İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

MANUFACTURING, TESTING AND COST ANALYSES OF CRANKSHAFTS

M.Sc. Thesis by
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Programme : Material and Manufacturing

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KRANK MİLİ ÜRETİMİ ,TEST EDİLMESİ VE MALİYET ANALİZİ

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FOREWORD

I would like to express my deep appreciation and thanks for my advisor Prof. Dr. Turgut Gülmez who leads this thesis. Without his experience and support my thesis can not be completed

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Tolgahan Kaya

Mechanical Engineering

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ABBREVIATIONS

T_AIR : Inlet air temperature
S415_FSN : Exhaust Smoke measurement
P_OIL : Oil pressure
T_OIL : Oil temperature
T_MAN : Inlet manifold air temperature
TWO : Engine water outlet temperature
SFC : Specific fuel consumption
Boost_pr : Boost Pressure
EGR : Exhaust Gas Recirculation
CS : Carbon Steel
AS : Alloy Steel
CS-HS : High Sulphur Carbon Steel
AS-HS : High Sulphur Alloy Steel
MA : Micro Alloy
ADI : Austenite Ductile Iron
T_FUEL_I : Fuel inlet temperature
T_FUEL_O : Fuel outlet temperature
P_FUEL_I : Fuel inlet pressure
P_FUEL_O : Fuel outlet pressure

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MANUFACTURING, TESTING AND COST ANALYSES OF CRANKSHAFTS

SUMMARY

Increasing competition in the market forces the manufacturing technology to improve quality and to lower the cost. Nowadays automotive companies are trying to get high power from very small engines with low fuel consumption. Currently, 1 litter turbocharged diesel engines with 90kW maximum power is available in the market.

Possible solutions to lower the cost is to reduce the weight and not to over engineered components in the design. Moreover improved surface treatment and heat treatment processes allow to strength the components.

Among thousand components in the engine crankshaft is one of the most complex, expensive and advanced product. Even if forging method is expensive many automotive company prefer to use forged crankshaft in their design to be safe side, not to face with a problem during the life of the engine. However different manufacturing methods and materials are available that result in altered mechanical properties.

Casting and forging are the main manufacturing methods for automotive industry, indeed for metal components production. Ductile steels, carbon steels, austempered steels, microalloyed steels are mostly used materials for metal components.

Carburizing, nitriding, heat treatment, inducing residual stress are the surface treatment methods to improve the mechanical properties of the produced components.

Available manufacturing methods, materials and surface treatment methods have different cost affect to final component. Reducing the cost reduce the mechanical properties, improving mechanical properties increase the unit price of the crankshaft. Annual volume is another parameter affects the unit cost.

As there are many alternative to produce a crankshaft there is high opportunity to lower the cost. Due to the high opening in the cost reduction many companies and universities work on crankshaft and build cost models for manufacturing of crankshaft in details MIT's one is looking over than 200 parameters [25].

Dubensky mentioned that it is important to found optimum design. In order to achieve this first force requirement of the system have to be analysed. Once system necessity is set, available material and methods that can fulfil the requirements should be thought.

In this thesis an alternative cast crankshaft is manufactured instead of a forged crankshaft. Forged crankshaft is in production however studies show that it is possible to replace it with cast one although it may have lower mechanical properties. Developed cast crankshaft is tested with high speed idle test for 250,000km which corresponds to lifetime of the engine.

Cast crankshafts successful completion of the test indicates that it can fulfil the engine requirements and can be used instead of forged crankshaft.

KRANK MİLİ ÜRETİMİ, TEST EDİLMESİ VE MALİYET ANALİZİ

ÖZET

Pazarda artan rekabet üretim teknolojisini daha kaliteli ve daha ucuz ürünler ortaya koyması için zorlamaktadır. Son zamanlarda otomotiv firmaları küçük motorlardan yüksek güç ve düşük yakıt tüketimi elde etmeye çalışıyor. Günümüzde 90kW güç üreten 1 litrelik turbolu dizel motorlar mevcutdur.

Maliyetleri düşürmenin muhtemel yolları ağırlıkları azaltmak ve aşırı güvenli tasarımlar yapmamaktır. Bunlara ek olarak gelişen yüzey setleştirme işlemleri ve ısıl işlemler daha yüksek mukavemette parçalar üretmemizi sağlıyor.

Motorda bulunan 1,000 parça içerisinde en kompleks, pahalı ve gelişmiş olanlarından birisi krankmilidir. Dövme işleminin pahalılığına rağmen, aşırı korumacı bir yaklaşım ile çoğu otomotiv firması tasarımlarında dövme krankmili kullanmaktadır. Fakat farklı üretim yöntemleri ve malzemeler sayesinde değişik mukavemette ürünler elde edilebilir.

Otomotiv endüstrisinde kullanılan temel üretim yöntemleri döküm ve dövmedir. Sünek çelik, östemperlenmiş çelik, alaşımsız çelikler, mikroalaşımlı çelikler metal parçaların üretimi için kullanılan malzeme çeşitlerinin başlıcalarıdır.

Karbürleme, nitrürleme nitrokarbürüzasyon gibi yüzey sertliği artırıcı uygulamalar mekanik özelliklerin iyileştirilmesi için uygulanan başlıca yüzey işleme yöntemlerdir.

Mevcut üretim yöntemleri, malzeme ve yüzey işleme çeşitlerinin üretilecek olan parçaya farklı maliyet etkisi bulunmaktadır ve nihai fiyatı etkilemektedir. Maliyeti düşürmek, mekanik özelliklerin azalmasına, mekanik özelliklerin iyileştirilmesi ise maliyet artışına sebep olmaktadır. Yıllık üretim miktarı ise birim fiyatı etkileyen diğer bir önemli etkendir.

Krankmili üretiminde çok fazla değişken olduğu için maliyet azaltma ihtimalide yüksektir. Maliyet azaltma ihtimalinin yüksek olmasıda birçok şirket ve üniversitenin bu konu üzrinde çalışmasını ve maliyet hesabı çıkaran detaylı modeller hazırlamalarını sağlamıştır. MIT üniversitesi tarafından hazırlanmış bir model 200'den fazla değişkene göre sonuç çıkarmaktadır [25].

Dubensky tasarım yaparken en uygun tasarımın yapılması gerektiğini vurgulamktadır. Bunu başarabilmek içinde sistemin gereksinimleri bulunmalıdır. Sistemin gereklilikleri belirlendikten sonra, mevcut malzeme ve üretim yöntemlerinden gereklilikleri sağlayacak bir tasarım düşünülmelidir [4].

Bu tezde dövme krankmiline alternatif olarak döküm kranmili üretilmiştir. Dövme krankmili piyasadaki mevcut motorlarda kullanılıyor olmasına rağmen Çalışmalar sonucunda daha düşük mukevemet değerlerine sahip döküm krankmili ile değişebilceği anlaşılmıştır. Geliştitilen döküm krankmili 250,000km yani motor ömrü kadar yüksek hızlı rodaj testi ile test edilmiştir.

Döküm krankmilinin testi başarılı olarak tamamlaması, döküm krankmilinin motor gerekliliklerini tam olarak sağlayabildiğini ve dökme krankmili yerine kullanılabilceğini göstermiştir.

1. INTRODUCTION

Internal combustion engines are converting the chemical energy of the fuel to mechanical energy. They are one of the main power sources for over hundred years in power stations, vehicles and agricultural applications. There are approximately thousand of component in the engine and crankshaft is one of the largest and complex geometry among these components which convert the linear motion desired rotary motion. Over hundred years engines have been manufactured and available in market for sale. To be competitive in the market almost design of all components are very important. In many industries, especially the automotive industry, there is a constant demand for components to be lighter, stronger, and cheaper than current available ones. Therefore all steps of the design for a crankshaft is very important to have a less weight, long life and less expensive products. Companies chase all possible improvements to have smaller engines with better fuel consumption and higher power output.

Constant technology improvement in manufacturing in the speciality of crankshaft is shown in Figure 1.1. Advances in steel making technology are essential for reducing impurities in the materials for crankshafts. The removal of phosphorous and sulphur are especially important along with degassing. As shown in Figure 1.1, we used the tap degassing process until around 1988. Subsequently we employed the ladle furnace process in which the molten steel is transferred from an electric furnace to a ladle and refined in there. The ladle furnace process efficiently removes impurities such as sulphur, and gasses such as oxygen, and is proven to be an effective method of reducing non-metallic inclusions [1].

The down-sizing and high-power generation of diesel engines require higher fatigue strengths of the pin fillets and improved gripping strength of the shrink fit journals. In the last 30 years the yield point of the material has increased by a factor of 1.5.

The most important characteristic of a crankshaft is the fatigue strength of fillets. One way to improve the fatigue strength further is by applying external forces to the material surface. Various improvements have been made on the fillet, cold rolling, equipment to roll in the narrow spaces of the pin fillet between large webs, which are becoming even narrower with the down-sizing of diesel engines.

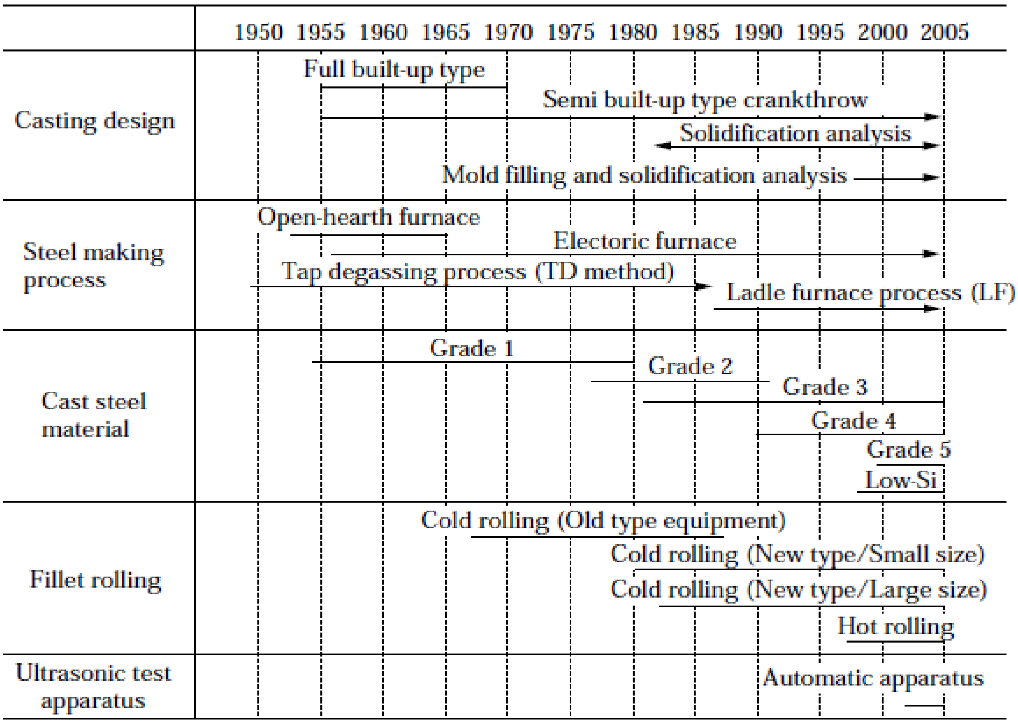


Figure 1.1 : Time table of improvements in manufacturing

As crankshaft is one of the most expensive and complex components and it has a big opportunity to be optimised to have a lighter, cheaper, and stronger design. Therefore the aim of this study is to find an alternative material and manufacturing method for a forged crankshaft of a 2 litter diesel engine.

After brief description of the crankshaft, Dubensky method is described for designing much more optimum crankshaft for the automotive companies [4]. Main manufacturing process of casting and forging is analysed in details and available surface treatment methods is shown with experimental results. Cost analyses of these alternative production methods are investigated via using two different cost models first one created by MIT [14] and the other one by Nallicheri [6].

Performing these analyses and literature review allow to understand all important points and steps of the casting and forging of crankshaft. Material alternatives and surface treatments are learned with their cost effect.

With the knowledge of alternative material, manufacturing and surface treatment methods a new cast crankshaft is designed instead of forged one. Developed cast crankshaft has approximately 10 % lower tensile, yield and toughness than the forged crankshaft however it can pass the durability test and can fulfil its 250,000km working life without any failure. This means forged crankshaft can be replaced with the alternative cast crankshaft with cost reduction of 20 % per piece.

At the end, this study shows that it is possible to replace forged crankshaft of a 2 litter engine with a cast one even if it has lower mechanical properties by achieving 20 % cost reduction.

2. CRANKSHAFTS FOR INTERNAL COMBUSTION ENGINE

2.1 What is Crankshaft?

A crankshaft is designed to convert the up and down motion of the pistons into horizontal rotation. Crankshaft has a wide range of use in the industry, it can convert the linear motion to rotating for one cylinder lawnmower whereas also it can for a very large multi cylinder marine engines. Automobile industry is the most common application area of the crankshafts as it can convert the linear movement of the piston into rotary motion in an internal combustion engine.

2.2 Parts of Crankshaft and Function in Internal Combustion Engine

A crankshaft consists of main journals, webs, counterweights, main bearing journal, connecting pin journals, mount for camshafts drive sprocket, main journal oil way to lube crankpin journal, crankpin oil hole and flywheel mounting flange as shown in Figure 2.1.

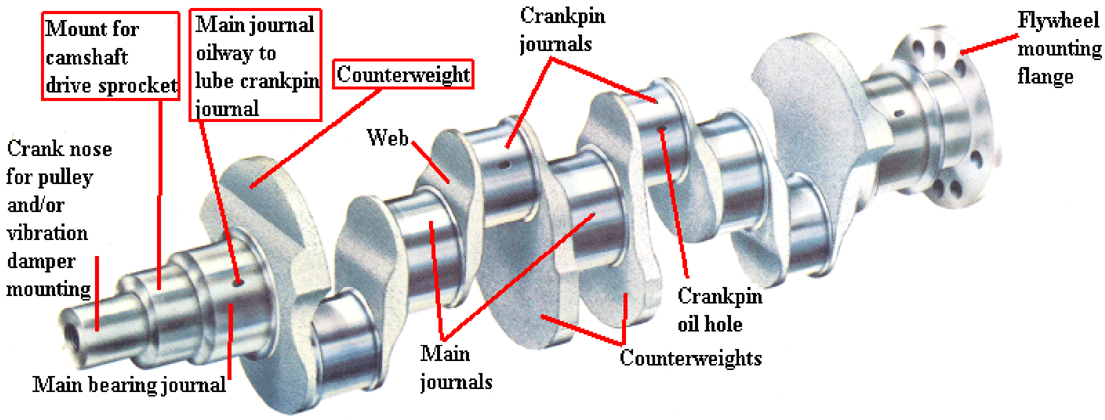


Figure 2.1 : Components of a crankshaft

In this study four cylinder a four cycle diesel engine will be analysed therefore four cylinder crankshafts and engine working principle is explained.

The crankshaft, connecting rod, and piston constitute a four bar slider-crank mechanism that converts the sliding motion of the piston to a rotary motion. As 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.

However displacement is powered by the combustion which has sudden shocks therefore linear displacement is not smooth. Use of another device cannot resist these sudden force fluctuations. As the main concept of a crankshaft is to convert the sudden un-balanced linear displacements to a smooth rotary output, crankshaft is the accepted device for generators, pumps and compressors. Use of crankshaft is the main concept to translate sudden displacements to a smooth rotary output, which is the input to many devices such as generators, pumps, and compressors.

A complete cycle of a four-stroke engine consists of intake, compression, power and exhaust. Figure 2.2 shows these four steps. Top dead center is the initial starting point of the cycle. At this position piston is at farthest away point from the crankshaft.

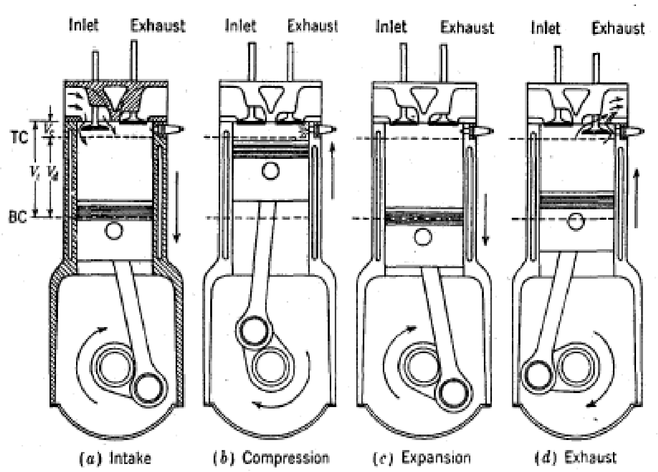


Figure 2.2 : Four step of combustion

In Figure 2.3 and Figure 2.4 mounting schematic of piston, crankshaft, connecting rod, intake valve, exhaust valves, cam shaft and other sub-components can be seen. During the intake cycle, piston move from farthest away point to bottom dead center and air-fuel mixture drawn into the cylinder through the intake valves. First cycle, intake, finishes after intake valves close and second cycle compression starts. Piston again moves to top dead center which compresses the air-fuel mixture inside the combustion chamber. When the piston reaches to top dead center third cycle, power, starts and air-fuel mixture is ignited. This ignition fire up the chemical reaction results in a large force on the piston. This force drives the piston down to the bottom top dead center. This linear motion is converted to rotary motion by crankshaft. When piston reaches to top dead center exhaust cycle finishes and last cycle exhaust starts. In this cycle exhaust valves are opened by cam shaft and the burned gases are forced out through exhaust by the piston motion from bottom to top dead center. All burned gas goes out when piston reaches to top dead center which also means one four stroke cycle is completed. Crankshaft rotates 720 degree, two complete rotations; during the four stroke cycle and each cycle of the engine correspond to 180 degree rotary motion of the crankshaft.

