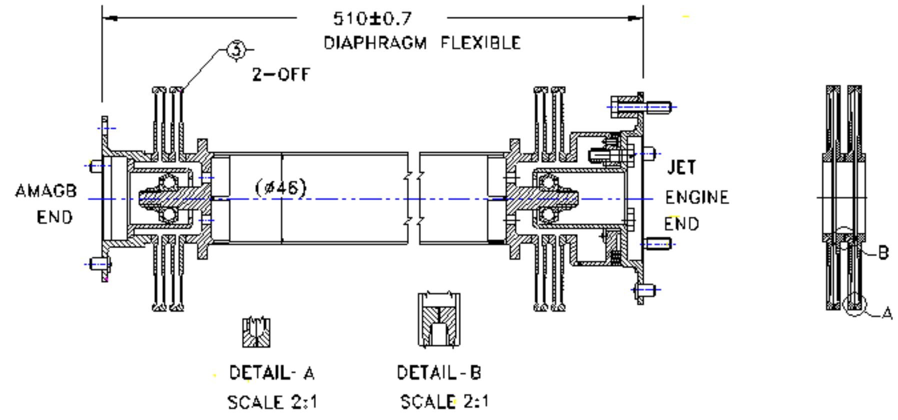


Fig.1 PTO SHAFT ASSEMBLY

Flexible Diaphragm

Flexible Diaphragm is a thin disc shaped part. The thin section has a varying thickness of 2.2mm at the radius of 22mm to 0.4mm at the radius of 52mm. The section profile approximates to hyperbolic curve. The component is depicted in fig.2. The profile data for the surfaces L & M are identical and one surface is the mirror image of the other about a mean line.

Design Requirements

From fig.2 it may be observed that the diameters 36mm and 104mm are to be concentric within 0.03mm and surfaces P and Q are to be flat and parallel within 0.05mm. The surface finish of surfaces L and M are to be finished by lapping to Ra 0.1μm. The required dimensional tolerances are also indicated in the component drawing.

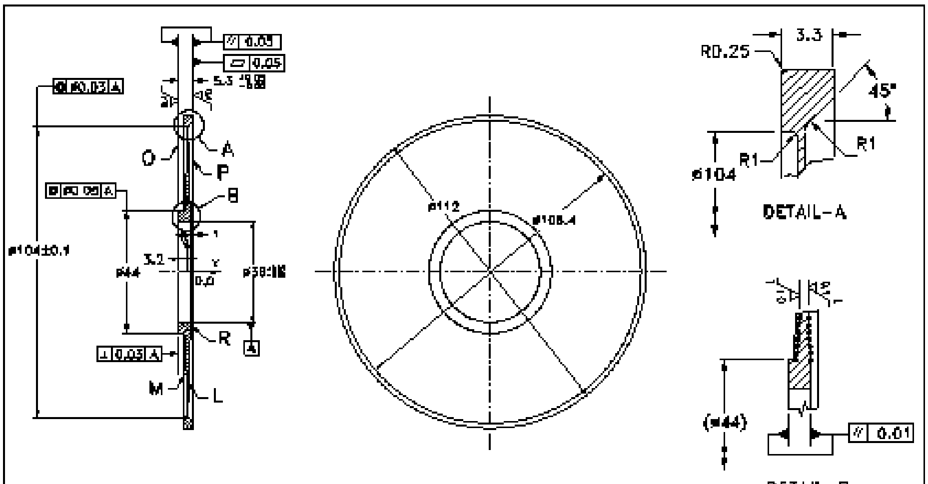


Fig.2 FLEXIBLE DIAPHRAGM

Manufacturing approach

The shape and size of the component implies that this is highly difficult to produce by resorting to the conventional machining methods. It would be easier to produce the component by unconventional methods such as ECM and so on. Due to various reasons it had become essential to produce the part by machining.

Considering the design requirements given in section 2.1 and the raw material made available, different process technologies have been developed and established.

