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A Study of 4 Cylinder Engine Crank shaft

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ABSTRACT

Crankshaft is one of the largest components in the internal combustion engine that has a complexGeometry consisting of cylinders as bearings and plates as the crank webs. Aim of the project is to find out life cycle of crankshaft, inputs are given by OEM's original equipment manufacturer. Based on the inputs static analysis is carried out for three materials to find out best suitable material for crank shaft. Based on the static results the fatigue analysis is carried out for the suitable material component and design improvements will be based on fatigue test. Transient analysis is must for any automotive component, further decided design dynamic analysis is carried out to check the dynamic behavior and finally all the analysis are carried out to find out the best design for crank shaft. Kinematic analysis is carried out to find out the crank angle with respect to force. About 720degrees the crank shaft is rotated and checked at different rpm's what is the force acting at each angle is to find. Design is developed using CATIA V5 software and imported in to Altair Hypermesh, Static, fatigue and dynamic analysis are carried out using Altair Optistruct solver. Using Altair Hyperview post processing is visualized. Altair Hyper graph is to visualize the graphical plots for dynamic analysis results.

Keywords: Crankshaft, OEM, Catia V5

INTRODUCTION

OVERVIEW:

A crankshaft converts linear motion of the pistons into rotary motion. It is an important part in all types of engines employed in applications like aircrafts, reciprocating compressor, marine engines, vehicle engines as well as diesel generators.

In an internal combustion engine, the reciprocating motion of the piston is linear and converted to rotary motion through crankshaft. A crankshaft consists of main journals, web, and connecting rod journals commonly known as "crank pins". The crankshaft rotates on bearing inside the engine. Large multi-cylinder engines usually have more than two main bearing at the ends and include center part of the crankshaft for support. The piston connects to the crank shaft on bearing journal called as crank pin. Crank pins are offset from the central rotating axis of the crankshaft using the piston to move, when the crankshaft rotates, the web create the offset between the central axis and crankpin. The no of crank pin depends on type of engine and type of cylinders where multi-cylinder engine will have one crank pin for piston when all cylinders are in a line. If it is a V-engine two pistons will attach to the same crank pins. Crankshaft will be classified by the no of "crank throws" or "simple throws", where a simple throw is a combination of two webs and crank web. For straight four cylinders engine will have four crank pins. Crank shaft should be balanced if not damage to the engine may cause as well as vibration are recognized. Balancing of crankshaft partly achieved by counter balance weight on crank shaft.

Crankshaft is among the largest components in internal combustion engines. It is employed in different types of engines, from small one cylinder lawn-mowers to large multi-cylinder diesel engines. Crankshaft is one of the most critically loaded components and experiences cyclic loads in the form of bending and torsion during its service life. Figure 1 shows a typical automotive crankshaft consisting of main journals (located on shaft centerline), connecting rod journals (located off-centerline), a trust bearing journal, cranks that connect the journals and hold the component together, and a number of auxiliary parts.

FUNCTION OF CRANKSHAFT:

The function of crankshaft in an internal combustion engine is to translate the linear motion of the piston into rotary motion and this rotary motion can use to power the device. The most common type engine is the four cycle engine which uses the Otto cycle or diesel cycle.

Those four cycles are intake, compression, combustion, exhaust.

Intake cycle: The piston moves down and air-fuel mixture is drawn into the cylinder through intake valve.

Compression cycle: The piston moves up compressing the air-fuel mixture in the compression cycle.

Combustion cycle: The compressed air –fuel mixture is ignited at the top of the compression stroke. When gases in the combustion chamber ignite results in expansion and enlarge force on the piston, the force pushes the piston down resulting in rotation of crankshaft.

Exhaust cycle:- The exhaust valve open the gases in the cylinder are forced out during the upward motion of the piston as the crankshaft rotates. The entire process results in 720 degrees rotation of crankshaft each cycle takes 180 degrees to complete.

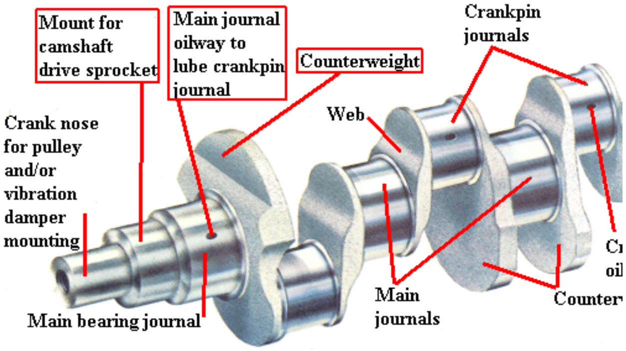

Fig 1: Crankshaft in 4 cylinder diesel engine

CRANK SHAFT FAILURES:

The failure of crank shaft can damage other engine components including the connecting rod or engine blocks. Crankshaft failures often occur in crankpin fillet areas. Fatigue is the primary cause of failure of crankshafts due to the cyclic loading and presence of stress concentration at the fillets. Fatigue crack initiation was observed at critical location of the crankshaft and high stresses found at fillets in crankshaft. While sharp corners can be avoided with the use of fillets other measures are often necessary in order to increase the fatigue performance of crankshafts.

Failures of crankshafts are classified in to three categories:

1. Operating sources
2. Mechanical sources
3. Repairing sources

Operating sources: Things such as misuse of engine and a lack of lubrication,

Mechanical sources: failures can include misalignment or vibration of crankshaft due to balance issues repairing sources: These are caused by repair to an engine or finishing of a crankshaft such as improper grinding, incorrect bearing or mis-alignment.

Fatigue failure starts with a crack at some point in the material. The cracks are likely to be occur in the following regions. (i) Regions of discontinuity, such assoil holes, keyways, screw threads, etc., (ii) Regions of irregularities in machining operations such as scratches on the surface, stamp mark, inspection mark, (iii) Internal crack due to material defect like blow holes. These regions are subjected to stress concentration due to crack. The crack spreads due to fluctuating stresses, until the cross-section of the component is so reduced that the remaining portion is subjected to sudden fracture.

PURPOSE OF STUDY:

Fatigue analysis is performed to predict the life of the crankshaft finally the geometry and material were optimized for the crankshaft and static and fatigue analysis are performed again to predict the best life and service of the crankshaft.Crankshaft is a large component with a complex geometry in the engine, which converts the reciprocating displacement of the piston to a rotary motion with a four link mechanism. Since the crankshaft experiences a large number of load cycles during its service life, fatigue performance and durability of this component has to be considered in the design process. Design developments have always been an important issue in the crankshaft production industry, in order to manufacture a less expensive component with the minimum weight possible and proper fatigue strength and other functional requirements. These improvements result in lighter and smaller engines with better fuel efficiency and higher power output.

Function of Crankshafts in IC Engines

The crankshaft, connecting rod, and piston constitute a four bar slider-crank mechanism, which converts the sliding motion of the piston (slider in the mechanism) to a rotary motion. Since the rotation output is more practical and applicable for input to other devices, the concept design of an engine is that the output would be rotation. In addition, the linear displacement of an engine is not smooth, as the displacement is caused by the combustion of gas in the combustion chamber. Therefore, the displacement has sudden shocks and using this input for another device may cause damage to it. The concept of using crankshaft is to change these sudden displacements to a smooth rotary output, which is the input to many devices such as generators, pumps, and compressors. It should also be mentioned that the use of a flywheel helps in smoothing the shocks.

Service Loads and Failures Experienced by Crankshafts

Crankshaft experiences large forces from gas combustion. This force is applied to the top of the piston and since the connecting rod connects the piston to the crankshaft, the force will be transmitted to the crankshaft. The magnitude of the force depends on many factors which consist of crank radius, connecting rod dimensions, weight of the connecting rod, piston, piston rings, and pin. Combustion and inertia forces acting on the crankshaft cause two types of loading on the crankshaft structure; torsional load and bending load.There are many sources of failure in the engine. They could be categorized as operating sources, mechanical sources, and repairing sources (Silva 2003). One of the most common crankshaft failures is fatigue at the fillet areas due to bending load caused by the combustion. Even with a soft case as journal bearing contact surface, in a crankshaft free of internal flaws one would still expect a bending or torsional fatigue crack to initiate at the pin surface, radius, or at the surface of an oil hole.