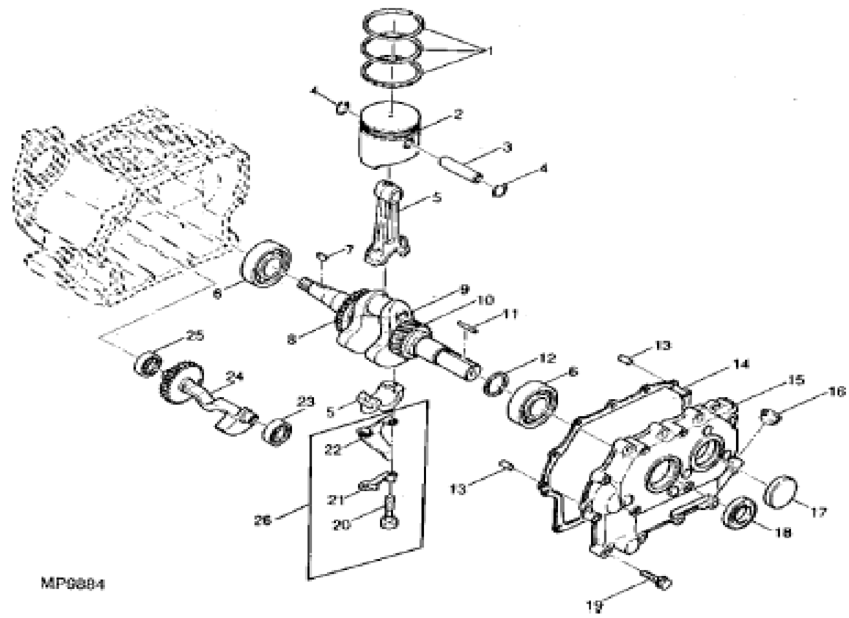


Figure 2.3 : Mounting schematic of engine

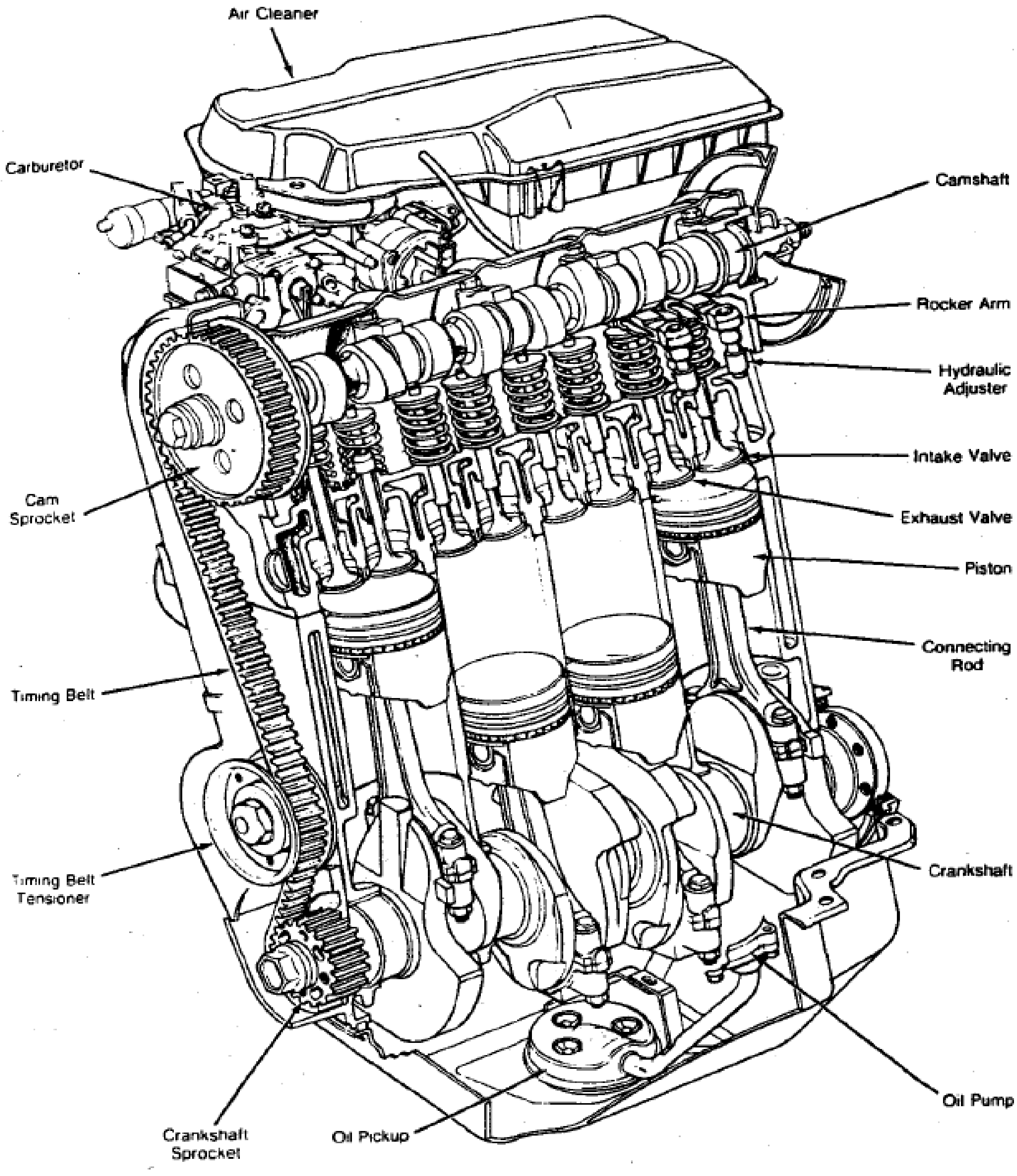


Figure 2.4 : Overview of four cylinder crankshaft

2.3 Design of Crankshaft for Internal Combustion Engines

Automotive product development is a complicated process. Growing competition in the automotive industry improve the expectations of the customers, moreover regulations are getting more and more strict.

As crankshaft is one of the most important engine components its design process is also complicated. Piece cost, design period, manufacturing time, weight and durability targets is set before design initiated.

Dubensky says that there are mainly four steps for an automotive component development namely; concept development stage, pre-production engineering stage, production engineering stage and failure analysis and redesign stage. This may be initial step to start the design however there are many other points have to be considered. Dubensky prepare a crankshaft concept design flow chart from start to a detailed end drawing. Below steps summarize the Dubensky’s flow chart in Figure 2.5 [4];

- Design start with the engine type, bore, stroke, connecting rod, piston mass and ring mass details.
- Crankshaft specifications, material, processing variables, main diameter and length parameters have to be computed according to first inputs.
- Peak torque, power, corresponding gas pressure and turbo charging affect are important parameters are used to calculate rotating mass and reciprocating mass.
- Loads at peak power and torque are used to maximum piston and inertia force on to the crank.
- According to the dimensions of the crankshaft support reactions is calculated.
- Bending moment, normal and torsional bending stress is performed from all load and dimension data calculated up to now.
- Bending fatigue strength is worked out by using relevant equations.

- Safety factor is calculated from Goodman diagram and compared with the initial design goal. If the design acceptable, design is finalized otherwise optimization has to repeat according to the steps as described.

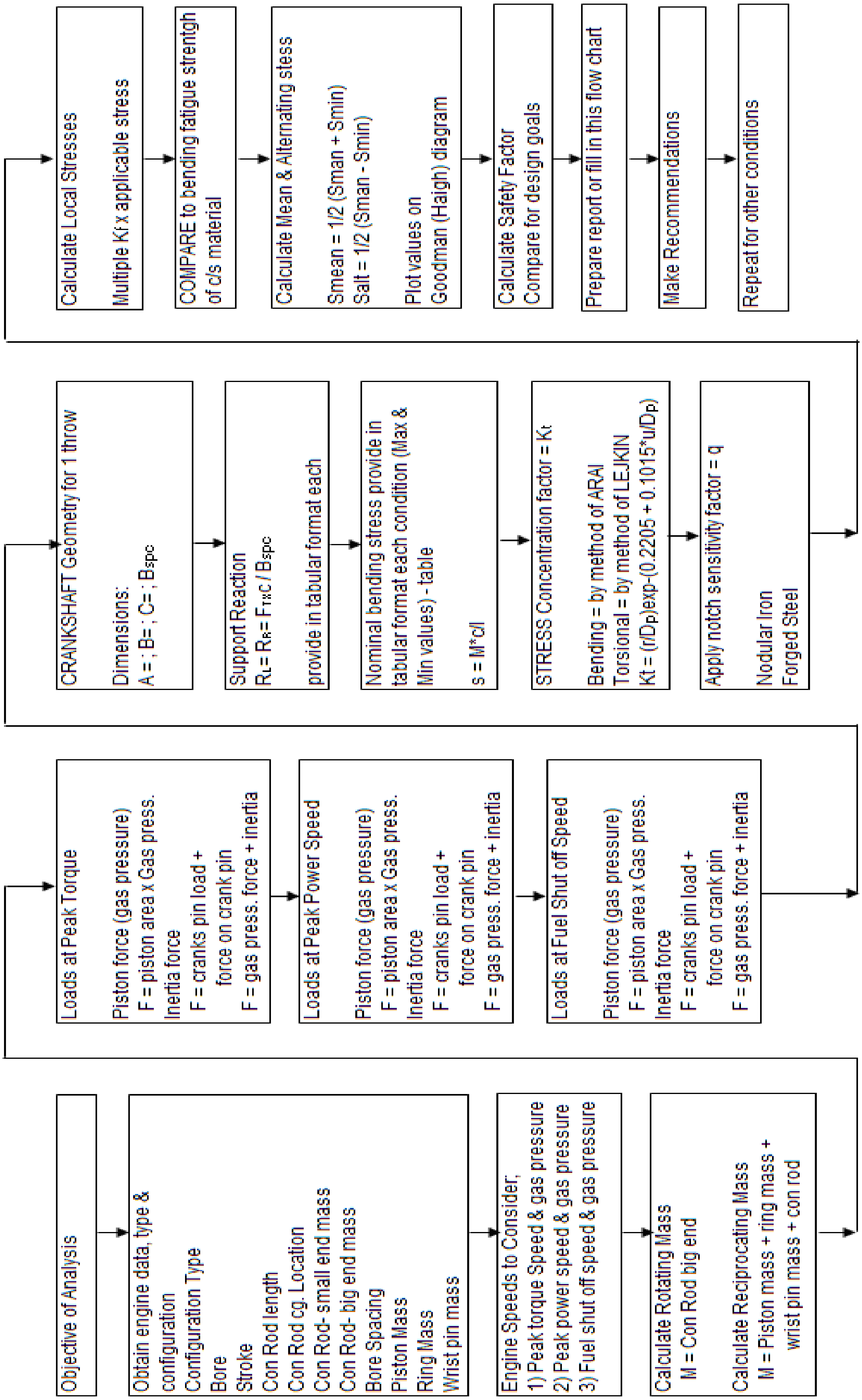


Figure 2.5 : Components of a crankshaft

3. MANUFACTURING OF CRANKSHAFTS

Crankshafts of internal combustion engines have to be designed for infinite life because when crankshaft fails engine cannot be used properly any more. Design of the crankshafts has to be done as described in conceptual design section not to face problems.

Manufacturing is important as conceptual design as it directly affect the mechanical properties of the engine. There are several methods for crankshaft manufacturing process however most common used methods are casting and forging. Sub steps of casting and forging has influence on the properties of the crankshaft.

3.1 Casting

Casting process starts with heating the metal up to its liquid phase and than pouring the molten material into mold and waiting until solidifies in the mold and than solid part is ejected out from the mold. Casting is a very old process that is used to manufacture many different components geometrically complex.

Crankshaft manufacturing by casting may have different sub-steps according to raw material and required mechanical properties. A general method can be seen step by step in Figure 3.1 [8]. Casting design, pattern making, molding, pouring, riser cutting is the common steps that have to be followed for all crankshafts manufacturing by casting. Annealing, fillet rolling, heat treatment are the steps that applied according to design requirements.

Chatterley used cast crankshafts in his comparison study of crankshaft production potential [1]. He describes the manufacturing steps in details. Aluminium construction was used for solid crankshaft pattern. Silica sand with two part setting resin is used for mold material and cranks were poured into this mold. Strip time was 15 minutes and at least 24 hour was waited for hardening. Runner system was integrated a cavity for the Germalloy inoculants at the base of the sprue. 10ppi filter was applied in addition to dross trap. Flat in gate is used for metal flow from feeder. 25 % raw iron, 50 % return scrap and 25 % steel scrap is the charge material composition.

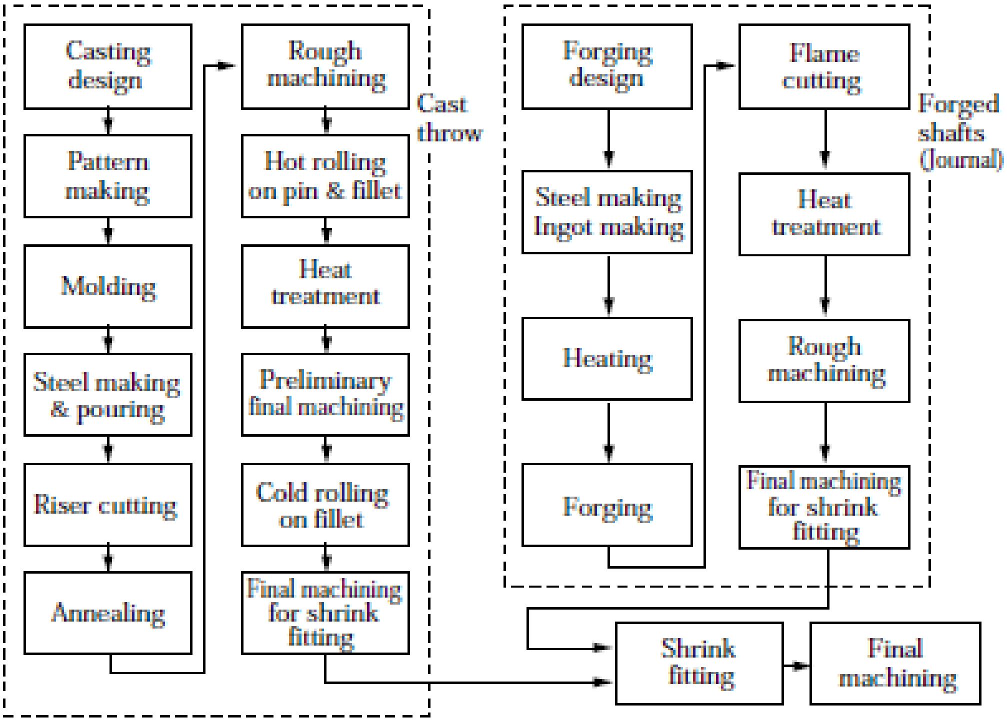


Figure 3.1 : Flowchart of casting process

Charge material was heated to 1520 °C in electric induction furnace. After with sandwich process melted material tapped on to MgFeSi + Ce in the ladle. In mould treatment caused 0.1 % Si addition to the matrix although no inoculation was carried out. Filling the molds take 14 seconds. Final chemical composition is shown in Table 3.1.

Table 3.1: Chemical composition of cast crankshaft

Alloying Element	Percentage by Mass
C	3.46
Si	2.33
Mn	0.16
S	<0.01
P	0.01
Mg	0.048
Ni	1.34
Cu	1.50
Mo	0.14

Machining process follow the casting step. Cast cranks have to be machined according to their technical drawing. As casting can give very draft dimensions of the final product, bulk material were reduced by turning with high speed steel cutting tool. However all processes were not performed with this tool, subsequent operations were carried out with 10 % cobalt/tungsten carbide cutting tools together with TiN (titanium nitride) ceramic coated drills, taps and keyway cutters. Oil holes were drilled before heat treatment process.

Heat treatment process follows the first machining step. Indeed this heat treatment process not applied to all cast cranks. It is a surface treatment method more details given in the surface treatment section. Crankshafts were austenitise at 880°C for 1 hour and than quenched in to molten salt bath at 375°C for 2 hours. Parts reach to room temperature by air cooling after quenching. Heat treatment result in a distortion level in the cranks however it is low and acceptable according to similar studies.

Final machining is applied after heat treatment process to give the tolerance details of the crankshafts. This post heat treatment machining of the part-machined specimens mainly consist of grinding operations of different locations of the crankshafts. Grinding operations were performed to ensure that the crankshafts are in the tolerance according to their technical drawing dimensions.

Inducing residual stress on to the fillets by cold rolling fillet step is performed according to the project requirement and actually it is not a sub-step of casting it is surface treatment process that increases the fatigue strength of the crankshaft. Details of fillet rolling are given in the surface treatment section.

After all operations completed a final grinding operation took place in order to remove the surface roughness and bring the component to its dimensional tolerance.

3.2 Forging

Forging is a manufacturing process involving the shaping of metal using localized compressive forces. Forging process is used to produce a wide range of product. Crankshaft is one these components and in automotive industry most of the companies used cast crankshafts as it allows getting high mechanical properties.