Initially the component was machined out of Rolled plate or round bar. After several attempts, finally an effective method producing from round bar stock using hydraulic backup was established.

Machining from bar stock

The bar stock is of 120 mm in diameter. The bar is sliced into discs of thickness 10mm. The process sequence for producing the diaphragm from the discs of 10 mm thick is given below.

Process sequence

1 Blank turning
2 Profile turning of surface L and boring
3 Step boring at surface Q
4 Profile turning of surface M using fixture with hydraulic backup
5 OD turning using fixture
6 Bench work and
7 Inspection of cross section in 3D CMM.

Development of fixture with hydraulic backup

Initially, wax backup was used for turning the second side of the profile from rolled plate. The same wax back up was tried while machining the part from round bar too. However wax is also compressible though to a very less extent.

It is common practice to use hydraulic or pneumatic clamping methods for machining thin parts [3]. It is thought of to utilize the incompressible nature of liquid in giving backup while machining thin parts and thus an attempt is made in that line.

The major considerations in developing the hydraulic fixture are (i) the surfaces of the diaphragm matching with the fixture should have proper bearing to avoid leakage of liquid medium (ii) proper clamping of the part is to be ensured (iii) the fixture should be as simple as possible and (iv) the fixture should also provide reference datum for taking dimensions of the part.

In operation 2 the first side of the profile(surface L) is machined, surfaces P & R are turned and a distance of 1 ± 0.005 is maintained between these two surfaces.

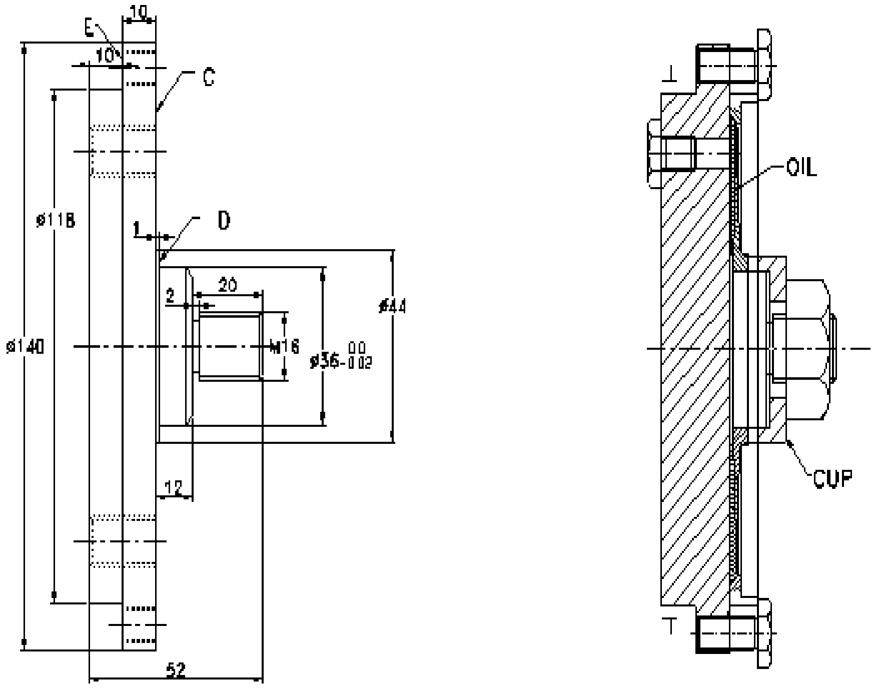


Fig.5(a) TURNING FIXTURE Fig.5(b) MACHINING SETUP

The turning fixture is depicted in fig.5 (a). It consists of three datum surfaces C, D & E. Surfaces C & D are precision turned parallely and a distance of 1mm is maintained. Surface E is parallel to surface C & D and perpendicular to Ø36 and Ø118.