Due to the crankshaft geometry and engine mechanism, the crankshaft fillet experiences a large stress range during its service life. Figure shows a crankshaft in the engine block from side view. In this figure it can be seen that at the moment of combustion the load from the piston is transmitted to the crankpin, causing a large bending moment on the entire geometry of the crankshaft. At the root of the fillet areas stress concentrations exist and these high stress range locations are the points where cyclic loads could cause fatigue crack initiation, leading to fracture.

History of crankshaft:

The **crankshaft**, sometimes abbreviated to *crank*, is responsible for conversion between reciprocating motion and rotational motion. In a reciprocating engine, it translates reciprocatinglinearpiston motion into rotational motion, whereas in a reciprocating compressor, it converts the rotational motion into reciprocating motion. In order to do the conversion between two motions, the crankshaft has "crank throws" or "crankpins", additional bearing surfaces whose axis is offset from that of the crank, to which the "big ends" of the connecting rods from each cylinder attach.It is typically connected to a flywheel to reduce the pulsation characteristic of the four-stroke cycle, and sometimes a torsional or vibration damper at the opposite end, to reduce the torsional vibrations often caused along the length of the crankshaft by the cylinders farthest from the output end acting on the torsional elasticity of the metal.

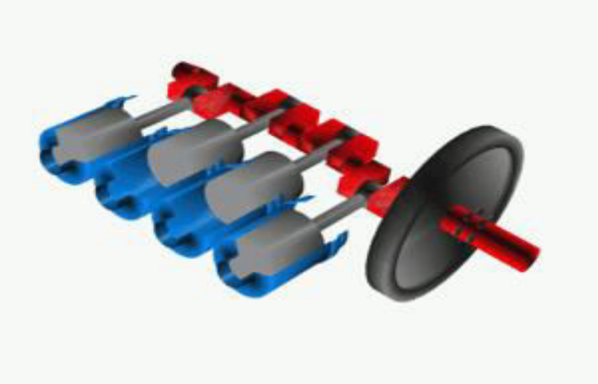

Fig 2: Crank Shaft attached to fly wheel

Fatigue strength:

The fatigue strength of crankshafts is usually increased by using a radius at the ends of each main and crankpin bearing. The radius itself reduces the stress in these critical areas, but since the radius in most cases is rolled, this also leaves some compressive residual stress in the surface, which prevents cracks from forming.

Construction:

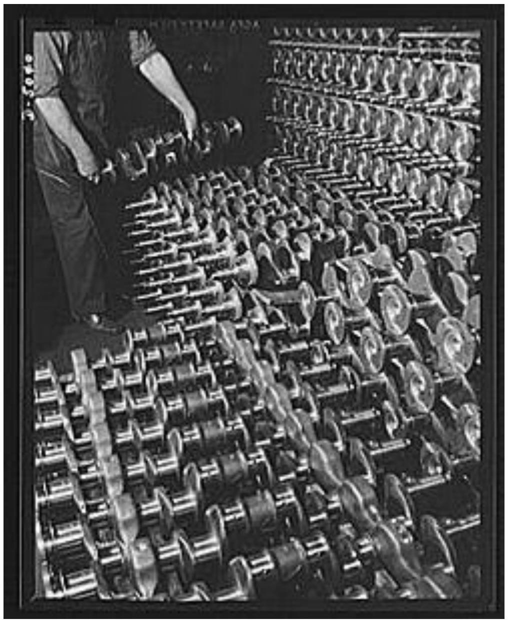

Fig 3: Continental engine marine crankshafts, 1942

Crankshafts can be monolithic (made in a single piece) or assembled from several pieces. Monolithic crankshafts are most common, but some smaller and larger engines use assembled crankshafts.

FORGING AND CASTING:

Fig 4: **forged crankshaft**

Crankshafts can be forged from a steel bar usually through roll forging or cast in ductile steel. Today more and more manufacturers tend to favor the use of forged crankshafts due to their lighter weight, more compact dimensions and better inherent dampening. With forged crankshafts, vanadiummicroalloyed steels are mostly used as these steels can be air cooled after reaching high strengths without additional heat treatment, with exception to the surface hardening of the bearing surfaces. The low alloy content also makes the material cheaper than high alloy steels. Carbon steels are also used, but these require additional heat treatment to reach the desired properties. Iron crankshafts are today mostly found in cheaper production engines (such as those found in the Ford Focus diesel engines) where the loads are lower. Some engines also use cast iron crankshafts for low output versions while the more expensive high output version use forged steel.

Machining:

Crankshafts can also be machined out of a billet, often a bar of high quality vacuum remelted steel. Though the fiber flow (local inhomogeneities of the material's chemical composition generated during casting) doesn’t follow the shape of the crankshaft (which is undesirable), this is usually not a problem since higher quality steels, which normally are difficult to forge, can be used. These crankshafts tend to be very expensive due to the large amount of material that must be removed with lathes and milling machines, the high material cost, and the additional heat treatment required. However, since no expensive tooling is needed, this production method allows small production runs without high costs.

In an effort to reduce costs, used crankshafts may also be machined. A good core may often be easily reconditioned by a crankshaft grinding process. Severely damaged crankshafts may also be repaired with a welding operation, prior to grinding, that utilizes a submerged arc welding machine. To accommodate the smaller journal diameters a ground crankshaft has, and possibly an over-sized thrust dimension, undersize engine bearings are used to allow for precise clearances during operation.

Hardening

Most production crankshafts use induction hardened bearing surfaces, since that method gives good results with low costs. It also allows the crankshaft to be reground without re-hardening. But high performance crankshafts, billet crankshafts in particular, tend to use nitridization instead. Nitridization is slower and thereby more costly, and in addition it puts certain demands on the alloying metals in the steel to be able to create stable nitrides. The advantage of nitridization is that it can be done at low temperatures, it produces a very hard surface, and the process leaves some compressive residual stress in the surface, which is good for fatigue properties. The low temperature during treatment is advantageous in that it doesn't have any negative effects on the steel, such as annealing. With crankshafts that operate on roller bearings, the use of carburization tends to be favored due to the high Hertzian contact stresses in such an application. Like nitriding, carburization also leaves some compressive residual stresses in the surface.

Stress on crankshafts

The shaft is subjected to various forces but generally needs to be analyzed in two positions. Firstly, failure may occur at the position of maximum bending; this may be at the centre of the crank or at either end. In such a condition the failure is due to bending and the pressure in the cylinder is maximal. Second, the crank may fail due to twisting, so the conrod needs to be checked for shear at the position of maximal twisting. The pressure at this position is the maximal pressure, but only a fraction of maximal pressure.

A crank is an arm attached at right angles to a rotating shaft by which reciprocating motion is imparted to or received from the shaft. It is used to convert circular motion into reciprocating motion, or vice-versa. The arm may be a bent portion of the shaft, or a separate arm or disk attached to it. Attached to the end of the crank by a pivot is a rod, usually called a connecting rod. The end of the rod attached to the crank moves in a circular motion, while the other end is usually constrained to move in a linear sliding motion.

The term often refers to a human-powered crank which is used to manually turn an axle, as in a bicyclecrankset or a brace and bit drill. In this case a person's arm or leg serves as the connecting rod, applying reciprocating force to the crank. There is usually a bar perpendicular to the other end of the arm, often with a freely rotatable handle or pedal attached.

Engines:

Almost all reciprocating engines use cranks (with connecting rods) to transform the back-and-forth motion of the pistons into rotary motion. The cranks are incorporated into a crankshaft.