Forging of the crankshaft consist of lots of sub steps which can be seen in Figure 3.2 as a flow chart. These steps are described in metal forming books and a summarized version is available in Fatemi's crankshaft project. These steps are [26];

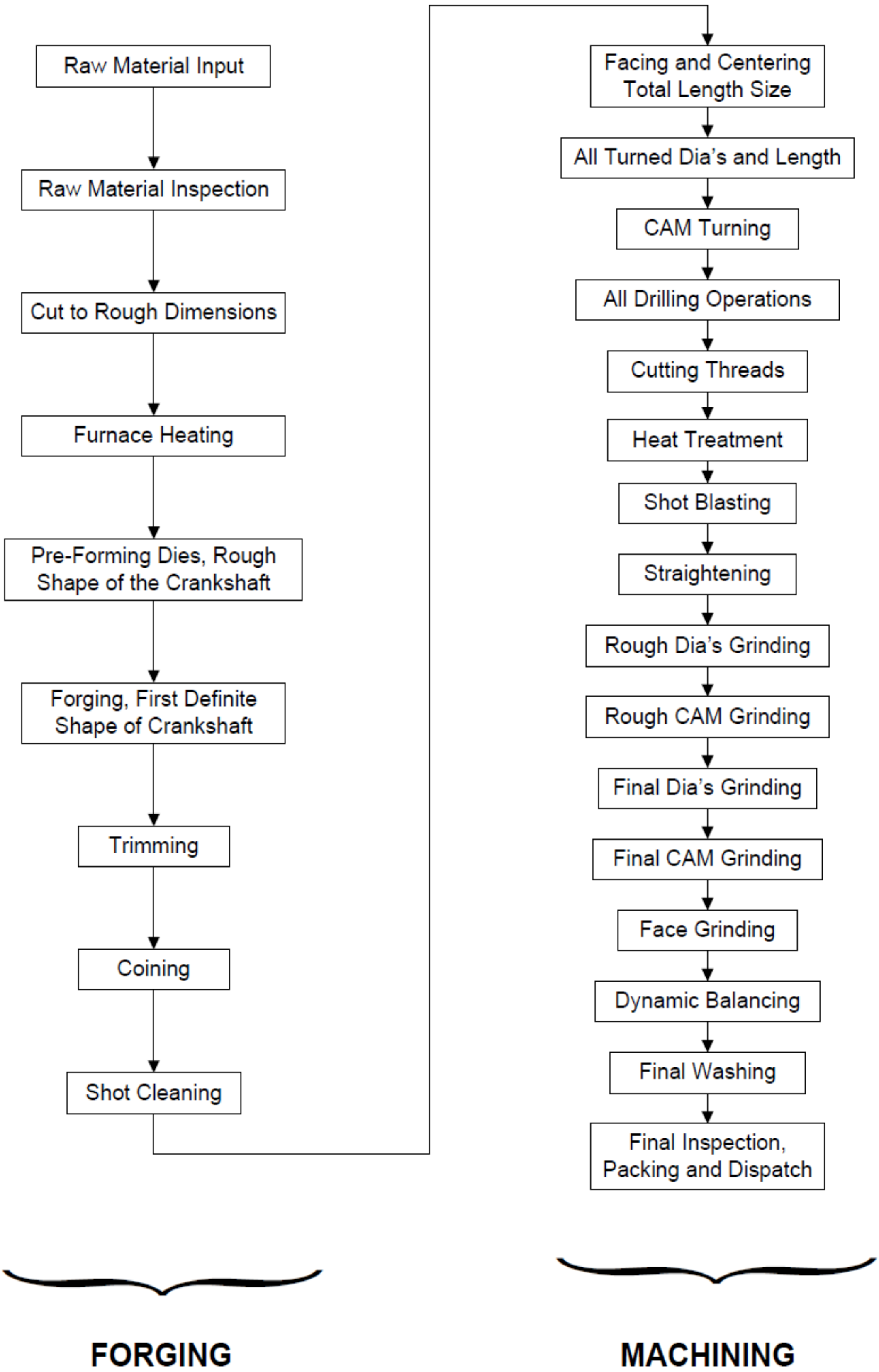


Figure 3.2 : Flow chart forging process

•	Raw material input stage is the selection of the material and AISI 1045 is used in Fatemi's study [5].

•	Raw material inspection stage is consisting of inspecting the chemical composition of the selected material.

•	Cut to rough dimensions stage is the process that raw bar is shape and cut to first rough dimensions.

•	In the furnace heating stage the shaped specimen is heated to the temperature of 900ºC to 1100ºC.

•	Pre-forming dies step is the actual start of the forging process. Specimen is forged in the dies for initial rough shape of the crankshaft.

•	Forging stage is applied after pre-forming to give the first exact shape of the crankshaft

•	Trimming stage follows the forging to cut the flashes around the edge of the component

•	Coining stage is the process which crankshaft gets its exact shape. In this process final blows of the hammer force the body to completely fill every part of the finishing impression. Figure 3.3 show the forging process in sequence. Above described steps can be understood with this figure.

•	Shot cleaning process is applied to remove the scales created during forging processes. Forging steps concluded with application of shot cleaning.

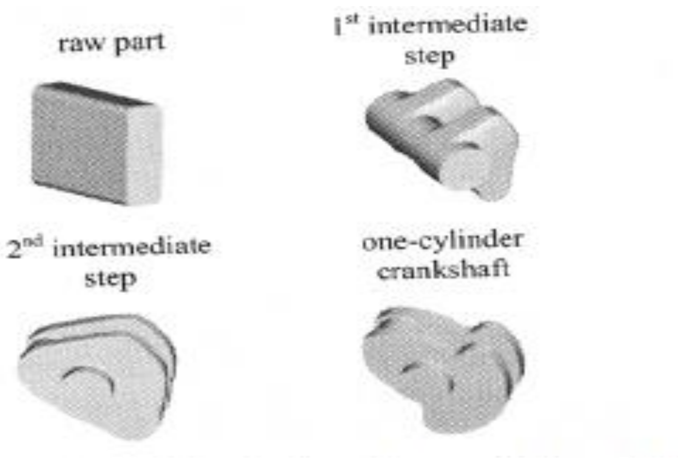


Figure 3.3 : Forging sequence for a one-cylinder crankshaft

- Facing and centering of the total length size is the first step of the machining process. In the facing process flat surfaces are manufactured by turning the face at right angle to axis of workpiece rotation. In centering process crankshafts' bearings are aligned to the final dimensions.

- Turning process is applied to give rough shape of the cylinder to all cylindrical parts.

- CAM turning stage is applied to on a lathe for manufacturing the cylindrical components. Cylindrical components are processed along two axes of motion to produce precise diameters and depths.

- All inner diameters are drilled in the drilling stage. Oil holes are the main drilling places at this stage.

- Cutting thread stage, 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.

- Heat treatment process is applied after thread cutting to get the required mechanical properties.

- Shot peening is applied after heat treatment either to remove scale from the surface or to induce residual stress.

- Rolling, drawing, non-uniform cooling result in curvatures on the crankshafts surface. Straightening process applied to eliminate or reduce these curvatures.

- Grinding process start after straightening. First rough grinding applied to align the crankshaft to its final dimensions.

- CAM grinding is applied to give rough shape to the eccentric cylinders in the crankshaft.

- After rough grinding final grinding is applied to bring the cylinder diameter to acceptable tolerance mentioned in the technical drawing.

- In the same way final CAM grinding applied for grooves and eccentric cylinders.

- Face grinding concludes the grinding process where the dimensions are finalized.

- Dynamic balancing is the final step of the whole machining process. Dynamic balance of the crankshaft is checked by mounting from its bearings. Mass and material removal locations are determined to maintain the balance.

- Final washing is applied after dynamic balancing to prepare the finished crankshaft for inspection.

- Final inspection is the process where all dimensions are checked according to the technical drawing and surface imperfections are investigated.

- In the final step approved crankshafts pass to packing and dispatch to send the customer.

These steps are the mainly used processes during the forging of the crankshafts. According to raw material chemical composition, crankshaft fatigue strength requirement, cost target and capability of the plant some of these sub steps may be omitted or order can be re-scheduled. For example, Wicklund performed a study to found out benefits of using micro alloyed steel instead of hot rolled steel. He omitted the heat treatment process as it is not necessary for micro-alloy steel. Adding fillet rolling process allows increasing the mechanical properties to desired values. New process diagram can be seen in Figure 3.4 [26]. More details of this kind of optimization are given in cost analyses and comparison sections. However it can be understood that these steps can be omitted or order can be changed according to requirement of the project. Optimum process chart have to be determined by using the guide given in the conceptual design section.

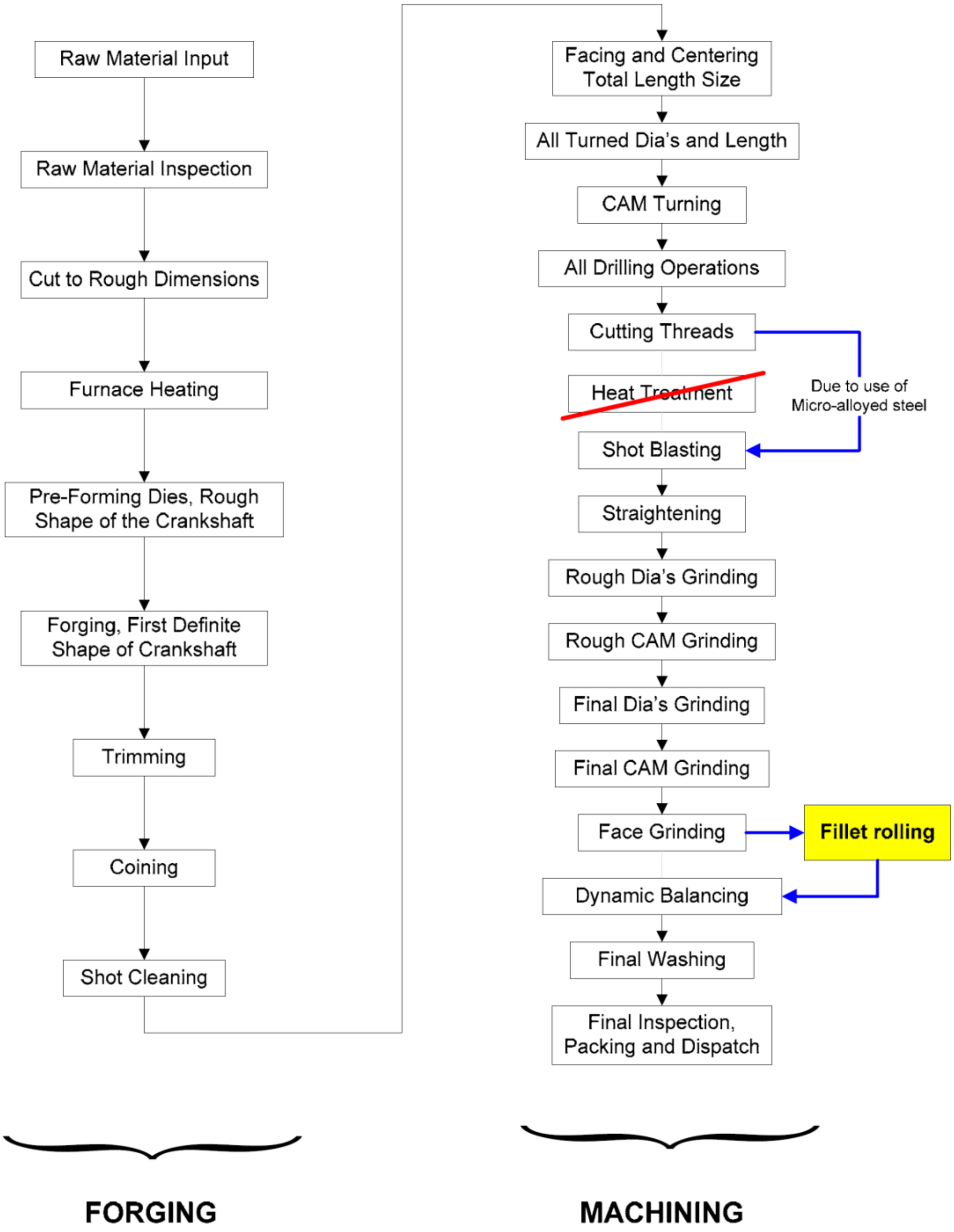


Figure 3.4 : Modified flow chart of forging

4. SURFACE TREATMENT METHODS TO IMPROVE FATIGUE LIFE

Crankshaft design and manufacturing is a complex process that is affected many parameters. From same material very different crankshafts can be produced according to applied surface treatments. It is possible to improve the fatigue life of crankshaft by applying various surface treatments. With proper surface treatment methods either more compact designs can be achieved or up to 50 % endurance limit can be increased. Three common surface treatment methods namely nitrocarburizing, heat treatment and inducing residual stress, and their experimental results are explained in this section.

4.1 Nitrocarburizing

Ferritic nitrocarburizing is a range of case hardening processes that diffuse nitrogen and carbon into ferrous metals at sub-critical temperatures. Despite the naming the process is a modified form of nitriding and not carburizing. The shared attributes of this class of this process is the introduction of nitrogen and carbon in the ferritic state of the material. The processing temperature ranges from 525 to 650 °C, but usually occurs at 565 °C. At this temperature steels and other ferrous alloys are still in a ferritic phase, which is advantageous compared to other case hardening processes that occur in the austenitic phase.

Honda Research and Development center and Daido Steel have done a study about nitrocarburizing to found out benefits of this process [9]. Aim of the study to eliminate the normalizing procedure by applying nitrocarburizing. They have found an optimum chemical composition for their application that is shown in Table 4.1. Thousand nitrocarburized crankshafts and conventional normalised crankshafts were manufactured. To compare these crankshafts mechanical properties such as; fatigue strength, hardness, machinability, microstructure and maximum deformation were measured.

Table 4.1: Chemical composition of the new developed steel

C	Si	Mn	S	Cr	N	Pb	Ca
0.30	0.25	0.80	0.05	0.05	0.020	0.20	added

Hardness value of conventional forged crankshaft is higher than the nitrocarburized crankshafts as can be seen in Figure 4.1. Hardness of the developed steel is lower than that of the conventional one. The developed steel has insignificantly larger dispersion of hardness than conventional steel. The condition of hot forging which affects as-forged hardness is somewhat difficult to fix. Although nitrocarburized cranks have lower hardness its machinability properties are much better than conventional ones. Cranks were turned with carbide tool at a speed of 5m/sec and drilled with HSS tool with a 1.4mm/sec cutting speed at same conditions. Results are shown in Figure 4.2.

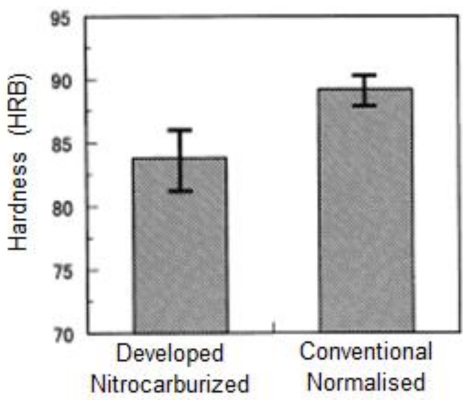


Figure 4.1 : Hardness of conventional and nitrocarburized crankshaft

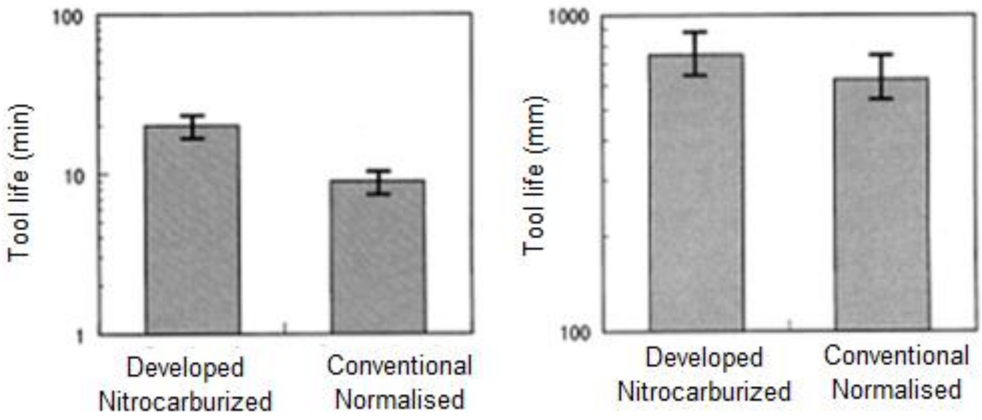


Figure 4.2 : Machinability properties of conventional and nitrocarburized crankshaft

Hardness distributions of two cranks are illustrates in Figure 4.3. The hardness distributions of diffusion zone of two steels are nearly same although the as forged hardness of the developed steel is lower than that of conventional one.

Fatigue strength test results are equal for both crankshafts in addition straightening of the crankshafts is also same for nitrocarburized and normalized crankshafts. Comparison of fatigue strength and straightening can be seen in Figure 4.4. It is mentioned that no troubles were observed during the test of 1000 crankshafts which indicate the results are reliable and repeatable.

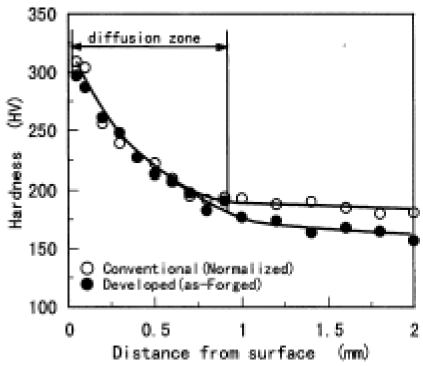


Figure 4.3 : Hardness distribution of conventional and nitrocarburized crankshaft

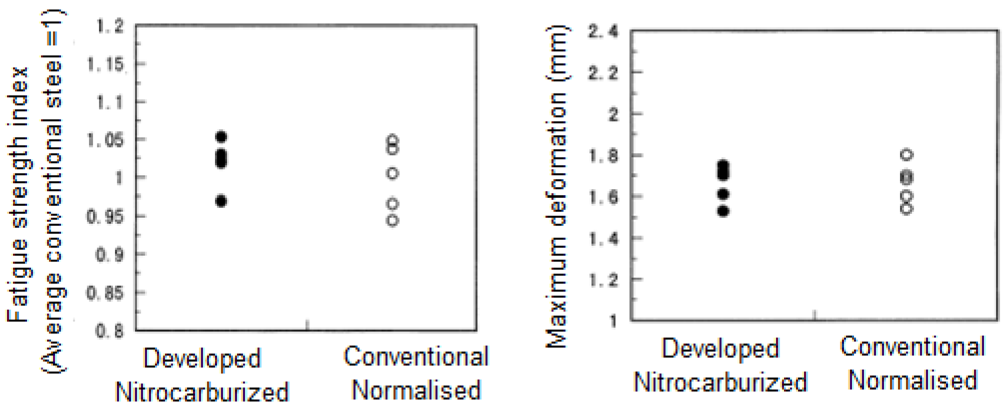


Figure 4.4 : Fatigue strength and straightening comparison

Hyundai has performed a study for nitriding [15]. They nitride the carbon steel to have higher fatigue strength like micro alloyed steels. Nitriding process consists of maintaining a work-piece in a 580°C ammonia atmosphere for up to 200 minutes. Figure 4.5 shows the process schematically. Under these conditions atomic nitrogen combines with surface iron to form iron nitride. The nitrogen slowly diffuses away from the surface, as long as the proper temperature is maintained. Therefore, the resulting case thickness depends on length of heat treatment.

They can increase the fatigue strength of bare sample from 9kN to 16kN. Up to 70 % fatigue strength improvement can be achieved with application of nitriding.