The machining setup for turning second side (surface M) is shown in fig. 5(b). The surfaces P & R of the component are butt against the surfaces C & D of the turning fixture, and the part is clamped at the center as well as on the outer edge. Straight cutting oil is filled between the surfaces L & C through the tapped holes provided at the back of the fixture plate and these holes are suitably sealed using threaded plugs with 'O' rings.

Effects of hydraulic backup

1 In the wax back up method, the wax was expendable; costlier compared to oil.
2 Straight cutting oil (servocut 945) available in the machine is used. Oil is cheaper.
3 The wax is to be melted on a heater, poured in the fixture and allowed to cool. Also it is to be re-melted to remove wax after machining. This consumes considerable preparatory time.
4 Filling of oil and draining is easier and quicker.
5 Wax is slightly compressible but oil is incompressible.
6 Even if the quantity of oil is just insufficient to fill the space in fixture, it does not harm the requirement as centrifugal action fills the rim section of diaphragm leaving empty space only at the hub portion where the section thickness is more and also at that section the part is rigidly clamped.

Experiments on tool geometry and cutting parameters

In order to improve surface finish, trials have been conducted with different tool geometries, considering problems associated with machining Titanium and its alloys [2]. It should also be noted that, to turn the part, a standard tool was modified as shown in fig.4, otherwise tool may gouge with component. The cutting parameters used during profile turning are as follows:

Cutting speed : 30m/min
Feed : 0.03mm/rev
Depth of cut : 0.05mm

The following table gives the surface finish values as against tool nose radius.

Table 1 Effect of nose radius on surface finish

Nose Radius(mm)	Surface finish (Ra in µm)
0.8	0.7
1.0	0.4
1.2	0.6

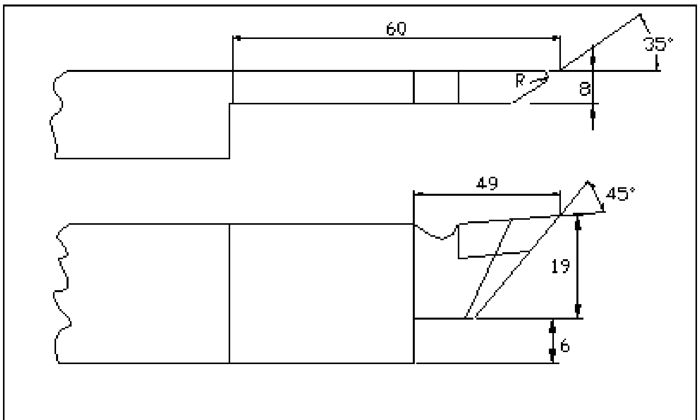


Fig.4 MODIFIED TOOL

Study on surface finish

The cutting parameters as used in the earlier method were used and the surface characteristics are analysed

1. In the product produced by the earlier method, minute chatter marks were noticed. There is no chatter mark in the product produced by using fixture with hydraulic backup.
2. The surface finish was measured & better surface roughness results were achieved