Mechanics

The displacement of the end of the connecting rod is approximately proportional to the cosine of the angle of rotation of the crank, when it is measured from top dead center (TDC). So the reciprocating motion created by a steadily rotating crank and connecting rod is approximately simple harmonic motion:

$$x = r\cos\alpha + l$$

Where x is the distance of the end of the connecting rod from the crank axle, l is the length of the connecting rod, r is the length of the crank, and α is the angle of the crank measured from top dead center (TDC). Technically, the reciprocating motion of the connecting rod departs from sinusoidal motion due to the changing angle of the connecting rod during the cycle, and is expressed (see Piston motion equations) as:

$$x = r\cos\alpha + \sqrt{l^2 - r^2\sin^2\alpha}$$

This difference becomes significant in high-speed engines, which may need balance shafts to reduce the vibration due to this "secondary imbalance".

The mechanical advantage of a crank, the ratio between the force on the connecting rod and the torque on the shaft, varies throughout the crank's cycle. The relationship between the two is approximately:

$$\tau = Fr\sin\alpha$$

Where $\tau$is the torque and F is the force on the connecting rod. But in reality, the torque is maximum at crank angle of less than α = 90° from TDC for a given force on the piston. One way to calculate this angle is to find out when the conrod smallend (piston) speed becomes the fastest in downward direction given a steady crank rotational velocity. Piston speed x' is expressed as:

$$x' = -r\sin\alpha - \frac{r^2\sin\alpha\cos\alpha}{\sqrt{l^2 - r^2\sin^2\alpha}}$$

For example, for rod length 6" and crank radius 2", numerically solving the above equation finds the velocity minima (maximum downward speed) to be at crank angle of 73.17615° after TDC. Then, using the triangle sine law, it is found that the crank to conrod angle is 88.21738° and the conrod angle is 18.60647° from vertical (see Piston motion equations#Example).

When the crank is driven by the connecting rod, a problem arises when the crank is at top dead centre (0°) or bottom dead centre (180°). At these points in the crank's cycle, a force on the connecting rod causes no torque on the crank. Therefore if the crank is stationary and happens to be at one of these two points, it cannot be started moving by the connecting rod. For this reason, in steam locomotives, whose wheels are driven by cranks, the two connecting rods are attached to the wheels at points 90° apart, so that regardless of the position of the wheels when the engine starts, at least one connecting rod will be able to exert torque to start the train.

Rinklegarg and Sunil Baghl. [1] Have been analyzed crankshaft model and crank throw were created by Pro/E Software and then imported to ANSYS software. The result shows that the improvement in the strength of the crankshaft as the maximum limits of stress, total deformation, and the strain is reduced. The weight of the crankshaft is reduced .There by, reduces the inertia force. As the weight of the crankshaft is decreased this will decrease the cost of the crankshaft and increase the I.C engine performance.

C.M. Balamurugan et al [2] has been studied the Computer aided Modeling and Optimization of crankshaft and compare the fatigue performance of two competing manufacturing technologies for automotive crankshafts, namely forged steel and ductile cast iron. The Three dimensional model of crankshaft were created by solid edge software and then imported to Ansys software. The optimisation process included geometry changes compatible with the current engine, fillet rolling and results in increased fatigue strength and reduced cost of the crankshaft, without changing connecting rod and engine block.

Gu Yingkui, Zhou Zhibo. [3] have been discussed a three-Dimensional model of a diesel engine crankshaft were established by using PRO/E software and analytical ANSYS Software tool, it shows that the high stress region mainly concentrates in the knuckles of the crank arm & the main journal and the crank arm & connecting rod journal ,which is the area most easily broken.

Abhishekchoubey, and JaminBrahmbhatt.[4] have been analyzed crankshaft model and 3-dimentional model of the crankshaft were created by SOLID WORKS Software and imported to ANSYS software. The crankshaft maximum deformation appears at the centre of crankpin neck surface. The maximum stress appears at the fillets between the crankshaft journals and crank cheeks and near the central point journal. The edge of main journal is high stress area.

R. J. Deshbhratar, and Y.R Suple.[5] have been analyzed 4- cylinder crankshaft and model of the crankshaft were created by Pro/E Software and then imported to ANSYS software The maximum deformation appears at the centre of crankshaft surface. The maximum stress appears at the fillets between the crankshaft journal and crank cheeks, and near the central point. The edge of main journal is high stress area. The crankshaft deformation was mainly bending deformation under the lower frequency. And the maximum deformation was located at the link between main bearing journal and crankpin and crank cheeks. So this area prones to appear the bending fatigue crack.

Materials and Manufacturing Processes:

The major crankshaft material competitors currently used in industry are forged steel, and cast iron. Comparison of the performance of these materials with respect to static, cyclic, and impact loading are of great interest to the automotive industry. A comprehensive comparison of manufacturing processes with respect to mechanical properties, manufacturing aspects, and finished cost for crankshafts has been conducted by Zoroufi and Fatemi (2005).

This Section discusses forging and casting processes as the two competing manufacturing processes in crankshaft production industry. Influencing parameters in both processes are detailed. Finally, the forged steel and the cast iron products are compared in terms of material properties and manufacturing processes.

Forging Process and the Influencing Parameters

Forging is the term for shaping metal by plastic deformation. Cold forging is done at low temperatures, while conventional hot forging is done at high temperatures, which makes metal easier to shape. Cold forgings are various forging processes conducted at near ambient temperatures, such as bending, cold drawing, cold heading, coining, and extrusion to produce metal components to close tolerances and net shape (http://www.jobshop.com/, 2007). Warm forging is a modification of the cold forging process where the workpiece is heated to a temperature significantly below the typical hot forging temperature, ranging from 500º C to 750º C (http://www.forging.org/, 2007). Compared with cold forging, warm forging has the potential advantages of reduced tooling loads, reduced press loads, increased steel ductility, elimination of need to anneal prior to forging, and favorable as-forged properties that can eliminate heat treatment (http://www.qcforge.net/, 2007). The use of the lower temperatures in cold and warm forging processes provides the advantages of reducing and even substantially eliminating the harmful scale or oxide growth on the component as well as enabling the component to be produced to a high dimensional accuracy (Koike and Matsui, 2001).

Despite these advantages, cold and warm forging processes have the limitations of close tolerance and net shape of the final component with the workpiece. Hot forging is the plastic deformation of metal at a temperature and strain rate such that recrystallization occurs simultaneously with deformation, thus avoiding strain hardening (http://www.jobshop.com/, 2007). Since crankshafts have complex geometries, warm and cold forging of the component is not possible. Therefore, crankshafts are manufacture using the hot forging process.

In impression (or closed die) hot forging two or more dies are moved toward each other to form a metal billet, at a suitable temperature, in a shape determined by the die impressions. These processes are capable of producing components of high quality at moderate cost. Forgings offer a high strength to weight ratio, toughness, and resistance to impact and fatigue, which are important factors in crankshaft performance.

In closed die forging, a material must satisfy two basic requirements: (a) The material strength (or flow stress) must be low so that die pressures can be kept within the capabilities of practical die materials and constructions, and (b) The capability of the material to deform without failure (forgeability) must be sufficient to allow the desired amount of deformation.

By convention, impression and closed die forging are considered to be hot working operations. In most practical hot forging operations, the temperature of the work-piece material is higher than that of the dies. The metal flow and die filling are largely determined by (a) the forging material's resistance to flow and ability to flow, i.e. its flow stress and forgeability, (b) the friction and cooling effects at the material interface and (c) the complexity of the forging shape. A multi-cylinder crankshaft is considered to have a complex geometry, which necessitates proper workpiece and die design according to material forgeability and friction to have the desired geometry (Altan et al., 1983).