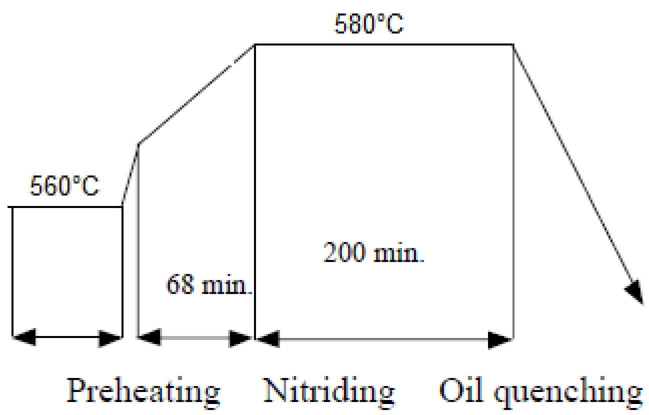


Figure 4.5 : Nitriding process

4.2 Heat Treatment

Metallic materials consist of a microstructure of small crystals called "grains" or crystallites. The nature of the grains (i.e. grain size and composition) is one of the most effective factors that can determine the overall mechanical behaviour of the metal. Heat treatment provides an efficient way to manipulate the properties of the metal by controlling rate of diffusion, and the rate of cooling within the microstructure. Annealing, hardening and tempering (quenching and tempering), precipitation hardening, selective hardening, case hardening, through hardening are the main heat treatment methods that applied to steel components to increase their mechanical properties.

Chatterley and Murrell have done a detailed study to analyse the heat treatment affect for crankshafts and select and optimum process for their ADI crankshaft application. In their study, optimum values are achieved for both austempering and austenitising process for ADI crankshafts [1].

First, austempering tests were done to found out the optimised temperature values. During the test Furnace austenitization in still air at 875°C for one hour, followed by salt bath quenching and isothermal holding at 400°C to 325°C with 25°C steps and waited 1, 2 and 4 hours at each quenching temperatures.

Tensile strength and elongation of all 12 groups crankshaft specimen is measured and compared to found out best austempering temperature and duration values. As expected reducing the austempering temperature increase the tensile strength and lower the ductility which means lower the elongation. Results are shown in Table 4.2. Both elongation and tensile strength optimum values can get at 350°C austempering temperature for two hours. Best tensile strength gets at 325°C however elongation is just only 3 % whereas elongation is 9 % at 350°C austempering temperature for two hours.

Second, austenitising temperature is selected by performing furnace austenitization in still air at 860°C, 880°C and 900°C for one hour and followed with 350°C austempering for two hours as selected optimum in the first step. Among three group austenitization at 880°C give best mechanical properties as can be seen in Table 4.3. Close results get at all of them as their microstructures are very similar however with 1064 MPa ultimate tensile strength and 6.75 % elongation optimum austenitization temperature is selected as 880°C.

In result it can be conclude that according to Chatterley and Murrell study an austenitization temperature of 880°C gave optimum results when combined with an austempering treatment of two hours at 350°C.

Crankshafts are manufactured to see the affect of the heat treatment. 6 of solid and 5 of hollow ADI cranks are manufacture both from 26B38 and 4C38 coded materials. Also A small number of crankshafts was also produced in 700/2 grade ductile iron. Above selected heat treatment was applied to ADI crankshafts. Mechanical properties of all cranks are found and tabulated in the Table 4.4.

Table 4.2: Heat treatment affect on mechanical properties of ADI crankshafts

Austempering Temp (°C)	Austempering Time (hrs)	Specimen Location	Proof Strength N/mm²			UTS N/mm²	El per cent	Average Values		Retained Austenite per cent
			0.10 per cent	0.20 per cent	0.50 per cent			TS N/mm²	El per cent	
400	1	Inner	394	434	512	593	1.5			
			333	389	483	620	1.5	607	1.5	n/a
		Outer	338	394	489	666	1.5			
			331	390	490	668	4	667	1	n/a
	2	Inner	350	407	508	763	2.5			
			350	408	508	708	2	736	2.3	50.6
		Outer	348	405	507	857	4.5			
			351	407	508	812	2	835	3.3	47.6
	4	Inner	387	434	522	792	3			
			387	434	522	729	2	761	2.5	n/a
		Outer	396	443	531	847	4.5			
			402	449	532	828	4.5	838	4.5	n/a
375	1	Inner	456	523	618	893	3.5			
			492	545	628	858	2	876	2.8	n/a
		Outer	489	547	634	914	3.5			
			483	541	630	916	4.5	915	4	n/a
	2	Inner	515	567	641	876	4.5			
			517	570	644	833	3.5	855	4	47.3
		Outer	522	574	647	933	6.5			
			526	578	651	942	6.5	938	6.5	49.6
	4	Inner	517	563	624	709	2			
			505	551	614	696	2	703	2	n/a
		Outer	493	542	610	745	3.5			
			500	548	613	730	3.5	738	3.5	n/a
350	1	Inner	453	509	594	725	2			
			458	514	599	729	2	727	2	40.0
		Outer	476	539	631	798	3			
			469	525	612	800	3	799	3	40.8
	2	Inner	610	679	769	1001	6.5			
			622	688	773	984	6	993	6.3	39.2
		Outer	624	690	777	1049	9			
			617	685	774	1036	9	1043	9	38.8
	4	Inner	634	694	767	926	5			
			639	696	766	916	5	921	5	36.7
		Outer	638	699	774	970	7			
			651	711	784	966	6	968	6.5	38.9
325	1	Inner	561	649	782	1021	3			
			554	645	778	1024	3	1023	3	n/a
		Outer	630	704	823	1088	4.5			
			616	703	828	1099	4	1094	4.25	n/a
	2	Inner	646	732	841	973	2.5			
			656	742	849	1008	2.5	991	2.5	32.9
		Outer	693	758	879	1073	4.5			
			709	784	885	1077	5	1075	4.75	31.4
	4	Inner	Heat Treatment Not Completed							
		Outer								

Table 4.3: Austenitization effect on mechanical properties of ADI crankshafts

Austenitising Temp (°C)	Austenitising time (hrs)	Specimen Location	Proof Strength N/mm²			TS N/mm²	El per cent	Average Values		Retained Austenite per cent
			0.10 per cent	0.20 per cent	0.50 per cent			TS N/mm²	El per cent	
860	1	Inner	597	657	735	922	5.5			
			612	668	741	924	5.5	923	5.5	35.4
		Outer	599	662	744	951	6.5			
			599	665	749	962	6.5	957	6.5	35.8
880	1	Inner	620	693	784	941	3.5			
			649	710	792	910	2.5	926	3	37.8
		Outer	720	789	880	1105	6.5			
			623	701	795	1023	7	1064	6.75	36.4
900	1	Inner	624	688	771	965	5.5			
			639	697	776	921	4	943	4.75	37.5
		Outer	619	684	768	947	4.5			
			618	684	771	960	4.5	954	4.5	37.7

4.3 Inducing Residual Stress

Residual stresses or locked-in stresses can be defined as those stresses existing within an object without the application of any service or other external loads. All manufacturing and fabricating processes such as casting, welding, machining, molding, heat treatment, plastic deformation during bending, rolling and forging introduce residual stresses into the manufactured object.

While uncontrolled residual stresses are undesirable, some designs rely on them. Surface compressive stresses gain resistance to metal fatigue and to some forms of corrosion, since cracks will not grow in a compressive environment. The fatigue properties of the part will be improved since the stresses are normally significantly higher at the surface due to applied residual stress.

Inducing residual stress to crankshafts is a very common application to improve their fatigue life. Shot peening and fillet rolling are the main methods applying residual stress. Amount of this stress is important as inducing more also lower the fatigue life like inducing less. Therefore optimum amount should be applied.

4.3.1 Shot peening

During the shot peening spherical particles are exploded to the surface of the finished crankshaft. Each strike of a shot makes a small indentation in the surface of the part, which result in compressive residual stresses. This increase the resistance to crack initiation therefore fatigue fracture or stress-corrosion cracking resistance has improved.

Burrell studied affect of the shot peening on six different crankshafts [24]. Fatigue test was performed by applying high frequency bending load. Strain gages are mounted in the fillets to monitor the load. Four different materials were used for forged crankshaft and two different for cast crankshaft. Improvement percent for each crankshaft can be seen in the below Table 4.4. It shows the increase of fatigue strength AISI 4340H forged crankshaft. Fatigue strength of fillets as ground is 358MPa whereas by applying shot peening it increases to 496MPa. 40 % improvement can be achieved just by shot peening application.

Table 4.4: Shot peening effect to fatigue strength

	Increase in Fatigue Strength
Forged steel AISI 15B55	25%
Forged steel AISI 4340H	40%
Forged steel AISI 1046	31%
Nodular cast iron	12.50%
Cast malleable iron (ARMASTEEL 88-M)	48%
Forged steel C1046	17.20%

4.3.2 Fillet rolling

Fillet rolling is a method of cold work deformation for internal combustion engine crankshaft journal fillets to increase durability and design safety factors. Fillet rolling process has been used to improve the fatigue lives of crankshafts for many years. With the application of fillet rolling fatigue driving stresses near the fillet surface due to operating loads are reduced and fatigue live increased.

Kamimura has performed tests to found out the effect of fillet rolling on ductile cast iron crankshafts [26]. Crankshafts were fillet rolled with 9 different rolling forces from 1.5kN to 5.2kN. Fatigue test were done for each crankshaft and results are compared. Figure 4.6 shows the S-N curve of each crankshaft. Fatigue strength is increasing considerably just applying optimum deep rolling method. Un-rolled crankshaft has 225MPa fatigue strength and it can be increased to 412MPa with application of 3kN rolling force to the fillets.

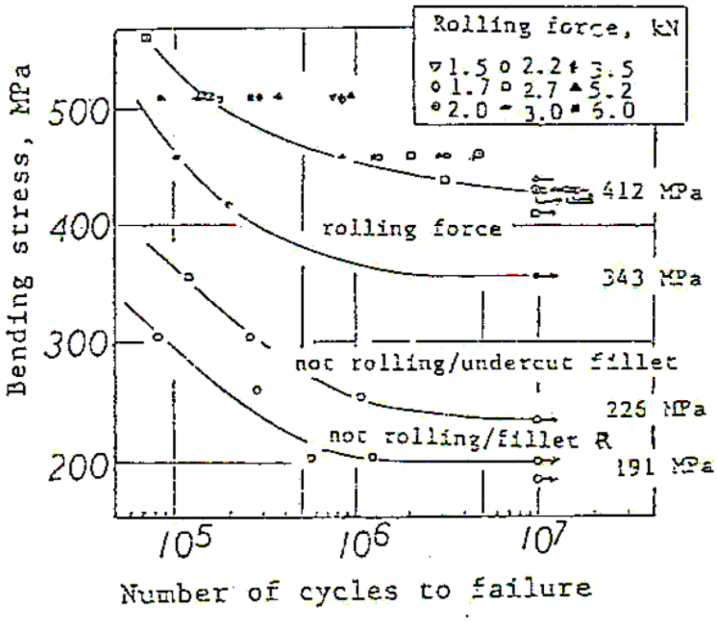


Figure 4.6 : S-N diagram of deep rolled ductile cast iron crankshaft with different rolling forces

Determining the rolling force is another important parameter for fillet rolling process. Cevik has performed a study to find the optimum value of for rolling force. Rolling force increased from 12.5kN to 28kN. Up to 20kN there is a remarkable increase at fatigue strength but after 22.8kN fatigue strength start to decrease. Undercut regions of the crankshafts of that rolled with 20kN and 22.8kN rolling forces were investigated. S-N curves of this study are shown in Figure 4.7. Excessive plastic deformation was observed at 22.8 one whereas no discontinuities were seen at 22kN rolling load crankshaft [2].

Rolling radius is another parameter at fillet rolling. Cevik changed the rolling radius form 1.45mm to 1.85mm. Results of this study can be seen in Figure 4.8. Increase of rolling force does not change the fatigue strength. According to Cevik’s conclusion there should be a peak fatigue strength value at a rolling load lower than 24kN.

From these studies for fillet rolling it can be concluded that increasing the rolling force give better fatigue strength by inducing higher compressive stress of the filler radius. However, there is a limit for rolling force, excess residual stress results in plastic deformation and start to lower the fatigue life. Therefore optimum rolling force has to be found according to material experimentally.

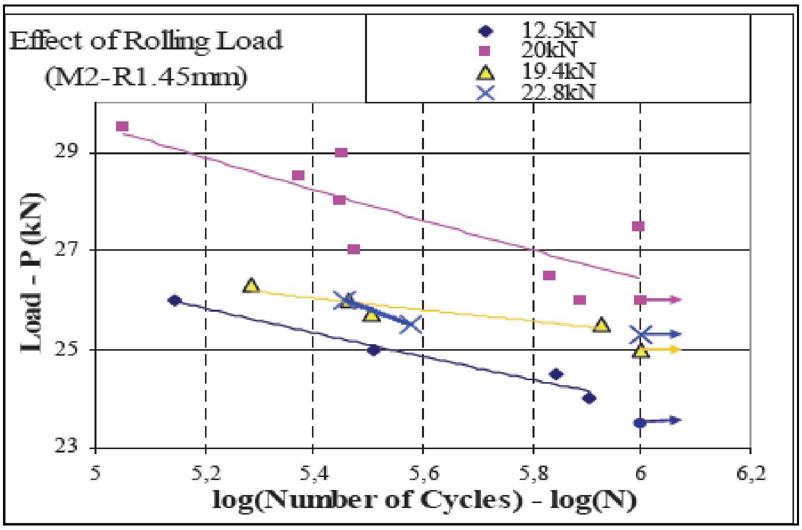


Figure 4.7 : P-N curve for different rolling forces

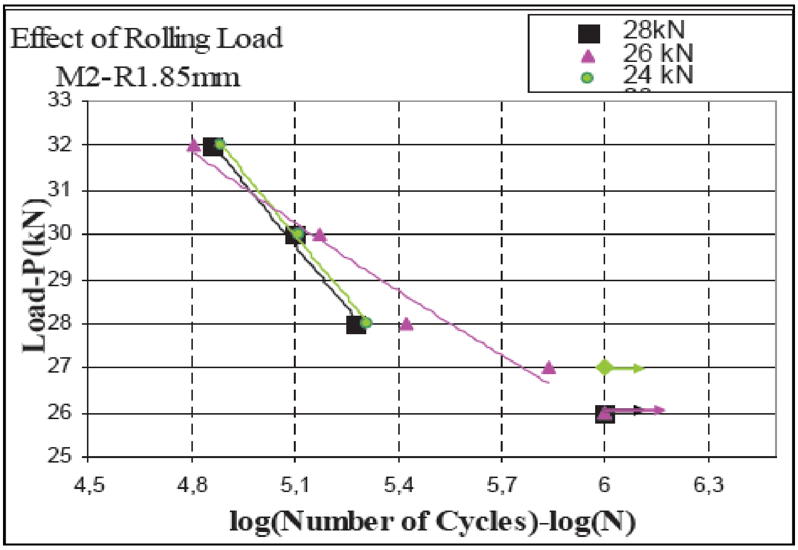


Figure 4.8 : P-N curve for different rolling forces 2

5. COMPARISON OF DIFFERENT MANUFACTURING and SURFACE TREATMENT METHODS

Automotive industry always tries to find improvements for all components and application because of the challenge in the market. Improving the fuel consumption by reducing the weight and increasing the life of the components and reducing cost by using alternative materials are the main ideas while searching a development. Ductile cast iron, ductile austempered iron, alloyed steels and their variants by chemical composition modification are the main materials that used for crankshaft manufacturing. Casting and forging are the main manufacturing method used for crankshafts in mass production.

Previous chapter details of forging and casting method are given now a comparison analyse is shown for these two manufacturing method from mechanical properties point of view. A literature review has done for this purpose and results of the different analyses are given in this chapter.

Jonathan Williams and Ali Fatemi have compared the forged steel and cast ductile iron for crankshafts manufacturing. Chemical composition of the materials is given in Table 5.1 that is used in their study. Final shape of compared one cylinder crankshafts is shown in Figure 5.1 [25, 26].

Table 5.1: Chemical composition of forged and ductile crankshafts

	Forged Steel	Ductile Cast Iron
C	0.45	3.44
Mn	0.81	0.48
P	0.016	0.019
S	0.024	0.004
Si	0.27	2.38
Al	0.033	0.01
Cr	0.1	0.09
Ni	0.05	0.06
Cu	0.13	0.31
N	0.008	--
O	13 ppm	--

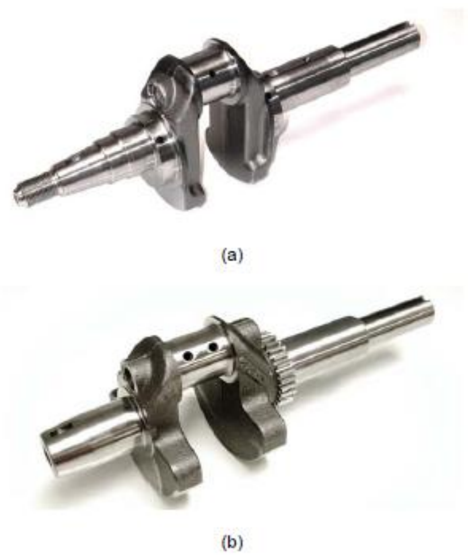


Figure 5.1 : Forged steel (a) and ductile cast iron (b) crankshaft

All mechanical properties of these crankshafts were measured in their study and results are tabulated in Table 5.2. As it can be seen in the table and also in Figure 5.2, forged steel has higher yield and ultimate strength than ductile iron approximately about 70 %.