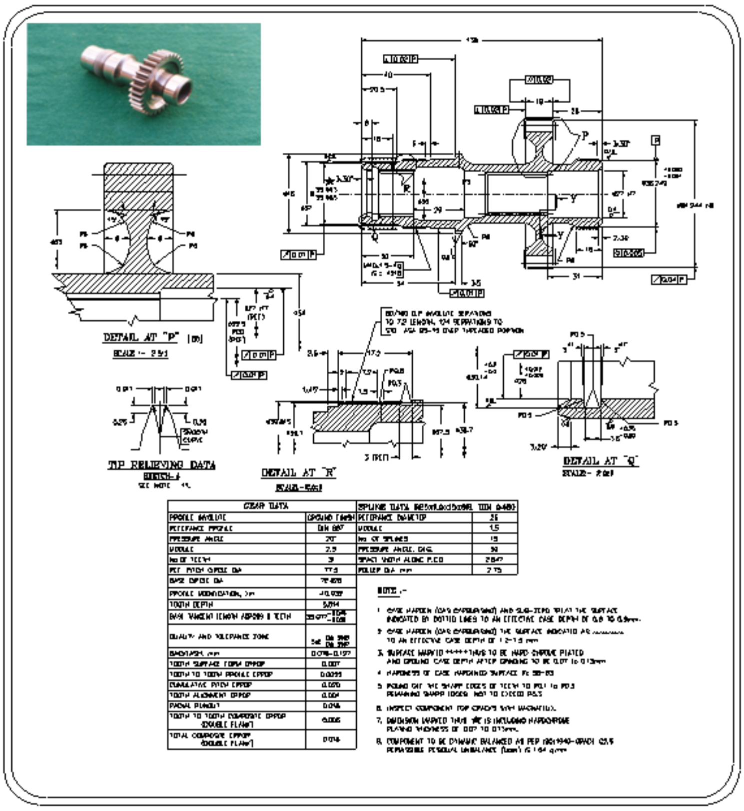
III. DEVELOPMENT OF SPUR GEARS FOR AIRCRAFT GEARBOX

Introduction

In AMAGB there are twelve major gear components driving two hydraulic pumps and one integrated drive generator (IDG). The hydraulic pump units activate the hydraulic lines in Aircraft and IDG supplies electrical power to the Aircraft. To appreciate the manufacturing criticalities involved in these gear components let us consider a typical gear as an example (Fig.1) say, Gear - PTO

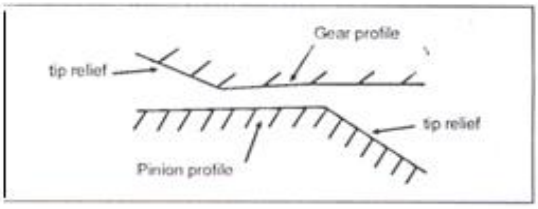
Gear PTO – Description

Gear - PTO is an important item in the AMAGB gear train (fig. 1.a) of 2 module with tip relief to 0.010 µm. It is a gear integral with shaft. This shaft itself acts as inner race of a bearing.

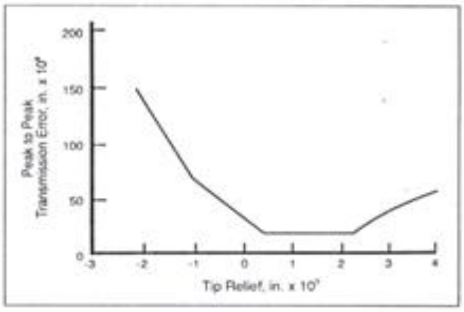


Effect of Tip Relief

Tip relief is provided tips of both the pinion and the gear as shown in sketch A of Fig. 2 shows the effect of tip relief amplitude on the peak-to-peak transmission error [2]. It is interesting to note that overall compliance of the modified tooth increased by about 20% and that the tooth contact at the top and bottom of the tooth was eliminated. The elimination of the contact reduces the stiffness change, which occurs when a new tooth enters contact.



(a)



(b)

Case Depth and Hardness on Gear Teeth

The gear teeth are to be carburised to a depth of 0.6 to 0.9 mm and hardened to have soft core (RC40) and hard case (RC 58 to 63).

Case hardened gears can withstand higher loads than through hardened ones, but the through-hardened gears are quieter in operation in normal cases, have high endurance limit and cost less [3]. However, since through-hardened gears are vulnerable to distortion due to heat-treatment, they are not recommended for high-speed drives. Moreover, unless grinding of gear teeth is practicable, through-hardened gears should not be used in applications where accuracy is of utmost importance. These gears have higher core strength because of higher carbon content, but are less ductile and less resistant to wear. Hardness normally varies from HRC 30 to 55. These gears are generally suitable for moderate strength and impact resistance.

As a post-treatment, hardened gear steels are sometimes tempered to permit machining of the teeth. Hardness is somewhat sacrificed thereby, but other properties are marginally altered.

Due to its comparative softness at the core, the case-hardened gears possess interior toughness. This in turn imparts shock or impact resisting capability to these gears.