Lubrication

In hot forging, in addition to lubrication effects, the effects of die chilling or heat transfer from the host material to the colder dies must be considered. Therefore, values of the friction factor, or coefficient of friction, obtained under certain forging conditions may not be applicable under other conditions. For example, for a given lubricant, friction data obtained in hydraulic press forging cannot be useful in mechanical press or hammer forging, even if the die and billet temperatures are comparable (Altan et al., 1983).

Shape complexity in forging

The main objective of forging process design is to ensure adequate flow of the metal in the dies so that the desired finish part geometry can be obtained without any external or internal defects. Metal flow is greatly influenced by part or die geometry. Often, several operations are needed to achieve gradual flow of the metal from an initially simple shape (cylinder or round cornered square billet) into the more complex shape of the final forging (Altan et al., 1983).

Heat treatment

All hot forged parts receive a certain amount of heat treatment in the process of being forged and, thereafter, may be used without additional heat treatment. For maximum usefulness, however, many forgings are heat treated one or more times before being put into service. For instance, bearing sections and fillet areas on crankshafts are heat treated in order to improve fatigue and wear properties of the material at these certain locations. Usually forgings are heat treated before and after their machining. The purpose of the initial treatment is to secure uniform structure of the metal and contribute to ease of machining of the forged part. The final treatment makes it possible to use the finished forgings for the service intended. For example, forged tools must be hard and tough, consequently, they must receive final hardening and tempering treatments (http://www.sme.org/, 2007). Today, microalloy steels are widely used for manufacturing forged steel crankshafts. The microalloyed steel can effectively eliminate the need for additional heat-treating, reducing the cost of forgings by 5% to 10% to the final cost (http://www.steel.org/, 2007).

Straightening and coining

When the flash is trimmed from the drop forging, the shape may become distorted, which is common in forged crankshafts because of geometry section changes and non-uniform cooling during forging process. Correction of this condition may be necessary. Correction to a certain degree may be accomplished by hammering the distorted forging in a special re-striking die. The correction is made while the forging cools. Other re-striking operations, called coining, are conducted on powerful and accurate presses after the forgings have cooled to room temperature. The forgings are brought to the correct size and shape in these presses, and final machining operations ordinarily performed are either entirely or partially eliminated (http://www.engineersedge.com/, 2007).

Microalloy steels provide more consistent mechanical properties, improved steelmaking and metal forming processes such as rolling and reduced surface flaws with less distortion than heat-treated forged steel. This reduces the need for straightening in the forging process and increases the machinability of the forged steel (http://www.steel.org/, 2007).

Casting Process and the Influencing Parameters

Casting is a manufacturing process by which a molten material such as metal or plastic is introduced into a mold, allowed to solidify within the mold, and then ejected or broken out to make a fabricated part. Casting is used for making parts of complex shape,such as crankshafts, that would be difficult or uneconomical to make by other methods (such as machining from solid material).

Sand-mold casting is adaptable to a very wide range of alloys, shapes, sizes, and production quantities. Hollow shapes can be produced in these castings through the use of cores. Sand-mold casting is by far the most common casting process used in the industry; some estimates are that as many as 90% of industrial castings use the sand-mold casting process (http://www.makinamuhendisi.com/, 2007).

Green sand

Green sand refers to the fact that water is added to activate the clay binder. Green sand-mold casting involves mixing sand with a suitable clay binder (usually a bentonite clay) and other additives, and packing the sand mixture tightly around a pattern that is constructed from the part design, but the pattern is not an exact replica of the part since various dimensional allowances must be made to accommodate certain physical effects. For most metals and most sizes and shapes of casting, green sand molding is the most economical of all the molding processes.

The moisture present in green sand produces steam when contacted by hot metal. Inability of the steam and other gases to escape causes problems with some casting designs, and blowhole damage results. The dimensional accuracy of green sand casting is limited. Even with small castings, it is seldom that dimensions can be held closer than ±0.5 millimeter (http://www.makinamuhendisi.com/, 2007).

Dry sand molds

Dry sand molding is a sand casting process using a mold made of greensand which is dried in an oven to remove the moisture and increase its strength. The absence of moisture eliminates the formation of water vapor and reduces the type of casting defects that are due to gas formation. The cost of heat, the time required for drying the mold, and the difficulty of handling heavy molds without damage make the process expensive compared to green sand molding, and it is used mostly when steam formation from the moisture present would be a serious problem (http://www.castsolutions.com/, 2007).

Skin drying

Most of the benefits of dry sand molds can be obtained by skin drying molds to depths from a fraction of an inch to an inch. With the mold open, the inside surfaces are subjected to heat from torches, radiant lamps, hot dry air, or electric heating elements to form a dry insulting skin around the mold cavity. Skin-dried molds can be stored only for short periods of time before pouring, since the water in the main body of the mold will redistribute itself and re-moisturize the inside skin (http://www.castsolutions.com/, 2007).

Comparison of Forging and Casting Processes

To some extent, forging and casting are competitive, even where different materials are involved with each process. As a general rule, the tooling investment is higher for forging than for casting. Thus, the use of forging tends to be restricted to applications in which the higher material properties of steel compare to cast iron or the higher properties of wrought steel compared to cast steel can be made use of in the design. Because forgings compete best in high strength applications, most producers take particular care in raw material selection and inspection. In many cases, either forging or castings may have adequate properties, and one process has no universal economic advantage over the other.

Some characteristics of castings as compared to forgings are as follows:

- Castings cannot obtain the strengthening effects of hot and cold working. Forging surpasses casting in predictable strength properties, producing assured superior strength consistently.
- A casting has neither grain flow nor directional strength and the process cannot prevent formation of certain metallurgical defects. Pre-working forge stock produces a grain flow oriented in directions requiring maximum strength. Dendritic structures, alloy segregations and like imperfections are refined in forging.
- Casting defects occur in a variety of forms. Because hot working refines grain pattern and imparts high

strength, ductility and resistance properties, forged products are more reliable. And they are manufactured without the added costs for tighter process controls and inspection that are required for casting.

- Castings require close control of melting and cooling processes because alloy segregation may occur. This results in non-uniform heat-treatment response that can affect straightness of finished parts. Forgings respond more predictably to heat treatment and offer better dimensional stability.
- Some castings, such as special performance castings, require expensive materials and process controls, and longer lead times. Open-die and ring rolling are examples of forging processes that adapt to various production run lengths and enable shortened lead times.

In spite of the aforementioned advantages of forgings over castings, castings may be an economical alternative, depending on part functionality requirements, production volume, and other considerations.

Operating Conditions and Failure of Crankshafts

Crankshaft is one of the largest components in the internal combustion engine that has a complex geometry consisting of cylinders as bearings and plates as the crank webs. Geometry section changes in the crankshaft cause stress concentration at fillet areas where bearings are connected to the crank webs. In addition, this component experiences both torsional and bending load during its service life. Therefore, fillet areas are locations that experience the most critical stresses during the service life of the crankshaft. As a result, these locations are main sections of fatigue failure of the component. The size of a crankshaft depends on the number of cylinders and horsepower output of the engine. The size of the crankshaft could range from 3.2 kg for a single cylinder engine with the output power of 12 hp, to 300 tons for a fourteen cylinder diesel engine with the output power of 108,920 hp.

In an internal combustion engine, two load sources apply force on the crankshaft. The load applied by combustion in the combustion chamber to the piston is transmitted to the crankpin bearing by a four bar slider-crank mechanism. This is the main source of loading in the engine. The other load source is due to dynamic nature of the mechanism. Since the engine operates at high speeds, the centrifugal forces are present at different rotating components such as connecting rods. These load sources apply both torsional and bending load on the crankshaft.