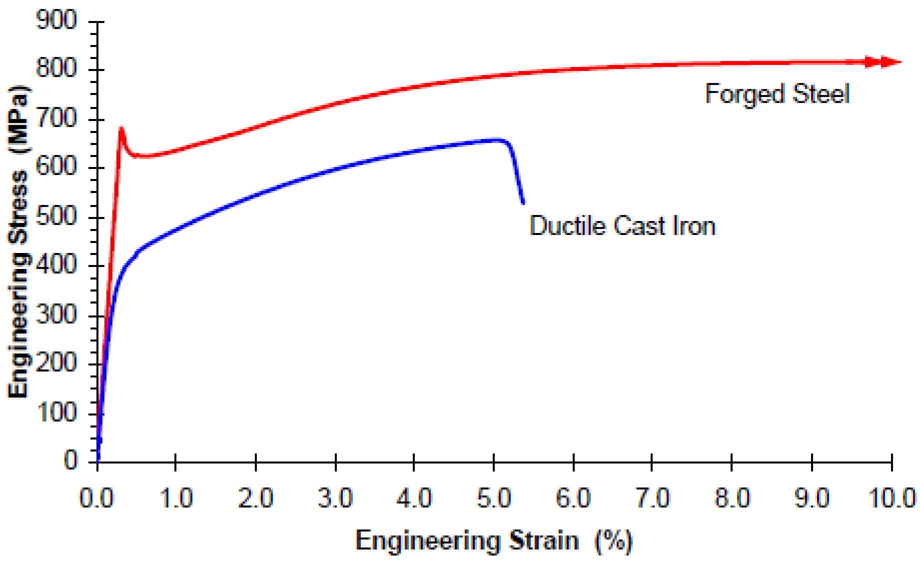


Figure 5.2 : Engineering stress of forged steel and ductile cast iron crankshaft

Table 5.2: Mechanical properties of forged steel and ductile cast iron crankshaft

Monotonic Properties	Forged Steel	Cast Iron	Ratio
Average Hardness, HRC	23	18	0.8
Average Hardness, HRB	101	97	0.96
Modulus of Elasticity, E, GPa	221	178	0.81
Yield Strength (0.2%offset), YS, MPa	625	412	0.66
Ultimate Strength, S_u, Mpa	827	658	0.80
Percent Elongation, %EL	54%	10%	0.19
Percent Reduction in Area, %RA	58%	6%	0.10
Strength Coefficient, K, MPa	1316	1199	0.91
Strain Hardening Exponent, n	0.152	0.183	1.20
True Fracture Strength, σ_f, MPa	980	562	0.57
True Fracture Ductility, ε_f	87%	6%	0.07
Cyclic Properties	**Forged Steel**	**Cast Iron**	**Ratio**
Fatigue Strength Coefficient, σ_f', MPa	1124	927	0.82
Fatigue Strength Exponent, b	-0.079	-0.087	1.10
Fatigue Ductility Coefficient, ε_f'	0.671	0.202	0.30
Fatigue Ductility Exponent, c	-0.597	-0.696	1.17
Cyclic Yield Strength, YS', MPa	505	519	1.03
Cyclic Strength Coefficient, K', MPa	1159	1061	0.91
Cyclic Strain Hardening Exponent, n'	0.128	0.114	0.89
Fatigue Strength at 10^6 cycles, MPa	359	263	0.73
Note: Forged steel taken as the base for all ratio calculations			

Failure cycle according to applied moment amplitude test results can be seen in Figure 5.3. A failure criterion is accepted as 2mm crack present. Forged steel has 6 times longer life than cast iron as seen in the plot. All test results are summarized in Table 5.3.

Table 5.3: Crankshaft life prediction summary

Applied Moment Amp. (N-m)	Cycles at First Observed Crack	Crack Initiation from Fitted Data	Cycles at 5% Change in Disp. Amp.	S-N Prediction	ε-N Prediction
Forged Steel Crankshaft					
630		29,248	45,568	67,391	30,071
	--	45,302	69,670	67,391	30,071
	--	58,236	90,853	67,391	30,071
517	165,000	145,000	234,289	248,471	100,918
	120,000	98,741	213,885	248,471	100,918
	--	204,174	396,011	248,471	100,918
350	>3,240,000	N/A	N/A	N/A	N/A
Cast Iron Crankshaft					
630	11,504	7,132	17,353	2,162	517
	11,692	9,256	17,380	2,162	517
	8,021	8,021	20,957	2,162	517
517	31,464	25,512	47,513	9,202	1,353
	34,898	24,096	52,790	9,202	1,353
	42,750	37,380	54,966	9,202	1,353
431	113,043	75,200	132,877	32,988	3,716

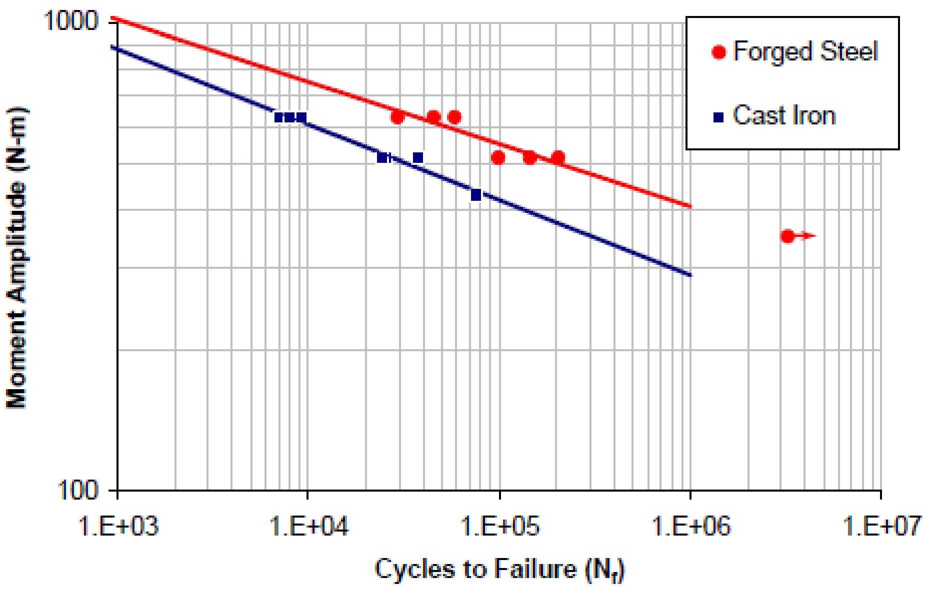


Figure 5.3 : Applied moment amplitude test results

Chatterley studied crankshafts in details to found an optimum manufacturing method as mentioned earlier sections. ADI, forged, cast crankshafts are used in his study. Heat treatment and fillet rolling applied to ADI and cast crankshafts to improve their mechanical properties. Weights of the produced crankshafts are given in Table 5.4. ADI crankshafts have lighter weight than forged steel. Hollow crankshaft has thicker crankwebs that make them heavier than solid ADI crankshafts. Also broader webs of the forged crankshaft have an impact at its weight.

For all crankshafts fatigue life was found. Tests were run for 10 million cycles of loading. Specimens have fractured before 10 million cycles was recorded by counter on the drive motor. Results are given in the Table 5.5. It can be understood that fillet rolling is very crucial for crankshafts that improve their fatigue life. Although, fillet rolling increases fatigue strength of ADI crankshafts, forged steel crankshafts have higher fatigue strength than ADI and ductile crankshafts. Cast crankshafts have lower fatigue strength than the ADI crankshafts.

Table 5.4: Weight of produced ADI crankshafts

Crankshaft Type and Condition	Mass, g
Forged steel, fully machined	16,266
Solid, as-cast ADI, un-machined	15,417
Solid ADI, fully machined	12,486
Hollow ADI, fully machined	13,385

Table 5.5: Summary of bending fatigue tests on ADI crankshafts

Crankshaft Material	Fatigue Limit at 10 x 10^6	
	Applied Bending Moment ± Nm	Approximate Applied Stress**, ± N/mm^2
Forged Steel	1050	660
Un-rolled Solid ADI	500	280
Rolled* Solid ADI	750	420
Rolled* Hollow ADI	650	360
Rolled* Solid 700/2 Iron	800	450
Solid ADI Rolled at + 25% Rolling Force	850	475
Solid ADI Rolled at + 50% Rolling Force	1000	560

Hoffman and Turonek were studied different materials while finding a cost model for forged crankshaft manufacturing. They have studied SAE 1050 carbon steel (CS), SAE 4140 medium carbon alloy steel (AS) and 0.10 % sulphur level of these materials. In addition to these two microalloy material were used in their study. Chemical compositions of these materials are given in Table 5.6.

Table 5.6: Chemical composition of compared crankshafts

Steel Code	**Chemical composition with respect to %**							
	C	Mn	Si	S	Cr	Mo	V	Al
CS	0.51	0.8	0.3	0.03	0.1	0.01	-	0.03
CS-HS	0.49	0.8	0.35	0.09	0.12	0.01	-	0.03
AS	0.4	0.73	0.23	0.02	1.07	0.16	-	0.04
AS-HS	0.42	0.9	0.2	0.11	1.03	0.18	-	0.03
MA1	0.37	1.38	0.64	0.05	0.14	-	0.08	-
MA2	0.49	1	0.4	0.04	0.1	-	0.06	-

Crankshafts were manufactured from these materials and fillet rolling applied to some of them. Than fatigue strength of these crankshafts are measured. Results are given in Table 5.7.

Higher sulphur percentage does not affect the mechanical properties as there is slight change in both hardness and fatigue strength. However, effect of fillet rolling on to carbon steel is about 20 % whereas its effect is about 40 % for microalloyed crankshafts.

Mechanical properties difference of two different microalloyed crankshafts result from their carbon content. MA1 has lower carbon therefore has more ferrite than MA2. This allows improving its fatigue strength by fillet rolling gradually.

From the results of Hoffman and Turonek it can be said that carbon alloy steel has highest fatigue strength, second microalloyed steels and the last is carbon steels. If cost is not a constraint highest mechanical properties can be achieved with carbon alloy steel.

Table 5.7: Mechanical properties of compared crankshafts

Steel Code	Surface Hardness HB	Fillet Rolled	Fatigue Strength kgf/mm2
CS	240	yes	53
CS-HS	245	yes	52
CS-HS	245	no	43
CS-HS	260	no	51
AS	275	yes	80
MA1	270	yes	72
MA1	240	no	50
MA2	245	yes	59
MA2	235	no	47

Intermet Corporation has done an investigation for crankshafts to get lighter design with new materials for specific purposes as well as general use. A list of the different companies crankshafts are given in their study. It can be seen in Table 5.8. Cast ductile irons (D5203, D5506, Dc Hi-Hard), austempered ductile iron, new developed austempered iron (MADI) and carbon alloy steel were used at these crankshafts [3].

MADI crankshafts have better mechanical properties than forged crankshafts; whereas, ADI is better than MADI but elongation of MADI is favourable than ADI. According to ultimate tensile strength the best is ADI, MADI follow it both better than forged steel and the worst sis ductile iron as expected.

All these crankshafts tested by vehicle testing and all meet the testing requirements and available components in the market.

Table 5.8: Mechanical properties of different companies crankshafts

		Average (unless noted)			
Crankshaft	Material	UTS (MPa)	YS (MPa)	Elong (%)	Hardness (BHN)
DC 1.8 liter	forged steel	778	462	12.4	233
DC 2.4 liter	forged steel	963	648	9.5	273-288
Toyota 2.2 liter	forged steel	806	508	12.9	242
Toyota 2.5 liter[1]	forged steel	851	553	7.3	259-273
Ford 2.5 liter	forged steel	776	456	10.9	248
General Motors	forged steel	850[2]	580[2]		248-302
D5203 5.7 liter	cast DI	610	402	2.7	225
D5506 5.7 liter	cast DI	707	407	6.8	225
DC "Hi-Hard"[3]	cast DI	783	438	4.0	253
MADI 1.8 liter	cast DI	796	488	12.0	249
MADI 2.4 liter[4]	cast DI	834	506	15.3	258
MADI 4.7 liter	cast DI	774	502	12.9	246
MADI 5.7 liter	cast DI	748	492	10.4	244
ADI 4.7 liter	cast DI	1002	634	6.5	312
ADI 5.7 liter	cast DI	1009	644	9.9	298
ADI 5.7 liter	cast DI	1076	748	8.9	325

In another study fatigue strength of crankshafts that were manufactured from different micro alloyed steels and austempered cast irons are given in below Figure 5.4. Very high fatigue strength can be achieved with selection of the material and controlled manufacturing steps by ADI crankshafts. 1100MPa fatigue strength can be get by rolled and un-notched ADI crankshafts which is much more higher than the fatigue strength of forged steels.

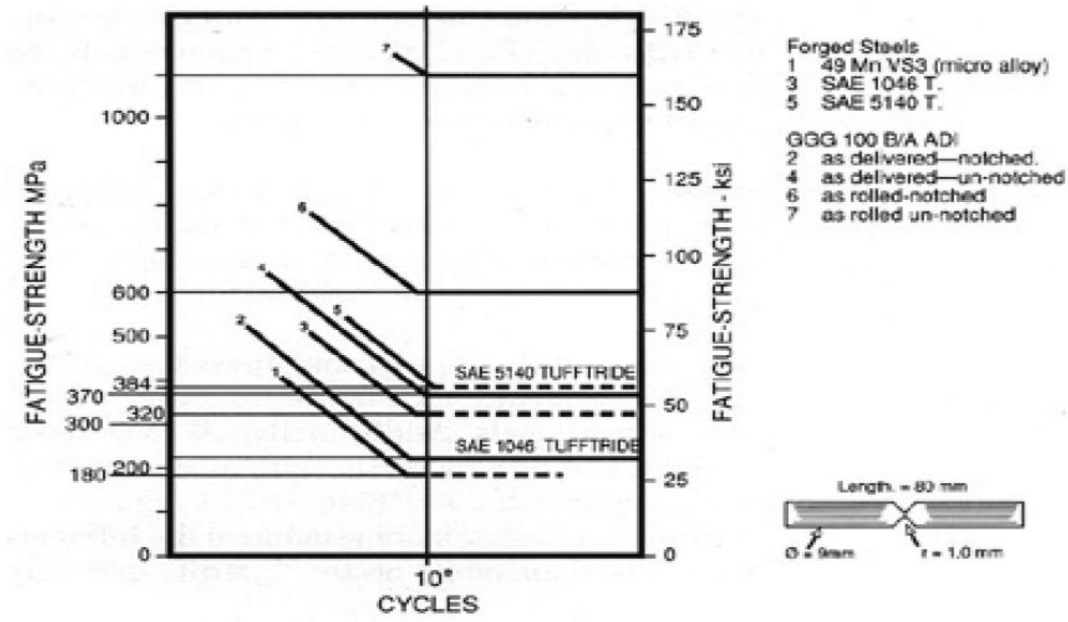


Figure 5.4 : Fatigue strength comparison of crankshafts

Forging and casting is the main method while manufacturing crankshaft. Different studies are examined and as a conclusion Table 5.9 is created. For many of the perspectives forging is superior to casting however cost is the very important parameter for companies and lower price cost can be achieved via casting method.

Table 5.9: Summary of characteristic comparison between forging and casting process

Property \ Process	Forging	Casting
Strength	High	Medium
Ductility	High	Low
Toughness	High	Medium
Fatigue crack growth resistance	Good	Poor
Directional strength capability	Yes	None
Heat treatment response	Good	Requires close control
Internal defects	Possible	Many
Production volume	High	High
Production rate	High	Low (sand casting) to high (die casting)
Initial tooling cost	High	Medium
Production cost	Low	Low
Shape complexity	Limited	High (in die-casting)
Dimensional versatility	High	Limited
Dimensional accuracy	Medium	Medium
Surface finish	Good to poor	Poor
Material versatility	High (ferrous and non-ferrous)	Limited

As seen in the table forging is much more better method than casting however as mentioned above studies different type of materials allow improving the mechanical properties indeed superior values can be achieved in casting. Tooling investment is also higher for forging therefore for small number of manufacturing batches casting may be more profitable. These processes are investigated from cost point of view in the cost analyses chapter and more details are given in that section.

Forging permit to determine grain flow and gain directional strength whereas it is not possible in casting. Moreover, metallurgical defects are observed in casting process due to the nature of the method. According to condition of the application, maximum strength and direction can be estimated and a grain flow can be given in forging in addition dendritic structures, alloy segregations and imperfections can be refined.

Hot forging refines grain pattern and improve higher strength, ductility which make forging more reliable, imperfections are much less compared to casting. Because of imperfections melting and cooling steps have to be controlled carefully. Segregations are unavoidable in the casting and heat treatment response of forging is more unsurprising and better dimensional accuracy achieved; whereas, casting is unpredictable and heat treatment may affect the straightness of finished components.

In spite of abovementioned favourable properties of forging, casting may be economical alternative due to lower material cost depending on the functionality requirements of application area.

6. ALTERNATIVE CAST MATERIAL FOR CRANKSHAFTS

This section of the thesis mainly get from the ductile cast iron web site [22] and focuses on to the cast materials.

6.1 Cast Iron

Cast Irons are a family of ferrous metals with a wide range of properties produced by being cast into shape as opposed by being formed. Cast Irons contain 2 % to 4 % Carbon and 1 % to 3 % Silicon. Other elements are used to control specific properties. Cast irons have a wide range of mechanical properties which make them suitable for use in engineering components. The wide spread use of cast iron is as a result of its low cost and versatile properties.

An iron-carbon liquid containing over 2 % C cooled very slowly will result in a graphite (pure carbon) and iron crystallising out to form cast iron. In the practice at normal cooling rates the metastable cementite Fe_3C is formed.

High carbon content metals can, under controlled conditions, solidify as stable iron-graphite systems or metastable iron-carbide systems. Rapid cooling discourages the nucleation graphite and encourages the formation of metastable iron carbide. Longer holding times at higher temperatures and slower cooling and the addition of certain alloying elements encourage the formation of stable iron-graphite phase.

Cast iron contains significant amounts of silicon in addition to the high carbon content. Cast irons are therefore really iron-carbon-silicon alloys. The presence of silicon in iron carbon alloys promotes the formation of graphite.

The true phase diagram for iron-carbon is similar to the metastable one on the carbon steel page. The phase diagrams for iron-carbon-silicon is similar but the eutectic/eutectoid points are moved to the left. A diagram for containing 2 % silicon is shown Figure 6.1.