Case Depth and Hardness on Shaft Zone

On the shaft, the zone where bearing is mounted needs to be carburised to a depth of 1.2 to 1.5mm and hardened to 58 to 63 RC. The shaft itself acts as the inner race of the bearing, which is considered as weight reducing effort in Aircraft gearbox design.

Differential Case Carburising

We see, thus, that the gear tooth and shaft area are carburised to different case depths and to achieve this proper process planning is essential.

Hard Chrome Plating

On the shaft, the zone where dynamic seals are assembled need to be hard chrome plated to a depth of 0.07 to 0.13 mm, which has hardness of 1200 VPN.

Hard Chromium (thick chromium) is plated on steel, heat resistant, Copper base alloys, Aluminium alloys, etc., to obtain a surface with:

- High hardness
- Low co-efficient of friction and hence as a bearing surface
- Improved anti-seizure and anti-galling properties to restore dimensions of worn out or over machined surfaces (eg. Bearing surfaces)

Chromium is not normally suitable for parts having hardness more than RC 45. Thickness of hard-chromium plating is usually limited to 0.5 mm for aeronautical applications. As a practice, hard chromium will be plated in excess and ground or honed to the final dimension of the surface. Where hard-chromium is meant for increase of corrosion resistance, the coating may be composed of a nickel undercoat and chromium top coat, with minimum 15 µm chromium and a total thickness of 50 µm. Hard chromium plating causes a significant reduction in fatigue strength of high strength steels, which may be rectified to some extent by shot peening the surface prior to hard-chromium plating and by post heat-treatment. If resistance to fatigue is an important consideration, hard-chromium coating is not to be deposited in fillet areas. Hard-chromium plating is usually limited to parts operating below 400^{0}C.

Center Grinding

The component is to be finished to have concentricity error of 0.01 mm over the cylindrical diameters from one end to other. And also the cylindricity errors are to be within 0.005mm. To achieve these, the important operation to be carried out after hardening treatment is center grinding. Planetary conical wheel type center grinding machine is used for grinding on both the ends.

Turning after Hardening

The component is thoroughly machined after hardening and center grinding. This results in bright surface free from quench cracks, if any, and also it will be easy to dynamically balance the part after complete processing. Web thinning to the profile specified in detail 'P' of Fig.1 is carried out using special turning tools. Thread cutting operation is carried out on CNC lathe to have clean threads without burrs.

Grinding of Cylindrical Surfaces

The diameters are toleranced to 4 µm and also high surface finish (Ra.0.15) needs to be achieved. Thus the part is ground with care using dead center to minimize run out. Also the part is super finished at the final stage.

Spline Cutting

Special spline cutters need to be used for cutting internal splines and they were imported.

Gear grinding

The gear teeth are profile ground and to achieve accuracies as per DIN class 5, the machine used should be accurate and rigid and suitable mandrels are to be developed. Reishauer gear grinding machines were used for gear profile grinding. The ground gears are subjected for nital etching tests.

Serration cutting

Serrations as per Detail 'R' of Fig.1 are cut using specially developed press tools on a hydraulic power press. These serrations are used for assembling lock nuts, which are as per proprietary standard.

Cross hole drilling

After case hardening, core hardness is RC 40. To drill cross-holes, high speed sensitive drilling attachment was used.

Dynamic balancing

As the gears are running at 17,000 rpm they are required to be dynamically balanced as per ISO: 1940 – Grade G2.5. Permissible residual unbalance is 1.04 g-mm.

Oxide phosphating

The parts are finally treated for oxide phosphate to protect from environmental deteriorations.

Inspection

Gears are checked thoroughly to assess individual errors and composite errors. For this Involute profile testers, Roll testers and other standard measuring instruments and gauges are used. Case depth and hardness are checked on test pieces processed along with the component batch. Depth of chrome plating is controlled by process. However, test samples can also be used during plating.