Silva (2003) classifies the cause of journal bearing failure or damage (jagged journals) to three possible sources; "(a) operating sources such as oil absence on carter, defective lubrication of journals, high operating oil temperature, improper use of the engine (over-revving); (b) mechanical sources such as misalignments of the crankshaft on the assembling, improper journal bearings (wrong size), no control on the clearance size between journals and bearings, crankshaft vibration; (c) repairing sources such as misalignments of the journals (due to improper grinding), misalignments of the crankshaft (due to improper alignment of the crankshaft), high stress concentrations (due to improper grinding at the radius on both sides of the journals), high surface roughness (due to improper grinding, origination of wearing), improper welding or nitruration, straightening operation, defective grinding, the assembling, improper journal bearings (wrong size), no control on the clearance size between journals and bearings, crankshaft vibration; (c) repairing sources such as misalignments of the journals (due to improper grinding), misalignments of the crankshaft (due to improper alignment of the crankshaft), high stress concentrations (due to improper grinding at the radius on both sides of the journals), high surface roughness (due to improper grinding, origination of wearing), improper welding or nitruration, straightening operation, defective grinding.

Another crack detection method was introduced by Baxter (1993). He studied crack detection using a modified version of the gel electrode technique. In this technique the critical location of the crankshaft was covered by a thin (~0.5 µm) polymer film. After the fatigue test, the surface was inspected with a gel electrode probe. Applying a voltage between the electrode as cathode and the crankshaft as anode, induced a current to flow to any fatigue sites in the contact area. Information was displayed qualitatively as a direct image of the fatigue sites and quantitatively as the spatial distribution of charge flow to the surface. This technique could identify both the primary fatigue cracks and a distribution of secondary sites of less severe fatigue damage. The most useful aspect of this study is that the ELPO film can be applied before or after the fatigue test, and in both cases.

Dynamic Load Determination and Analysis

Jenson (1970) performed an experimental study to determine the load applied to a V8 crankshaft. The load determination in this study started with the selection of the crankshaft sections to be investigated.

In order to measure the bending and torsion loads applied to each section of the crankshaft, bending and torsion strain gage bridges were mounted in pairs. After mounting the strain gages, the crankshaft was carefully assembled in the engine and then the engine was completely assembled and installed on a dynamometer stand. The loads at several speed increments were recorded to capture peak bending and torsion loads, which in general do not occur at the same crankshaft angle.

Henry et al. (1992) implemented the dynamic load in their FEM model with consideration of internal centrifugal, external bearing, and torsional dynamic loads. In their study, internal loads were calculated by assuming constant FEM mass forces. Therefore, for any engine speed, the resulting displacements were calculated only once. Considering the classical gas and inertia forces acting on the crankpin bearings result in external bearing loads. A statistically determinate method or an indeterminate one was used to calculate the journal bearings reactions considering the clearances and engine block compliance. And finally a classical mass-spring model with harmonic response was created in order to calculate the dynamic twisting moments. The result was the crank internal moment at each throw and throughout the cycle. Only one torsional displacement calculation was performed per throw, and the displacements at each cycle step were scalar multiples of these results.

An analytical investigation on bending vibrations was done for a V6 engine by Mourelatos (1995). He used a crankshaft system model (CRANKSYM) to analytically verify a vibration problem related to the flywheel for the mentioned crankshaft. As described in their study, CRANKSYM could perform an analysis considering the crankshaft structural dynamics, main bearing hydrodynamics and engine block flexibility. The program considers the gyroscopic effect of the flywheel, loads applied on the belt, crankshaft bent and block misboring, and the anisotropy of the block flexibility as seen from a rotating crankshaft. This program could also calculate the dynamic stress history on the crankshaft during the whole engine cycle. The CRANKSYM requires a finite element mesh of the whole crankshaft assembly. The output of CRANKSYM includes the natural frequencies of the crankshaft-flywheel system, the bearing loads with respect to an engine fixed coordinate system, and the axial displacement of a point on the outer perimeter of the flywheel. In this program the crankshaft structural analysis predicts the crankshaft dynamic response based on the finite element method.

The classical model of crankshaft vibration was used in Payer et al. (1995) studies to determine the time dependent displacement-vector x of the crankshaft for the calculation of its transient stress behavior. The following equation was used in their studies:

DESIGN AND MANUFACTURING CONSIDERATIONS

A thorough conceptual design process for a crankshaft requires input design data from the engine specifications and operating conditions, design task including design for rigidity, static strength and durability, and manufacturing processes and considerations. According to this flowchart, preliminary dimensions are specified based on the engine design data and previously designed comparable components. This preliminary design should be verified for rigidity, deformations, static strength, and fatigue strength under different load-case scenarios (i.e. bending, torsion, and combined bending and torsion loading conditions) considering appropriate factors of safety. Other design factors such as lubrication requirements, frequencies of vibration in torsion and bending and engine sound level are to be included afterwards. When the basic requirements of the preliminary design are fulfilled, alternative manufacturing processes should be evaluated to obtain the most feasible and cost effective manufacturing plan. Following preparation of manufacturing plan and simulating the processes, a prototype component should be manufactured and tested to verify the design requirements. A detailed flowchart including a step-by-step calculation procedure for crankshaft conceptual design is provided by Dubensky (4).

Crankshafts are typically manufactured by casting and forging processes. Manufacturing by forging has the advantage of obtaining a homogeneous part that exhibits less number of microstructural voids and defects compared to casting. In addition, directional properties resulting from the forging process help the part acquire higher toughness and strength in the grain-flow direction. While designing the forging process for crankshaft, the grain-flow direction can be aligned with the direction of maximum stress that is applied to the component (along the axis of the shaft and

Related to bending).

According to Shamasunder (1), there are three typical stages in crankshaft forging; reducer rolling (to prepare a perform), blocker forging (to give a basic profile to the perform), and finisher forging (to give the desired contours to the crankshaft). In each stage, a well-planned deformation is induced to ensure metal flow into the die cavity in both top and bottom dies. As the forging continues, top and bottom dies squeeze the billet. Each point in the workpiece moves in a particular direction with a specific velocity as determined by the die cavity profiles. Metal flow pattern will result in a complete filling of the die cavity to produce a sound forging quality. Grain flow pattern is an indicator of forging quality as well as directional strength.

Manufacturing of the blank forged crankshaft could be followed by a number of post-processing steps including machining, heat treatment, induction hardening, and surface rolling. The heat treatment step is not applied if micro alloyed steels are selected as materials of construction for the crankshaft, lending to considerable cost saving. A typical procedure of the post-processing stage of a 42CrMo4 alloy steel crankshaft including machining, heat treatment and surface hardening. The forging process is followed by annealing to remove the unwanted residual stresses generated by the refinement procedure applied to forgings. The annealed parts are subject to straightening after quenching and tempering, to correct for deformations due to the heat treatment. Additional annealing is then performed to remove the residual stresses generated during straightening. Next, in the machining stage, the part is turned and ground to obtain the required dimensions and tolerances. Finish grinding should be carefully selected to avoid the occurrence of unfavorable tensile residual stress distributions that would remain in the material even after induction surface hardening and grinding and would reduce fatigue strength of the material. Induction surface hardening is followed by stress annealing if the depth of the surface hardening is smaller than the depth of the damaged layer, since in this way it is possible to change the unfavorable stress state in the surface layer induced by machining. After induction surface hardening, the magnitude and distribution of residual stresses should be such that they contribute to the fatigue strength of the material. Induction surface hardening is followed by finish grinding and non-destructive magnetic inspection of the surface to reveal the possible existence of cracks.

Fillet rolling has traditionally been used to induce compressive residual stresses at the crankshaft fillets. The compressive residual stress generated at this critical area increases fatigue life of the component. Optical measurements at the deep-rolled crankshaft fillets show that the amount of compressive residual stress increases significantly in the axial direction, which coincides with the direction of bending stresses the component is subject to (6). In addition, prior to rolling crankshaft fillets, the stress gradients are very high near the fillet surface such that the stress magnitude drops very quickly with increasing distance away from the fillet surface (7). This makes the process of fillet rolling quite beneficial.