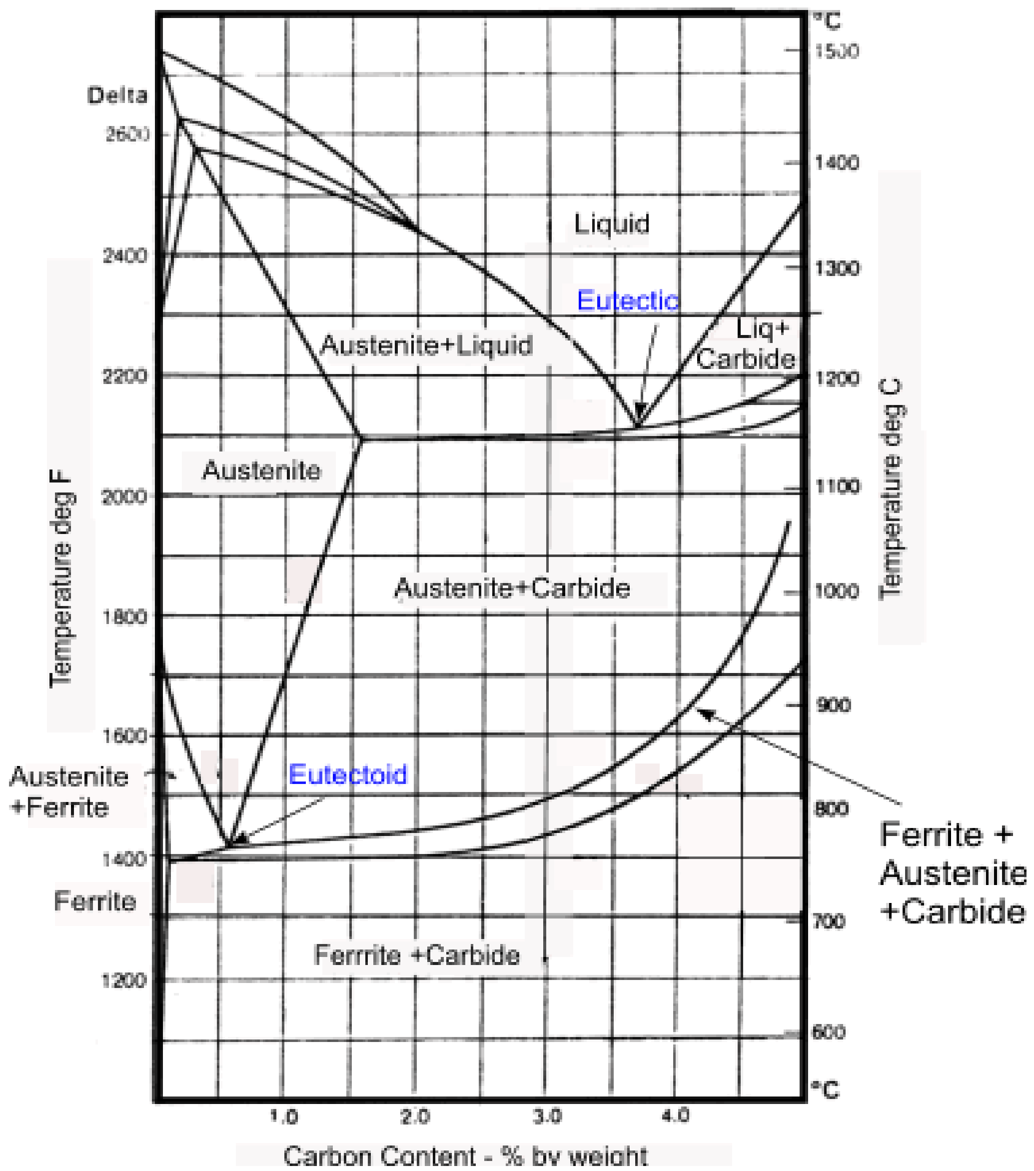


Figure 6.1 : Phase diagrams for iron-carbon-silicon

Iron castings, as objects of art, weapons of war, or in more utilitarian forms, have been produced for more than 2000 years. As a commercial process, the production of iron castings probably has no equal for longevity, success or impact on our society. In a sense, the iron foundry industry produces an invisible yet vital product, since most iron castings are further processed, assembled, and then incorporated as components of other machinery, equipment, and consumer items.

The term "cast iron" refers not to a single material, but to a family of materials whose major constituent is iron, with important amounts of carbon and silicon, as shown in Figure 6.2. Cast irons are natural composite materials whose properties are determined by their microstructures - the stable and metastable phases formed during solidification or subsequent heat treatment. The major micro structural constituents of cast irons are: the chemical and morphological forms taken by carbon, and the continuous metal matrix in which the carbon and/or carbide are dispersed. The following important micro structural components are found in cast irons.

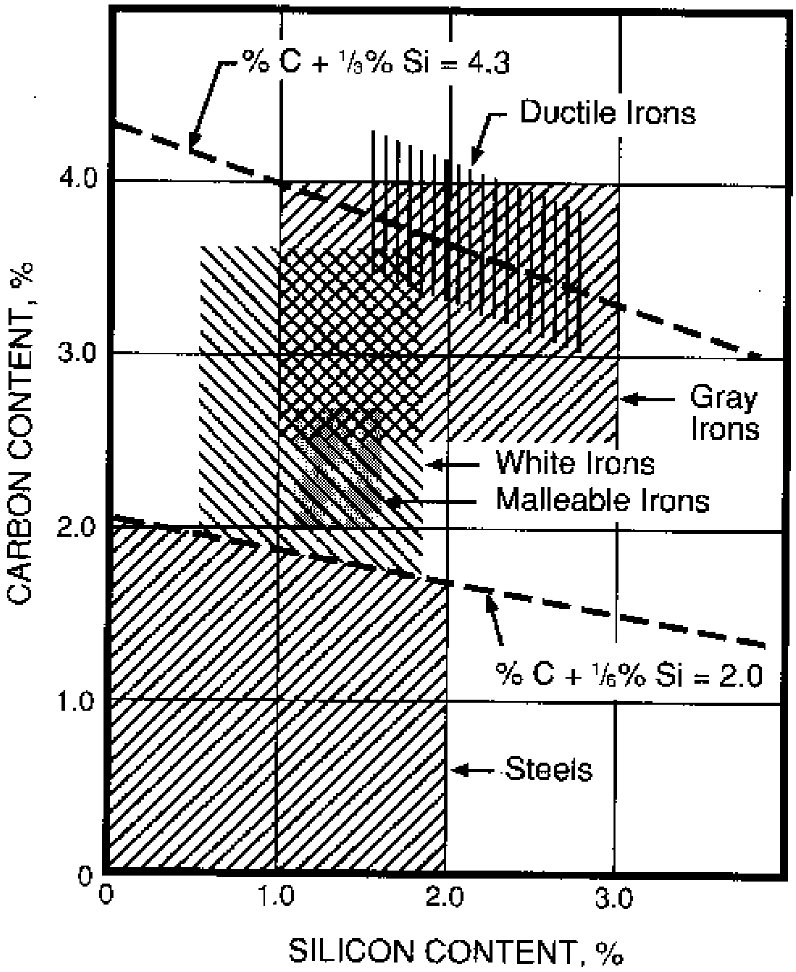


Figure 6.2 : Cast iron family

Graphite; this is the stable form of pure carbon in cast iron. Its important physical properties are low density, low hardness and high thermal conductivity and lubricity. Graphite shape, which can range from flake to spherical, plays a significant role in determining the mechanical properties of cast irons [22].

Carbide; carbide or cementite, is an extremely hard, brittle compound of carbon with either iron or strong carbide forming elements, such as chromium, vanadium or molybdenum. Massive carbides increase the wear resistance of cast iron, but make it brittle and very difficult to machine. Dispersed carbides in either lamellar or spherical forms play in important role in providing strength and wear resistance in as-cast pearlitic and heat-treated irons.

Ferrite: This is the purest iron phase in a cast iron. In conventional Ductile Iron ferrite produces lower strength and hardness, but high ductility and toughness. In Austempered Ductile Iron (ADI), extremely fine-grained acicular ferrite provides an exceptional combination of high strength with good ductility and toughness.

Pearlite: Pearlite, produced by a eutectoid reaction, is an intimate mixture of lamellar cementite in a matrix of ferrite. A common constituent of cast irons; pearlite provides a combination of higher strength and with a corresponding reduction in ductility which meets the requirements of many engineering applications.

Martensite: Martensite is a supersaturated solid solution of carbon in iron produced by rapid cooling. In the un-tempered condition it is very hard and brittle. Martensite is normally tempered, heat treated to reduce its carbon content by the precipitation of carbides, to provide a controlled combination of high strength and wear resistance.

Austenite: Normally a high temperature phase consisting of carbon dissolved in iron, it can exist at room temperature in austenitic and austempered cast irons. In austenitic irons, austenite is stabilized by nickel in the range 18-36 %. In austempered irons, austenite is produced by a combination of rapid cooling which suppresses the formation of pearlite and the super-saturation of carbon during austempering, which depresses the start of the austenite-to-martensite transformation far below room temperature. In austenitic irons, the austenite matrix provides ductility and toughness at all temperatures, corrosion resistance and good high temperature proper-ties, especially under thermal cycling conditions. In austempered Ductile Iron stabilized austenite, in volume fractions up to 40 % in lower strength grades, improves toughness and ductility and response to surface treatments such as fillet rolling.

Bainite: Bainite is a mixture of ferrite and carbide, which is produced by alloying or heat treatment.

6.1.1 Types of cast iron

Cast irons generally contain more than 2 % C and a variety of alloying elements. These are generally classified by a rather simple and archaic system. Classification is done on the basis of the appearance of their fracture surface, their microstructure and properties. There has been two class of cast irons historically, one having a gray fracture appearance and other having a white fracture appearance, named as gray cast iron and white cast iron respectively. Those irons having both gray and white appearance are called mottled iron. It is interesting to note that these names still apply today. Over the years, other cast irons have been evolved which have their name derived from their mechanical property, such as malleable iron and ductile iron. More recently compacted graphite iron and austempered ductile iron have been introduced. There are four factors which lead to the different types of cast irons namely, the carbon content, the alloy, the impurity content, the cooling rate and the heat treatment after casting. These parameters control the composition as well as the form of parent matrix phase present.

Comparison is given in below Table 6.1 for alternatives of cast iron; grey cast iron, white cast iron, malleable iron, ductile or nodular cast iron and Ni-hard type cast irons. Highest tensile strength and elongation percent can be getting by nodular cast iron. Nodular Cast Iron is obtained by adding magnesium just before casting. This encourages the graphite to form spheres or nodules. Ductile iron consists of graphite spheroids in a matrix of ferrite, pearlite or both. The graphite spheroids provide some much improved mechanical advantages compared to the graphite flakes in grey cast iron. Ductile cast iron is similar to grey cast iron in having a low melting point, good fluidity, castability, excellent machinability and wear resistance. However compared to grey cast iron it has improved strength, ductility toughness and hot workability.

Ductile iron as found wide acceptance and competes favourably with steel such that its use in engineering has increased in recent times as while grey cast iron and malleable cast iron has fallen in popularity as other materials such as plastics have found favour.

Table 6.1: Comparison of cast iron

Name	Nominal composition [% by weight]	Form and condition	Yield strength [0.2% offset]	Tensile strength [MPa]	Elongation [% (in 5 cm)]
Grey cast iron (ASTM A48)	C 3.4, Si 1.8, Mn 0.5	Cast	—	172	0.5
White cast iron	C 3.4, Si 0.7, Mn 0.6	Cast (as cast)	—	172	0
Malleable iron (ASTM A47)	C 2.5, Si 1.0, Mn 0.55	Cast (annealed)	33	359	12
Ductile or nodular iron	C 3.4, P 0.1, Mn 0.4, Ni 1.0, Mg 0.06	Cast	53	483	18
Ductile or nodular iron (ASTM A339)	—	cast (quench tempered)	108	931	5
Ni-hard type	C 2.7, Si 0.6, Mn 0.5, Ni 4.5, Cr 2.0	Sand-cast	—	379	—
Ni-resist type	C 3.0, Si 2.0, Mn 1.0, Ni 20.0, Cr 2.5	Cast	—	186	2

Ductile iron has a clear advantage over malleable iron for applications where low solidification shrinkage is needed or where the section is too thick to permit uniform solidification as white iron (Solidification as white iron throughout a section is essential to the production of malleable iron).

6.1.2 Advantages of ductile iron

The advantages of Ductile Iron which have led to its success are numerous, but they can be summarized easily - versatility and higher performance at lower cost. As illustrated in Figure 6.3. Other members of the ferrous casting family may have individual properties which might make them the material of choice in some applications, but none have the versatility of Ductile Iron, which often provides the designer with the best combination of overall properties. This versatility is especially evident in the area of mechanical properties where Ductile Iron offers the designer the option of choosing high ductility, with grades guaranteeing more than 18 % elongation, or high strength, with tensile strengths exceeding 825 MPa. Austempered Ductile Iron offers even greater mechanical properties and wear resistance, providing tensile strengths exceeding 1600 MPa.

In addition to the cost advantages offered by all castings, Ductile Iron, when compared to steel and Malleable Iron castings, also offers further cost savings. Like most commercial cast metals, steel and Malleable Iron decrease in volume during solidification, and as a result, require attached reservoirs (feeders or risers) of liquid metal to offset the shrinkage and prevent the formation of internal or external shrinkage defects. The formation of graphite during solidification causes an internal expansion of Ductile Iron as it solidifies and as a result, it may be cast free of significant shrinkage defects either with feeders that are much smaller than those used for Malleable Iron and steel or, in the case of large castings produced in rigid molds, without the use of feeders. The reduction or elimination of feeders can only be obtained in correctly design castings. This reduced requirement for feed metal increases the productivity of Ductile Iron and reduces its material and energy requirements, resulting in substantial cost savings. The use of the most common grades of Ductile Iron as-cast eliminates heat treatment costs, offering a further advantage [22].

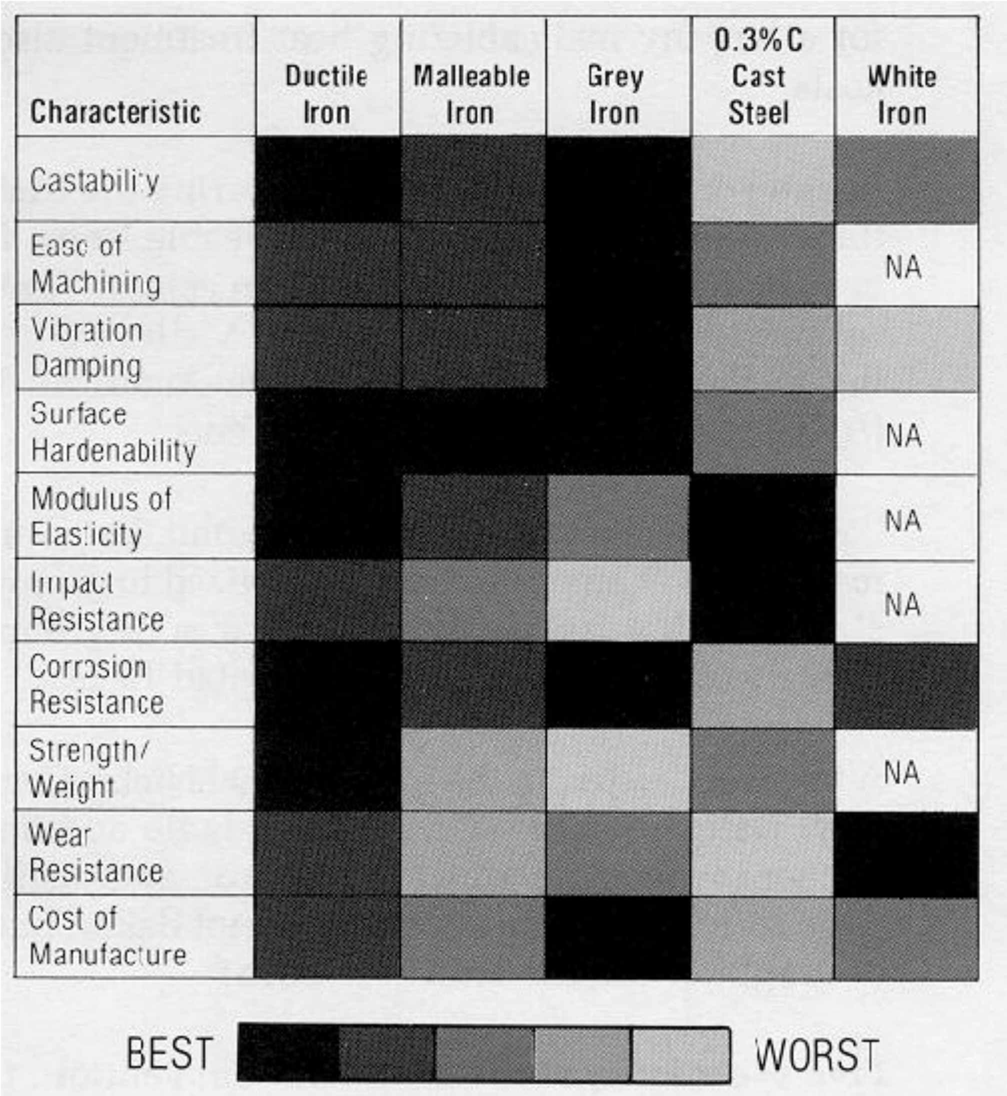
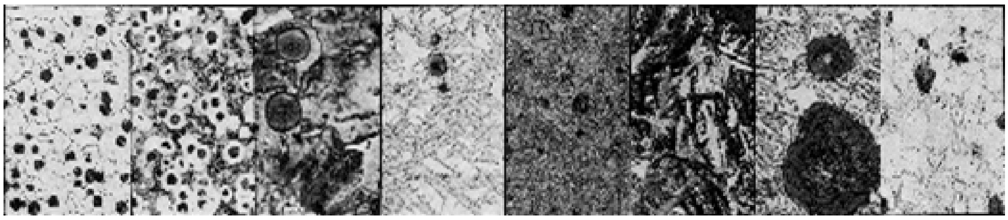


Figure 6.3 : Comparison of ductile irons

6.1.3 Ductile iron family

Ductile Iron is not a single material, but a family of materials offering a wide range of properties obtained through microstructure control. The common feature that all Ductile Irons share is the roughly spherical shape of the graphite nodules. This feature is essential to the quality and consistency of Ductile Iron, and is measured and controlled with a high degree of assurance by competent Ductile Iron foundries. With a high percentage of graphite nodules present in the structure, mechanical properties are determined by the Ductile Iron matrix. Figure 6.4 shows the relationship between microstructure and tensile strength over a wide range of properties [22].