IV. MACHINING OF AIRCRAFT BEARING RINGS

Introduction

Traditionally bearings have been manufactured either from high carbon through hardening steel or low carbon case hardening steel. Both high-carbon and low-carbon materials have survived because each offers a unique combination of properties that best suits the intended service conditions. But these materials are mostly used to manufacture bearings, which are intended for normal service applications. Whereas, in the case of special applications like Aircraft and stationary turbine engines where the bearings have to undergo high speed and higher temperature environment, high quality alloy steels are preferred most. Of the alloy steels, high quality High speed Steel as per AMS 6491B (M50) is one of the most widely used materials for aircraft applications. The attempt to machine such high quality steel for the specified application was taken up for the first time and the experiences, findings / problems encountered during machining are reported in this paper.

Bearing rings

Ball Bearing mainly consists of two parts viz. Outer race called Ring Outer and Inner race called Ring Inner. These bearing rings are required to be manufactured out of high quality high-temperature bearing steel M50 HSS. It is high carbon medium alloy steel consisting of important carbide forming elements like Chromium, Molybdenum and Vanadium. The composition of the material is given in Table-1. The extent of temperature ranges that are encountered during service is from -54°C to 150°C.

Table-1: Chemical Composition of HSS M50

Element	**Percentage**	
	min	max
Carbon	0.80	0.85
Chromium	4.00	4.25
Cobalt	-	0.25
Copper	-	0.1
Manganese	0.15	0.35
Molybdenum	4.00	4.50
Nickel	-	0.15
Phosphorus	-	0.015
Silicon	-	0.25
Sulphur	-	0.008
Tungsten	-	0.25
Vanadium	0.90	1.10

Problems faced and methodology followed

Generally, Inner and Outer rings of the ball bearings are processed individually from separate bar stocks. But in this venture, an economical way of manufacture was followed considering the cost and availability of raw material. The raw material for the two rings was prepared by trepanning on the face of the material followed by parting to separate

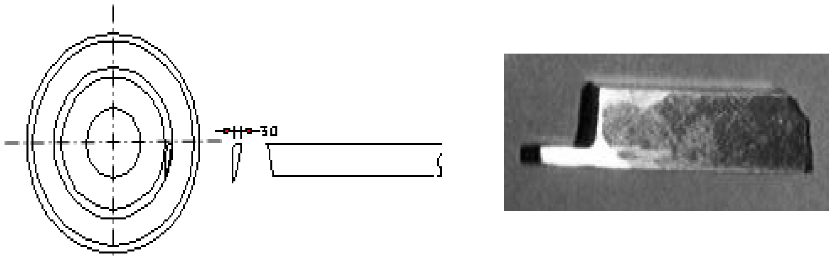


Fig.1: Trepanning Tool

Them into two pieces thereby saving considerable raw material. Trepanning on the face was attempted with thin and costly face grooving inserts and tool holders. Since the ratio of groove width to depth (aspect ratio) required to be trepanned is quite high, frequent breakage of inserts was encountered due to production of continuous chip during grooving of annealed material and chip clogging. Thus a novel method of trepanning the groove using a simple grooving tool was attempted which was found very successful. The grooving tool developed in-house is shown in Fig. 1.

The trepanning operation is carried out by initially face grooving to a certain depth and parting off the required thickness of the rings. Then the parted ring is reversed & held in lathe and face grooving to the remaining depth is carried out thus separating the inner and outer rings. This method of trepanning is shown in Fig.2.