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Park et al. (8) studied the effect of nitriding and fillet rolling on fatigue life of crankshafts made of microalloyed steel and quenched and tempered alloy steel. These experiments indicate that surface modification can increase endurance limit of crankshaft significantly. Both fillet rolled (at 900 kgf of rolling) and nitride samples show more than a factor of 1.8 increases in fatigue limit. In addition, it was found that higher rolling force induces higher compressive residual stress on the crank surface, leading to better endurance limit characteristics. Nevertheless, with residual stress reaching a certain optimum level, additional load only results in plastic deformation that is detrimental to fatigue limit. This optimum residual stress could be found experimentally or numerically using FEA. It should be noted that Gligorijevic et al. (9) reported a factor of 1.3 improvements in fatigue strength of nodular cast iron diesel engine crankshafts after nitriding.

Gundlach et al. (10) investigated the influence of fillet rolling and shot-peening in austempered ductile iron that is commonly used as an alternative for forged steel in manufacturing crankshafts and camshafts. Fillet specimens had tangential fillets of 1.02 mm, 1.52 mm, or 3.05 mm radius. They found that fillet rolling improves the fatigue strength of all three fillet geometries considered. They suggest that the fillet rolling force be increased as the fillet radius increases to attain the same degree of compressive stress and subsequently obtain comparable improvements in fatigue strength. Using

Optimum conditions for fillet rolling will improve the fatigue strength of the filleted specimens equal to or even above that of the smooth specimens. They also found that shot peening also improves the fatigue strength of the filleted specimens, but to a lesser degree than fillet rolling. Although the compressive residual surface stress by shot peening was higher than that of the fillet rolled specimens, the depth of penetration of the compressive stress developed by shot peening was appreciably shallower than by fillet rolling. However, they emphasized that both shot peening and fillet rolling decrease the notch sensitivity of the ADI and move the fracture from the fillets to the gage section of the test specimens.

Induction surface hardening is also used to induce compressive residual stresses at the critical locations of the crankshaft. A study by Grum (5) shows that significant favorable residual stress ranging from 1020 to 1060 Mpa at a depth of around 250 µm, then slowly dropping to a depth of 3.5 mm to around 800 Mpa, is generated at bearing locations by induction hardening of a forged CrMo steel crankshaft. Therefore, by gently varying the hardness and through compressive residual stresses in the transition area, it is possible to reduce the detrimental effect of the notch induced by stress concentration in parts under cyclic loading. However, according to the same study, a major difficulty in induction surface hardening is to ensure a very slight variation in hardness and the existence of compressive residual stresses in transition areas to the hardness of the base material.

PERFORMANCE COMPARISON OF COMPETING MANUFACTURING TECHNIQUES

The major crankshaft material and manufacturing processes currently in use are forged steel, nodular cast iron and austempered ductile iron (ADI). Chatterley and Murrell (12) compared fatigue strength of crankshafts made of forged steel, ductile iron and austempered ductile iron by conducting bending fatigue tests. Tests were performed on nitrided 1% chromium/molybdenum forged steel, fillet-rolled ductile iron with 700 Mpa tensile strength and 2% elongation, and fillet-rolled ADI (the austempered version of the ductile iron used). All crankshafts were designed to operate within a 4-cylinder turbo-charged diesel engine. The fatigue tests were carried out on a constant amplitude mechanical stroking machine. The crankshafts were firmly clamped with split

Clamping blocks across two main bearing journals, with the bending moment being applied by means of a moment arm bolted onto an adapter press-fitted onto either the front (nose) or flywheel end of the shafts. Results of the fatigue tests are summarized in 4. Fatigue strength at ten million cycles of the rolled ADI crankshaft was found to be inferior to the forged steel crankshafts. However, the ADI showed better fatigue strength than ductile iron.

Pichard et al. (13) investigated the possibility of replacing the traditional alloyed steels and cast iron with control-cooled microalloyed steel in order to save cost and increase productivity without compromising the mechanical properties including fatigue. Based on the results of their research, 35MV7 control-cooled microalloyed steel shows similar tensile and rotating bending fatigue strength as AISI 4142 quenched and tempered steel, while an improved machinable version of 35MV7 shows 40% higher turning index* and 160% higher drilling index† compared to AISI 4142 quenched and tempered steel. In addition, the behavior of 35MV7 microalloyed steel after induction hardening is equivalent to that of the referenced quenched and tempered steel. For the response to ion nitriding compared to the nitrided heat treated steels such as AISI 4142 and AISI 1042 grades, the surface values are identical, the conventional nitrided depth is greater and the treated layers are more homogeneous for the 35MV7 steel. For short nitriding treatments, the results obtained on the 35MV7 steel are much better than those obtained for AISI 1042 quenched and tempered steel, the fatigue limit increased by about 135%. In comparison with a quenched and tempered highly alloyed steel used in crankshafts (32CDV13) and for short nitriding treatments, the fatigue limit of 35MV7 steel is only 10% lower, while significant cost saving could be made by using 35MV7 steel. When forged steel are compared to cast iron and alloyed ductile iron used in crankshafts, the fatigue properties of forged steels are better that that of cast iron.

Gligorijevic et al. (9) named a number of advantages of nodular cast iron in crankshaft applications. According to them, nodular cast irons combine the favorable characteristics of other ductile materials, such as steel, with other advantages, such as easy machinability, design flexibility (i.e. the free selection of shape of the component and thus the ability to integrate several functions in a single part), high dimensional accuracy of the raw castings and the resultant cost reduction in final machining. They state that nodular cast iron has higher damping capacity and lower notch sensitivity. However, these statements may have overlooked the generally inferior fatigue properties of nodular cast iron compared to steels, and the significant role of casting voids and defects in reducing the crankshaft fatigue strength.

In the study of Gundlach et al. (10) discussed earlier, notch sensitivity of an ADI, namely a grade between ASTM A897 Grade 1 and 2, was investigated. As the severity of the fillet radius increased from 3.0 to 1.5 to 1.0 mm, the fatigue strength at ten million cycles decreased from 335 Mpa to 282 Mpa to 253 Mpa. The results of this study do not agree with those of Chatterley and Murrell (12) discussed earlier with respect to the effect of fillet rolling on durability performance of ADI.

DURABILITY ASSESSMENT OF CRANKSHAFTS

Durability assessment of crankshafts includes material and component testing, stress and strain analysis, and fatigue or fracture analysis. Material testing includes hardness, monotonic, cyclic, impact, fatigue and fracture (crack growth) tests on specimens made from the component or from the base material used in manufacturing the component. Component testing includes fatigue tests under bending, torsion, or combined bending-torsion loading conditions. Dynamic stress and strain analysis must be conducted due to the nature of the loading applied to the component. Complexity of the geometry of most crankshafts necessitates employing finite element analysis tools.

The stress distribution obtained by static analysis due to gas load in the fillet of a crankshaft. Although static analysis is commonly used in designing crankshafts, the nature of loading especially the torsional vibrations makes transient stress analysis inevitable. The fillet has shown to be the most critical location under primary static loading in crankshafts. Nevertheless, performing transient analysis on a three dimensional solid model of a crankshaft is costly and time consuming.

EXPERIMENTAL TECHNIQUES AND BENCH TESTING

Component testing is considered as a required step in durability assessment and its results incorporate the effects of geometry, surface finish, residual stresses, and directionality of properties on fatigue behavior. Because of the high cost of the component and test systems, and complex geometry of multiple-bearing one-piece crankshafts, fractions of the crankshafts consisting of one crank with two coaxially located main journals fixed in the grips of the testing machine are commonly used for fatigue testing. Although this fractionizing somewhat deviates from the real component service conditions, it provides a considerable reduction in the number of specimens and the cost of tests.