Matrix							
Ferritic Grade 5	Ferritic-pearlitic Grade 3	Pearlitic Grade 1	Martensitic (With retained austenite)	Tempered Martensitic	ADI Grade 150	ADI Grade 230	Austenitic
60,000 p.s.i. (414 mPa)	80,000 p.s.i. (552 mPa)	100,000 p.s.i. (690 mPa)	N.A.*	115,000 p.s.i. (793 mPa)	150,000 p.s.i. (1050 mPa)	230,000 p.s.i. (1600 mPa)	45,000 p.s.i. (310 mPa)



*Approximate ultimate tensile strength 87,000 p.s.i. (600 mPa) Hard, Brittle. (Note that the magnifications are different.)

Figure 6.4 : Ductile iron family

6.1.4 Effect of graphite shape

As would be expected from the dramatic differences in mechanical properties between Gray and Ductile Irons, that modularity plays a significant role in determining properties within the Ductile Iron family. Figure 6.5 illustrates the correlation between modularity and Dynamic Elastic Modulus. This relationship not only emphasizes the strong influence of modularity on DEM, but also indicates that DEM values obtained by sonic testing can be used to measure modularity (graphite volume and nodule count should be relatively constant).

Nodularity, and the morphology of the non-spherical particles produced as modularity decreases, exerts a strong influence on the yield and tensile strengths of Ductile Iron. Figure 6.6 shows the relationships between strength and nodularity for ferritic irons in which modularity has been changed by two methods: through magnesium control, or through lead control. When nodularity is decreased by reducing the amount of residual magnesium (the most common spheroidizing agent used in commercial Ductile Iron) the nodules become elongated, but do not become sharp or spiky. The result is a 10 % decrease in yield strength and a 15 % decrease in tensile strength when modularity is reduced to 30 %. Small additions of lead reduce modularity by producing intergranular networks of spiky or plate-like graphite which result in dramatic reductions in tensile properties.

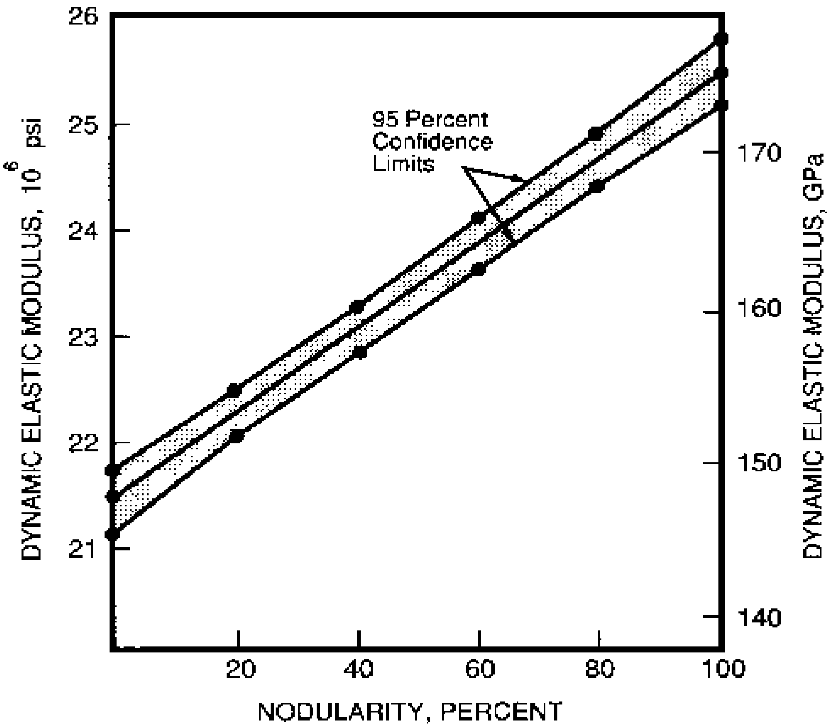


Figure 6.5 : Correlation between modularity and dynamic elastic modulus

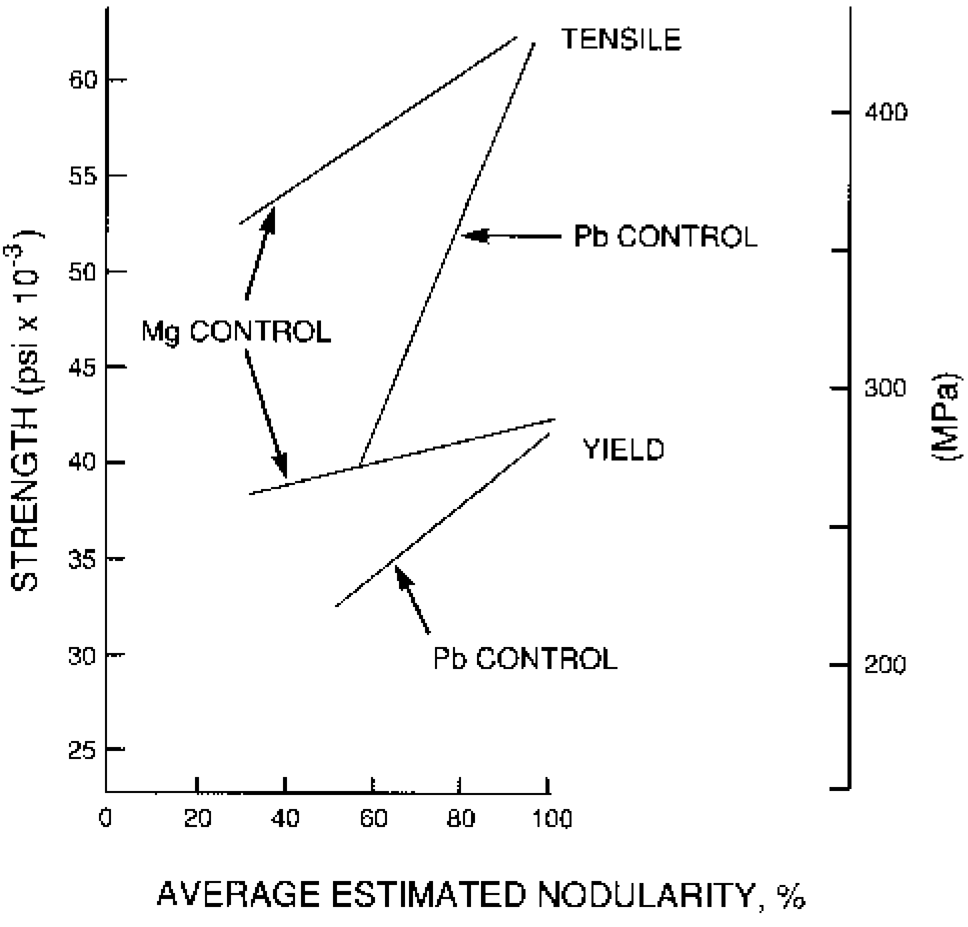


Figure 6.6 : Relationships between strength and nodularity for ferritic irons

The effect of nodularity on pearlitic Ductile Irons can be determined in Figure 6.7 and Figure 6.8 by comparing the tensile properties, at constant carbide levels, of irons with nodularities of 90, 70 and 40 %. These figures reveal two important features. First, compared to the Mg-controlled loss of nodularity for the ferritic iron in Figure 6.6, the pearlitic iron is much more sensitive to reduced nodularity. Second, at low carbide levels typical of good quality Ductile Iron, there is relatively little loss of strength as the nodularity decreases to 70 % but as nodularity deteriorates further, strength decreases more rapidly [22].

Effect of nodularity on elongation can be inferred by considering the influence of nodularity on the difference between the yield and tensile strengths, which is proportional to elongation. Both Mg and Pb controlled losses in nodularity reduce the difference between the yield and tensile stresses, indicating that loss of nodularity results in reduced elongation. The dramatic decrease in tensile strength produced by lead control indicates that the formation of spiky, intercellular graphite can severely embrittle ductile Iron.

Designers can virtually eliminate the effect of nodularity on tensile properties by specifying that the nodularity should exceed 80-85 % and that there should be no intercellular flake graphite. These criteria can be met easily by good production practices which ensure good nodularity through Mg control and prevent flake or spiky graphite by a combination of controlling flake-producing elements and eliminating their effects through the use of small additions of cerium [22].

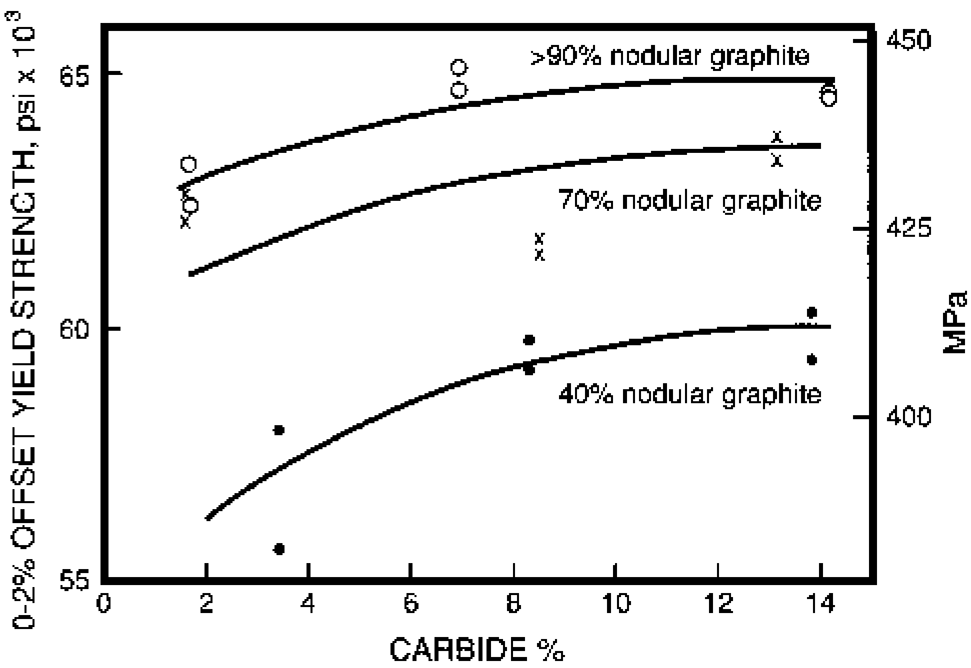


Figure 6.7 : Effect of nodularity on pearlitic ductile irons I

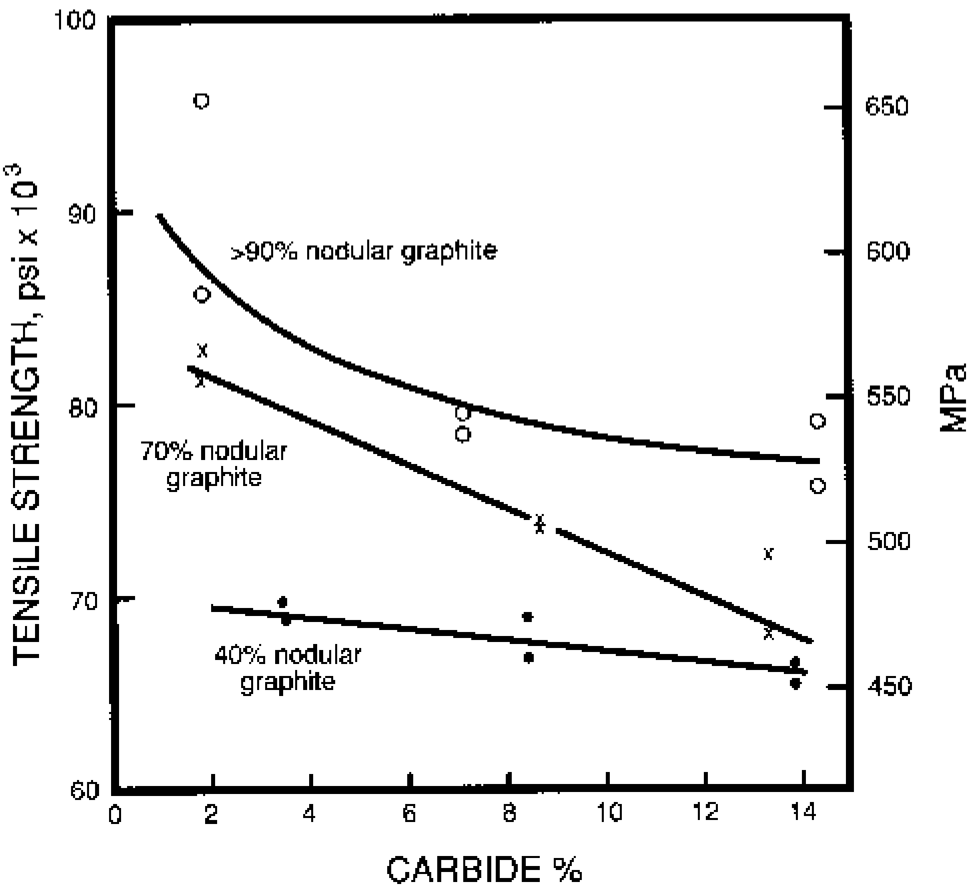


Figure 6.8 : Effect of nodularity on pearlitic ductile irons II

6.1.5 Effect of nodule count

Nodule Count, expressed as the number of graphite nodules/MM2, also influences the mechanical properties of Ductile Iron, although not as strongly and directly as graphite shape. Generally, high nodule count indicates good metallurgical quality, but there is an optimum range of nodule count for each section size of casting, and nodule counts in excess of this range may result in a degradation of properties. Nodule count percent does not strongly affect tensile properties, but it has the following effects on microstructure, which can significantly influence properties [22].

- Nodule count influences the pearlite content of as-cast Ductile Iron. Increasing the nodule count decreases the pearlite content, decreasing strength and increasing elongation.
- Nodule count affects carbide content. Increasing the nodule count improves tensile strength, ductility and machinability by reducing the volume fractions of chill carbides, segregation carbides, and carbides associated with "inverse chill".
- Matrix homogeneity is influenced by nodule count. Increasing the nodule count produces a finer and more homogeneous microstructure. This refinement of the matrix structure reduces the segregation of harmful elements which might produce intercellular carbides, pearlite or degenerate graphite
- Nodule count affects graphite size and shape. Increasing nodule count results in a decrease in nodule size which improves tensile, fatigue and fracture properties. Inoculation practices used to improve nodule count often make the nodules more spherical. Thus, high nodule count is generally associated with improved nodularity.

7. COST IMPACT OF DIFFERENT METHODS

Competition is its top level in automotive industry and crankshaft is a key component for an engine which is one of the most expensive parts among 7,000 components of a vehicle. Therefore detailed analyses have been done on crankshaft to fully understand and lower its price.

It can be concluded that geometry adjustment, weight, modification in manufacturing process and the use of alternative material are the main parameters that affect the final price of a crankshaft indeed a metal automotive component. A cost model was developed by Massachusetts Institute of Technology (MIT) aim to provide a better understanding of the total cost associated with manufacturing automotive engine components, and allows modification of pertinent material and process inputs to determine their contribution to the total cost. In same manner Nallicheri et al has a cost model for estimating the cost of a crankshaft.

In Nallicheri et al assumptions cost of crankshafts consists of variable and fixed cost.

Variable cost elements are independent of the number of elements produced such as the costs of material, direct labour, and energy whereas the fixed costs are those elements of piece cost which are a function of the annual production volume such as the costs of main machine, auxiliary equipment, tooling, building, overhead labour, and maintenance [6].

Cost break down for each manufacturing step is analysed by Nallicheri and MIT as can be seen at Table 7.1 respectively. Nallicheri done his study for 792,000 parts annually, annual volume is 100,000 at MIT’s study. As the year of the studies is different total costs are different. However percentage of the manufacturing steps is close to each other which mean both studies valid each other. As it can be seen from percentage graphs in the Figure 7.1 and Figure 7.2, raw material and machining have very close percentage values [14].