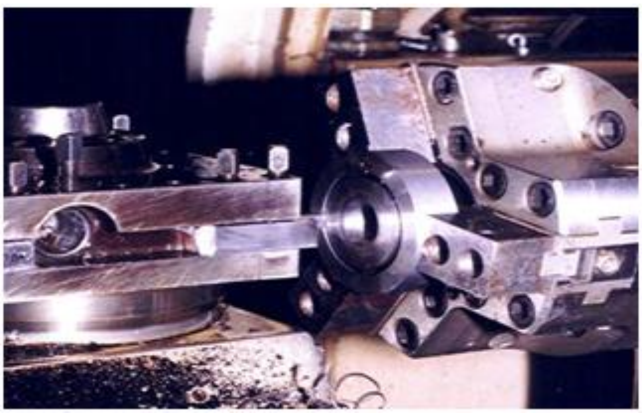


Fig. 2 Trepanning on a CNC lathe

After trepanning, the two rings were processed individually on CNC Lathes by developing suitable Mandrels. The raceway grooves are usually formed using form tools in production environment. But since the semi finishing operation was carried out in annealed state, the grooving operation using form tools was found to be unsuccessful. The surface finish could not be maintained due to excessive chattering due to higher contact area during forming. Also the ductile nature of the spherodite structure of the material leads to continuous chip production, burr formation in the tool exit point and to some extent formation of built-up edge on the tool face. Thus the use of form tool for raceway grooving was suspended and resorted to standard single point tools.

During raceway form turning, the burr formation was noticed at tool exit point. Hence the cutting parameters were modified suitably. Initially, taking standard data from the standard metal cutting Data Handbook, the cutting conditions were set. But the data given in the books are particular to the ideal conditions; hence considering wall thickness and work piece clamping rigidity the cutting parameters were optimized by conducting several trials. The optimized cutting data is shown in Table-2. Tool built-up normally arises due to higher friction and contact pressure between the tool face and underside of the flowing chip. Increasing the cutting speed, reduction of temperature by administering sufficient coolant and judicial selection of turning insert, which is having low coefficient friction, can reduce this problem. Hence Titanium Nitride coated P30 grade cemented carbide copy turning insert, which is having positive rake geometry, was selected and used and thereby alleviated contact pressure and ensured clean cutting during form turning.

Table-2: Optimized cutting parameters

Cutting conditions		
Operation	Speed (rpm)	Feed mm/rev
Roughing	500 rpm	0.05
Finishing	700 rpm	0.03

Even with all these efforts the required circularity could not be maintained owing to the slim wall thickness and annealed condition (soft state) of the work piece. To obviate this problem, it was resorted to clamp the components using hydraulic chuck in a CNC Lathe. As the contact pressure on the jaw points is the primary candidate for problems like ovality, it was decided to use collet type holding arrangement wherein more area could be brought into contact with chucking surface. Thus a collet type special holding arrangement, which is in the softer state, was devised and used to clamp the external surface of the ring inner and to clamp the ring inner, a close toleranced parallel type mandrel was used. The soft state of the collet type chuck jaws acted like soft jaw thus close tolerance could be achieved and also speed of operation could be enhanced. The hydraulic clamping helped to control the contact pressure. The Special collet type arrangement and mandrels are shown in Fig. 3&4.

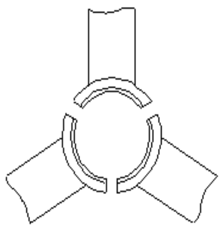


Fig. 5: Collet type holding Device

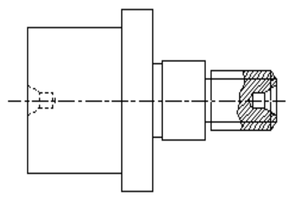


Fig. 6: Mandrel

The raceway profile was inspected using contour checking instrument and the radii of the grooves were inspected using custom-built ball type Go and No-Go gauges. With these efforts the Inner and Outer rings of the ball bearings were successfully machined to the required dimensional and geometrical parameters.

V. CONCLUSION

Machining technologies for Magnesium alloy casings cast with mini core technology has been developed, established and technology transfer effected. High precision gears have been developed and technology was made available to government and private industries.

The maiden approach to develop thin hyperbolic sectioned Flexible Titanium alloy diaphragm was most successful.

The initial attempts for the indigenous development of aircraft bearings using M50 alloy bearing steel have shown promising results beaconing the path for success.