Yu et al. (20) and Chien et al. (7) performed resonant bending fatigue tests on SAE J434C D5506 cast iron crankshaft sections. In the first study, resonant frequencies of a resonant bending system with notched crankshaft sections were obtained experimentally and numerically in order to investigate the effect of notch depth on the change of resonant frequency of the system. Resonant frequencies of the resonant bending system with crankshaft sections were obtained before and after introduction of the notches and the frequency drops were compared. The crack propagation in the component could then be related to the frequency drop due to existence of the notches.

As described earlier, Regul'skii et al. (19) performed fatigue tests on a ductile cast iron crankshaft of a motorcycle engine using machines with a crank mechanism for the excitation of alternating stresses are finding out. The cantilever mounted crankshaft fragments were tested in bending on a machine with inertial load excitation by rotating unbalanced masses through the connecting rod and crosshead. According to them, the shortcoming of the cantilever mounting of a crankshaft fragment in bending tests is that the loading pattern in such a mounting differs significantly from that in service, although it is in principle applicable for comparative tests. By fragmenting the crankshaft, a number of masses connected to the system are removed affecting the dynamic response of the system. In addition, as applied to the tests of motorcycle engine crankshafts, this arrangement provides no reduction in the number of the specimens tested, since only one specimen can be cut out from a crankshaft. Also, because of its small length, the whole crankpin would be in the grips, in which case, the fracture zone cannot be monitored.

COST ANALYSIS

A systematic cost estimation of crankshafts is provided in the work of Nallicheri et al. (23). Dividing the cost of crankshafts into variable and fixed cost, they evaluate and compare the production cost of crankshafts made of nodular cast iron, austempered ductile iron, forged steel, and microalloyed forged steel. The common variable cost elements are named as the costs of material, direct labor, and energy. The common elements of fixed cost are named as the costs of main machine, auxiliary equipment, tooling, building, overhead labor, and maintenance. Based on a cost model and assuming estimation parameters for a particular crankshaft made of the four materials and manufacturing processes, while the material costs of all the four processes are essentially similar, the labor cost contribution in the steel forging case is higher than that of nodular castings due to the more complex machining process for steel. The breakdown shows that the ADI and forged steel crankshaft costs are similar, with steel forging being 7% lower in cost than ADI. Since the use of microalloyed steel eliminates the need for heat treatment, it yields savings compared with other processes. Moreover, using microalloyed steel reduces machining costs compared to conventional forging due to eliminating part or all of heat treatment steps.

1. Crankshaft is one of the most critically loaded components of internal combustion engine and experiences cyclic bending and torsion loads during its service life. The main sources of loading are gas load due to the combustion process transmitted to the crankshaft by connecting rods, and inertia load due to the mass of the component and its attachments.
2. Fillets in the crankshaft act as stress raisers and endure the highest level of stress under service loading. They are the critical locations, where cracks can nucleate at a fillet surface due to combined cyclic bending and torsion.
3. Failure sources of crankshafts include oil absence, defective lubrication on journals, high operating oil temperature, misalignments, improper journal bearings or improper clearance between journals and bearings, vibration, high stress concentrations, improper grinding, high surface roughness, and straightening operations.
4. Crankshafts are typically manufactured from forged steel, nodular cast iron and austempered ductile iron (ADI). When forged steels are compared to cast iron and alloyed ductile iron used in crankshafts, the fatigue properties of forged steels are generally found to be better that that of cast iron.
5. Manufacturing by forging has the advantage of obtaining a homogeneous part that exhibits less number of microstructural voids and defects compared to casting. In addition, directional properties resulting from the forging process helps in higher strength in the grain-flow direction. Grain flow pattern is an indicator of forging quality as well as directional strength.
6. Fillet rolling has traditionally been used to induce compressive residual stresses at the crankshaft fillets, making the process of fillet rolling quite beneficial to fatigue strength. Using optimum conditions for fillet rolling will improve the fatigue strength of the filleted specimens equal to or even above that of the smooth specimens.
7. Shot peening also improves the fatigue strength of the fillet, but to a lesser degree than fillet rolling. Although the compressive residual surface stress by shot peening can be higher than that of fillet rolling, the depth of penetration of the compressive stress developed by shot peening may be shallower than by fillet rolling.
8. Induction surface hardening is also used to induce compressive residual stresses at the critical locations of the crankshaft. A challenge in induction surface hardening is to ensure a very slight variation in hardness and the existence of compressive residual stresses with proper magnitude and distribution in transition areas to the hardness of the base material.

9. Because of the high cost of the component and test systems and complex geometry of multiple-bearing one-piece crankshafts, fractions of the crankshafts consisting of one crank with two coaxially located main journals fixed in the grips of a testing machine are commonly used for fatigue testing. Due to lower relative importance oftorsion compared to bending loads, only bending tests are often conducted on crankshafts.
10. Diameter of main journals, length of main journals, diameter of crank-pins and length of crank pins have been considered as design variables in optimizing the geometry of crankshafts. Crank-pin pressure, fatigue safety factor of the main cheek, first mode torsional natural frequency, and the distance from oil hole to the nearest fillet have been used as the constraints in such optimization.
11. The use of microalloyed steel eliminates the need for heat treatment, resulting in cost savings compared to conventional forging of quenched and tempered alloy or carbon steels, while meeting or exceeding the fatigue strength of these steels. In addition, elimination of the heat treatment reduces machining costs.
12. The choice of a cost effective production route for crankshafts is dependent upon the production volume and the requirements of the engine. For high performance
13. Crankshafts with stringent strength requirements and at high volumes, micro alloyed forging steels are most cost effective. ADI crankshafts may be cost effective in low production runs. Cast crankshafts can be cost effective in high volume productions, only if the engine design can accommodate the lower strength.

Finite Element Modeling

Since the crankshaft has a complex geometry for analysis, finite element models have been considered to give an accurate and reasonable solution whenever laboratory testing is not available.Uchida and Hara (1984) used a single throw FEM model shown in chapter 4. In the extrapolation of the experimental equation in their study. In their study the web thickness of a 60° V-6 crankshaft was reduced while maintaining its fatigue performance and durability under turbo-charged gas pressure. In the study of the 60° V-6 engine crankshaft dimensions, the stress evaluation of the crankpin fillet part was extremely critical since, to reduce the crank’s total length, it was necessary to reduce the thickness of the web between main journal and crankpin as much as possible while maintaining itsstrength. FEM was used to estimate the stress concentration factor at thicknesses where confirmed calculation was not available.

A crankshaft durability assessment program based on three dimensional mechanical analyses was developed by RENAULT and was used by Henry et al. (1992) to predict the durability and calculate the fatigue performance of crankshafts. In the program, the stress calculations involved initial 3D FEM analysis with a coarse mesh for the whole crankshaft geometry.

In their durability assessment program, they had chosen a 3D numerical approach. The coarse mesh is used in the whole crankshaft model to avoid cut plane boundary condition approximations. The resulting displacements were then applied to a local small sized BEM fillet model. The resulting BEM fillet stress state was biaxial on the surface, unlike corresponding FEM results. This two-stage FEM/BEM stress calculation method was compared to several other numerical calculations and several crankshaft geometries in their study, which showed increased precision, resulting in improved initial design of a crankshaft.

A theoretical study followed by experimental results was conducted by Guagliano et al. (1993) to calculate the stress concentration factor in a diesel engine crankshaft. They conducted experimental tests by mounting strain gages at high stress concentration areas (crank fillet). A three dimensional model of the crankshaft was generated and numerical calculation was performed according to linear-elastic properties of the material and different loading conditions. Good agreement between experimental results and numerical results indicated the accuracy of stress concentration factor calculation.

An artificial neural network was developed by Shiomi and Watanabe (1995) in order to calculate the stress concentration factor at the crankpin fillet area from dimensional characteristics of the crankshaft. An artificial neural network was used to calculate the stress concentration factor based on mathematical approximations from a database which contained geometry properties of the crankshaft as well as stress concentration factors. In order to construct the database, finite element model of crankshafts with different geometries were created. Stress concentration factors were obtained from these models and results were inserted in the database. The finite element model results in accurate values for stress concentration factor and eliminates inevitable

Measurement errors due to experiments. A large number of mathematical functions had to be solved in order to create the approximation function, but after having the final equation, the stress concentration could be easily calculated for a given crankshaft geometry.

A nonlinear transient stress analysis for the rotating crankshaft of a 6-cylinder inline engine was presented by Payer et al. (1995). A method was shown in their study which enabled the nonlinear transient analysis to be both highly sophisticated and efficient for determining the fatigue behavior of crankshafts. They used a finite element program which uses two major steps to calculate the transient stress behavior of a rotating crankshaft;the strain energy method was used. Stiffness calculated with the solid element model of a crank throw was used to generate the beam mass model.

This model was used for the calculation of the transient deformations of the crankshaft.Prakash et al. (1998) modeled a complete crankshaft using the solid elements ofANSYS software. In order to verify the integrity of the FE model natural frequencies of the model was compared with those obtained from practical measurements. They evaluated the stress amplitudes using mode superposition method. As a prerequisite, reduced modal analysis was required for carrying out the mode superposition analysis. They selected the master degrees of freedom to exactly calculate the first few torsional natural frequencies. This method decouples the equations of motion and reduces computational effort required.An analysis of the stress distribution inside a crankshaft crank was studied by Borges et al. (2002).

The stress analysis was done to evaluate the overall structural efficiency of the crank, concerned with the homogeneity and magnitude of stresses as well as the amount and localization of stress concentration points. Due to memory limitations in the computers available, the crank model had to be simplified by mostly restricting it according to symmetry planes. In order to evaluate results from the finite element analysis a 3D photo elasticity test was conducted. The area of major interest wasthat closest to crankpin bearing, usually critical to bending loads.

Initial tentative meshing was performed over this 3Dgeometry, with several degrees of overall refinement and of local refinement. Due to limitations in computer memories, solving this initial model was not possible. According to experimental information from a photo elastic model, the theoretical model could be geometrically simplified by restricting symmetry planes.

Chien et al. (2005) studied the influence of the residual stress induced by the fillet rolling process on the fatigue process of a ductile cast iron crankshaft. The stress concentration near the fillet area of the crankshaft section was investigated by a 2D elastic finite element analysis in the ABAQUS software. Then, an elastic-plastic 2D plane strain FEA was conducted to obtain the residual stress distributions near the fillet due to the rolling process.A relatively fine mesh near the fillet was generated in order to accurately capture the characteristics of the stress field in this stress concentration area.

Dynamic Load Analysis of crankshaft

The crankshaft experiences a complex loading due to the motion of the connecting rod, which transforms two sources of loading to the crankshaft. The main objective of this study was the optimization of the forged steel crankshaft which requires accurate magnitude of the loading on this component that consists of bending and torsion. The significance of torsion during a cycle and its maximum compared to the total magnitude of loading should be investigated to see if it is essential to consider torsion during loading or not. In addition, there was a need for obtaining the stress variation during a loading cycle and this requires FEA over the entire engine cycle.

The main objective of this chapter is to determine the magnitude and direction of the loads that act on the bearing between connecting rod and crankshaft, which was then used in the FEA over an entire cycle. An analytical approach was used on the basis of a single degree of freedom slider crank mechanism.

The analytical approach was solved for a general slider crank mechanism which results in equations that could be used for any crank radius, connecting rod geometry, and connecting rod mass, connecting rod inertia, engine speed, engine acceleration, piston diameter, piston and pin mass, pressure inside cylinder diagram, and any other variables of the engine.

Stress Analysis and FEA

This stress analysis discusses geometry generation used for finite element analysis, describes the accuracy of the model and explains the simplifications that were made to obtain an efficient FE model. Mesh generation and its convergence are discussed. Using proper boundary conditions and type of loading are important since they strongly affect the results of the finite element analysis. Identifying appropriate boundary conditions and loading situation are also discussed. Finite element models of two components were analyzed; the cast iron crankshaft and the forged steel crankshaft. Since these two crankshafts are from similar engines, the same boundary conditions and loading were used for both. This facilitates proper comparison of this component made from two different manufacturing processes. The results of finite element analysis from these two crankshafts are discussed in this chapter. Above mentioned FE models were used for dynamic analysis considering the boundary conditions according to the mounting of the crankshafts in the engine.

In order to evaluate the FEA results, a component test was conducted with strain gages. FEA boundary conditions were changed according to the test setup. Strain gages were mounted on the forged steel crankshaft and results from FE analysis and experimental data were compared in order to show the accuracy of the FE model.

2.29 Component Specifications and Manufacturing Process

In order to carry out optimization process, it is necessary to have knowledge of the component dimensions, its service conditions, and material of construction, manufacturing process, and other parameters that affect its cost.As can be seen in this table, this high-strength low-alloy steel contains 0.45% carbon resulting in a yield strength of 625 Mpa and fatigue strength of 359 Mpa at 106 cycles (Williams and Fatemi, 2007).

The main manufacturing process of the forged crankshaft is hot forging and machining.

Each step of this flowchart is described below, where the information about the forging and machining processes were obtained from the metal forming books and OEM websites.

1. The row material samples of the AISI 1045 are inspected for chemical composition.
2. The material is shaped and cut to the rough dimensions of the crankshaft.
3. The shaped material is heated in the furnace to the temperature of 900ºC to 1100ºC.
4. The forging process starts with the pre-forming dies, where the material is pressed between two forging dies to get a rough shape of the crankshaft.
5. The forging process continues with the forging of the pre-formed crankshaft to its first definite forged shape.
6. Trimming process cuts the flash which is produced and appears as flat unformed metal around the edge of the component.
7. The exact shape of the forged crankshaft is obtained in the coining process where the final blows of the hammer force the stock to completely fill every part of the finishing impression.
8. The final shaped forged crankshaft is nowready for the shot cleaning process. In this step the scales remained from forging process are removed.
9. The machining process starts with the facing and centering of the total length size. The facing process is a machining operation that is a form of turning in which the tool is fed at right angles to axis of work piece rotation to produce flat surface. Centering refers to aligning the bearings of the component according to the final dimensions.
10. After alignment of all diameters the turning process will give a rough shape of cylinder to all cylindrical portions.
11. CAM turning is the process used to produce cylindrical components, typically on a lathe. A cylindrical piece of stock is rotated and a cutting tool is traversed along 2 axes of motion to produce precise diameters and depths. Turning can be either on the outside of the cylinder or on the inside (also known as boring) to produce tubular components to various geometries.
12. In the drilling operation, all inner diameters are drilled in the crankshaft geometry. The drilling mainly consists of oil holes.
13. Threads are cut on the inner surface of the bore at the back of the crankshaft and on the outer diameter of the front shaft.
14. Heat treatment is the next step to obtain the desired mechanical properties for the material.
15. Shot blasting consists of attacking the surface of a material with one of many types of shots. Normally this is done to remove scale from the surface.

16. Straightening process by application of external forces eliminates or reduces the curvatures, which can result by deformation during rolling, drawing, extrusion or due to non-uniform cooling. Thickness and geometry changes at different sections of a crankshaft cause non-uniform cooling during the forging process, which results in unwanted curvatures along the forged component.
17. After the straightening process the crankshaft is ready for grinding and being aligned to its final dimensions. Therefore, the grinding begins with the rough grinding of all diameters.
18. Since the crankshaft has eccentric cylinders the diameters have to be grinded using CAM.
19. The final grinding of diameters sets the cylinder diameters to their final acceptable tolerance. This is followed by grinding of other sections such as grooves using CAM.
20. The final step in grinding is face grinding, where the dimensions of the crankshaft will be finalized.

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