Table 7.1: Nallicheri and MIT cost break down

	$ per part	% of total
Building	0.29	0.64
Raw material	13.49	29.64
Heating	3.36	7.38
Sizing	0.62	1.36
Pre-forming	1.2	2.64
Forging	1.89	4.15
Trimming	0.48	1.05
Coining	0.16	0.35
Heat Treating	1.58	3.47
Shot blast	0.13	0.29
Inspection	0.87	1.91
Machining	21.43	47.09
Total	45.5	100

	$ per part	% of total
Building	1.9	2.7
Raw material	17.53	24.8
Cleaning	1	1.4
Shearing	0.69	1.0
Heating	1.38	2.0
Pre-forming	1.3	1.8
Forging	4.99	7.1
Trimming	0.63	0.9
Coining	0.88	1.2
Inspection	1.56	2.2
Heat Treating	2.69	3.8
Shot Clean	0.21	0.3
Machining	35.94	50.8
Total	70.7	100

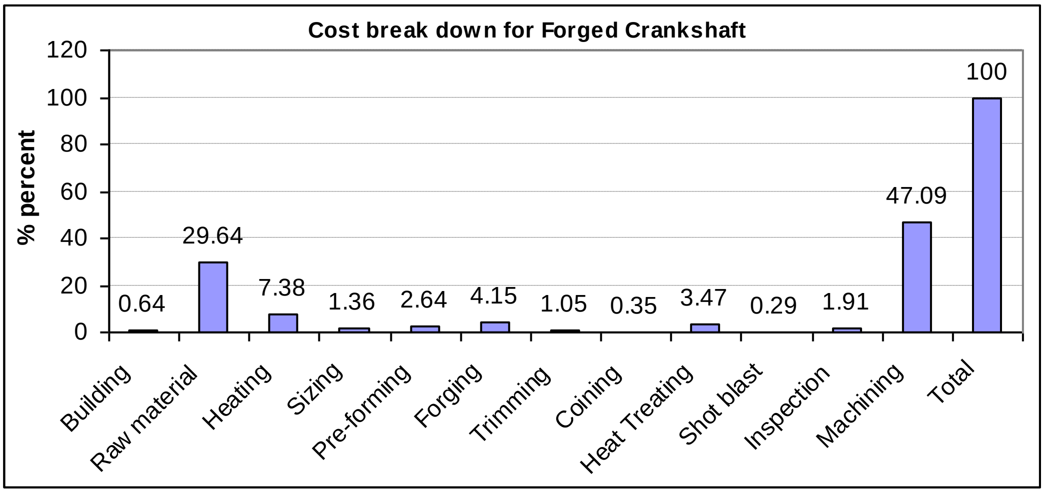


Figure 7.1 : Cost break down of Nallicheri

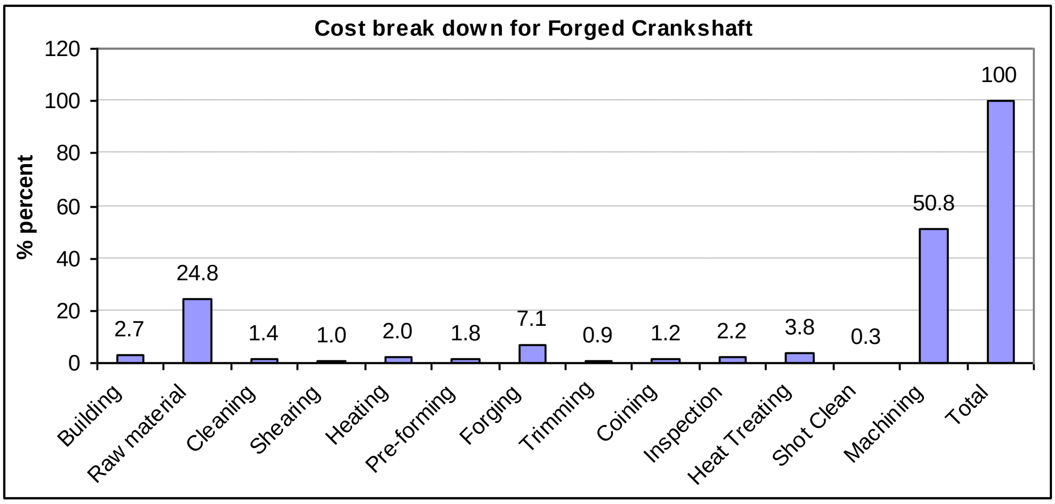


Figure 7.2 : Cost break down of MIT

Nallicheri examine the production cost of crankshafts for a production rate of 792,000 parts per year for four different materials; cast, forged microalloyed and Austempered Ductile Iron. Results of the study are shown in Figure 7.3 and Table 7.2. It can be seen that material costs are similar for all processes. Cheapest labour cost is for cast crankshaft whereas the highest price is for forged one which proportional with the complexity of the machining processes [6].

Table 7.2: Cost analyses of different crankshafts

	Cast	Forged	Microalloy	ADI
Variable Costs	26.79	28.08	26.56	31.09
Fixed Costs	12.04	17.4	11.6	18.03
Total	38.83	45.48	41.15	49.12
Forming Cost	23.26	23.74	22.83	25.87
Machining Cost	15.56	21.74	18.32	23.26
Total	38.83	45.48	41.15	49.13
Materials	17.44	13.99	15.06	16.02
Tooling	2.76	3.54	2.9	3.84
Labour	6.69	12.54	10.33	12.09
Capital	7.33	10.34	8.73	11.32
Maintenance	1.72	2.27	1.91	2.56
Other	2.88	2.89	2.22	3.29
Total	38.83	45.48	41.15	49.12

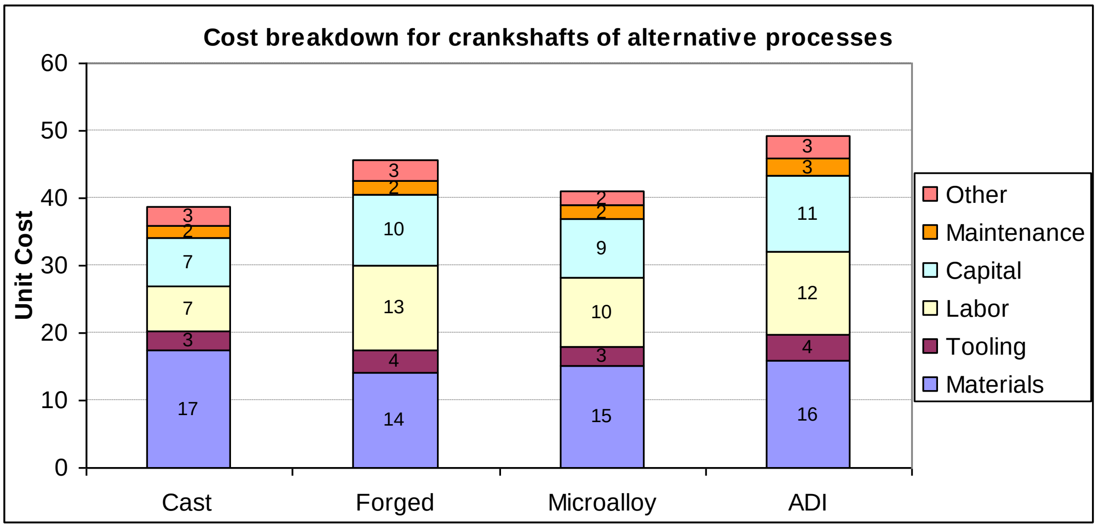


Figure 7.3 : Unit cost analyse of different crankshafts

Nallicheri also studied effect of the annual volume to cost and plot the graphs for four alternative materials as shown in Figure 7.4. Cheapest alternative is cast crankshafts. Although microalloyed cranks have higher material cost due to needles of heat treatment overall cost is lower than the forged crankshafts.

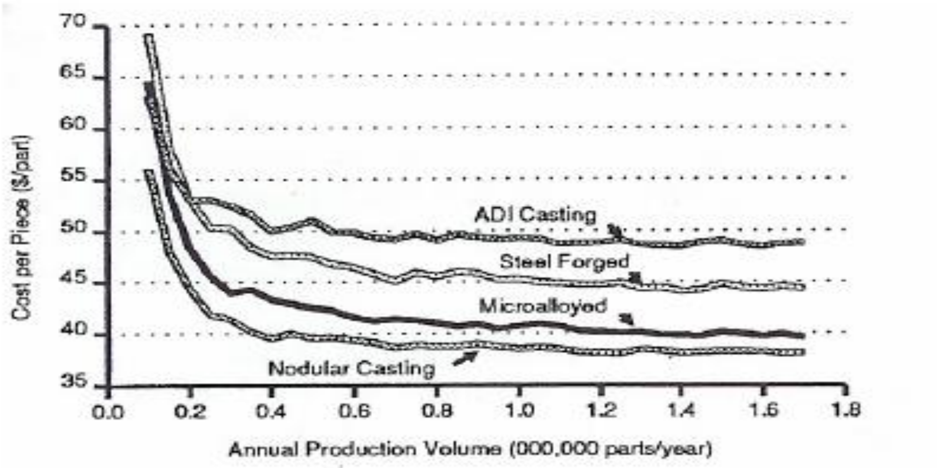


Figure 7.4 : Unit cost change according to annual volume

Cheapest alternative may not give the required high strength and other alternatives have to be considered. According to Nallicheri's study show that ADI crankshafts are cost effective if the annual volume lowers than 150,000. For higher volumes microalloyed forging steels are cost effective.

Basically according to the annual volume and strength requirement of the crankshafts a manufacturing method is going to be selected. With increasing power of the engines loads on the crankshafts are increased and cast ones can't tolerate these much forces. Microalloyed crankshafts offer best price with a good level of strength which make it favourable among these materials.

Hoffmann and Turonek use the cost model of MIT and investigate the cost effect of raw material cost, fatigue strength and machinability for forged steel crankshafts. Mainly four different raw materials selected with its different chemical composition six alternatives studied. Which are medium carbon steel SAE 1050 (CS) , medium carbon alloy steel SAE 4140 (AS) and CS-HS and AS-HS same grade of materials with a 0.10 % sulphur level and two microalloy grades (MA1 and MA2). Chemical compositions of these materials are shown in previous chapter in the Table 5.6.

In Hoffmann and Turonek's study four cylinder and six cylinder crankshafts were examined. Materials were selected according to the requirements of the engines. For all materials surface hardness and fatigue strength were evaluated that is shown in Table 5.7 in previous chapter [6].

As MIT cost model is used at this study cost parameters are the ones at Table 7.1. Piece cost assumptions are also shown in Table 7.3. Machining waste is 35 % for four cylinder crankshaft with a weight of 16.8 kg where as machining waste is 15 % for six cylinder one which is 21.4 kg.

Table 7.3: Table of cost per kg for compared materials

Material	Steel Costs $/kg
CS	0.517
AS	0.572
CS-HS	0.546
AS-HS	0.6
MA1	0.539
MA2	0.539

All crankshafts are fillet rolled and all other inputs, except as dictated by the material selection, are held constant. Results are shown in Table 7.4 and Table 7.5 respectively for four and six cylinder crankshafts.

Table 7.4: Cost data for four cylinder crankshafts

Steel Code	Annual Volume x1000	Material $	Forging $	Treat $	Machining $	Cost $	Mach'ng Invest'nt $ × MM	Total Cost x1000$
CS	100	17.5	14.3	2.9	35.9	70.6	10.5	17560
CS	200	17.5	14.3	2.9	25.5	60.2	12.3	24340
CS	300	17.5	14.2	2.9	22.9	57.5	15.2	32450
CS-HS	100	18.5	14.3	2.9	35	70.7	10.5	17570
CS-HS	200	18.5	14.3	2.9	24.5	60.2	12.3	24340
CS-HS	300	18.5	14.2	2.9	22	57.6	15.2	32480
MA	100	18.3	14.3	0	33.2	65.8	10.5	17080
MA	200	18.3	14.3	0	21.7	54.3	11.4	22260
MA	300	18.3	14.2	0	18.5	51	13.2	28500

Table 7.5: Cost data for six cylinder crankshafts

Steel Code	Annual Volume x1000	Material $	Forging $	Treat $	Machining $	Cost $	Mach'ng Invest'nt $ × MM	Total Cost x1000$
AS	100	19.8	15.5	3.1	39.4	77.8	14.9	22680
AS	200	19.8	15.5	3.1	28.6	67	17.6	31000
AS	300	19.7	15.4	3.1	27.1	65.3	23.8	43390
AS-HS	100	21.6	15.5	3.1	36	76.2	14.9	22520
AS-HS	200	21.6	15.5	3.1	24.7	64.9	17.6	30580
AS-HS	300	21.5	15.4	3.1	21.1	61.1	20.5	38830
MA	100	19.4	14.3	0	35.3	69	14.9	21800
MA	200	19.4	14.3	0	22.9	56.6	16.3	27620
MA	300	19.3	14.2	0	19.5	53	18.9	34800

Figure 7.5 and 7.6 show the total cost comparison of compared crankshafts for four cylinders and six cylinders respectively. Highest unit cost is for cast steel and alloyed steel. Lowest cost is for micro alloyed crankshafts.

By looking both 4 and 6 cylinder crankshafts data microalloyed materials are the most cost effective.

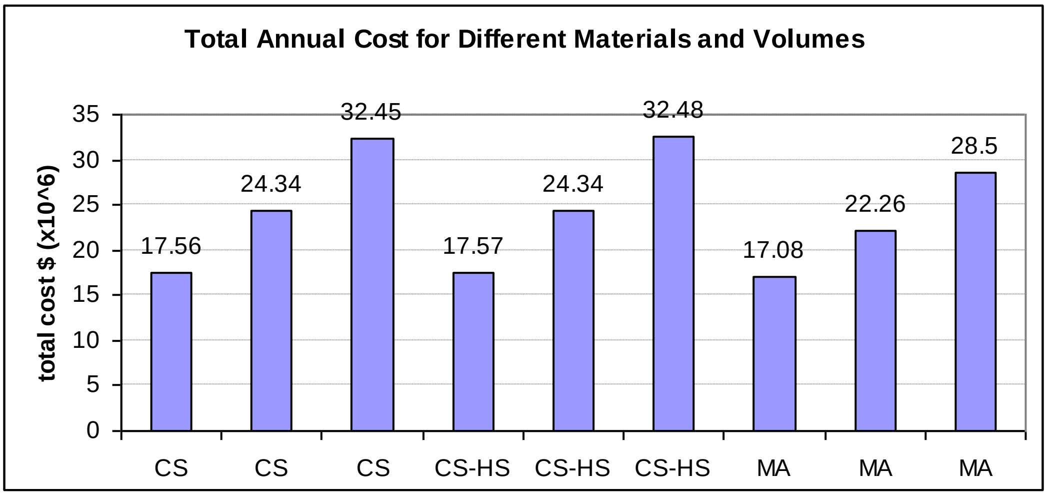


Figure 7.5 : Total cost comparison for four cylinder crankshafts

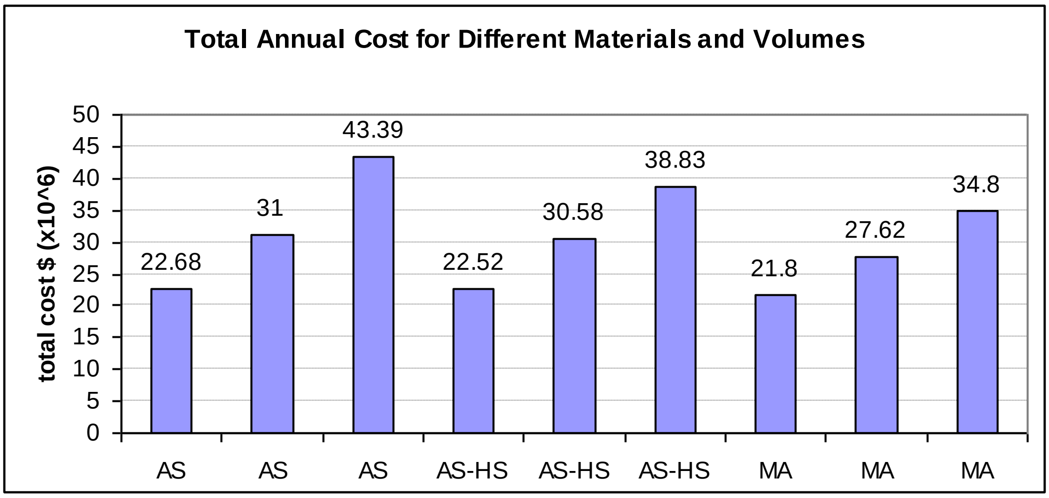


Figure 7.6 : Total cost comparison for six cylinder crankshafts

According to Hoffmann and Turonek results microalloy material could reduce the finish cost up to 19 % instead of AS and 11 % instead of CS. Better machinability characteristics has also an important role in their lower price.

8. PURPOSE OF THE STUDY

One of the automotive companies is using forged crankshaft and chase the opportunity to lower the manufacturing cost. Alternative material and manufacturing method is investigated for suitable replacement. Current crankshaft mechanical properties and chemical composition can be seen respectively in Table 8.1 and Table 8.2.

Table 8.1: Mechanical properties of forged crankshaft

	Yield Strength (MPa)	Tensile Strength (MPa)	Percent Elongation (%)
Forged	620	917	14

Table 8.2: Chemical composition of forged crankshaft

Material	C%	Si%	Mn%	Cr%	Al%	S%
Forged	0.4	0.55	1.35	0.16	0.01	0.09

Manufacturing steps of the forged crankshaft are; heating, forging, heat treating, induction hardening and inspection. 917 MPa is the tensile strength of the current forged crankshaft.

Manufacturing process section 3 and cost analyses investigation sections 5 indicate that it is possible to use casting method since mechanical properties are not very tight for the present forged crankshaft. Special operations are not used to increase the mechanical properties. According to above analysed Fatemi's study cast crankshaft has lower hardness and tensile strength than forged one. Existing forged crankshafts mechanical properties and chemical composition are close the one used in Fatemi's study. Fatemi's case cast crankshaft can be used as an alternative with proper heat treatment. Alternative to forged crankshaft, cast crankshaft can be used with ductile cast iron. Proper chemichal composition and heat treatment process can gain good mechanical properties to the cast crankshaft .

As indicated in the literature review sections there are studies to improve the mechanical properties of the crankshafts. Most of them main target is to get higher performances whereas some of the studies try to reduce tooling life time.

In this study my aim is not to increase the mechanical properties, I try to achive similar mechanical properties with forged crankshaft by using casting method. In the same time eliminate the surface treatment method by applying heat treatment method which increase the properties to desired level. Although fillet rolling has been applied to increase fatigue life of the crankshaft in forging process, my purpose is also get rid of from this extra process and acquire sufficent mechanical properties.

Achieving very close mechanical properties to forgin method by casting with elimination of surface treatment method which improve fatigue strength is the biggest challenge in this study. There are studies that get high mechanical properties via casting however in those studies both heat treatment and fillet rolling is applied to achive necessary requirement. This study may encourage the crankshaft manufacturers to use casting method instead of other expensive methods.

Design change or optimisation is not reuqiered in this study as existing crankshaft is only going to be replaced. 3D Cad drawing of the crankshaft is shared with the cranshaft manufacturer and it is manufactured in their plant. Details is explained in manufacturing section. Manufacturing steps are decided with the supplier as they have oner twenty years experience on casting.

Once crankshafts get they are visually investigated. Defected ones were marked by me and tensile testing specimens are manufactured from them by the CNC operators. 3 specimen is taken from 5 different batch for fatigue testing. Crankshafts cut into pieces for testing. After cast crankshafts were ready for testing, they were fixed to designed fixture by me and fixture is checked and a couple of test is done with my participation. Once we are sure from the fixture remaining fatigue tests were performed by operators. Engine is by engine build department according to the instrumentation guide that I gave to them. Tests are visually observed by operators and they send daily report to team.

Evaluation of the test results, coordination with the crankshaft supplier, engine build and testing department, fixing the encountered problems are my responsibility in addition to designing fixture and instrumentation locations as well as tensile specimen.

9. MATERIAL and MANUFACTURING of CAST CRANKSHAFT

9.1 Technical Drawing of the Cast Crankshaft

Cast crankshaft will have the same technical drawing with the forged one as cast one will be used in the same engine. Geometry modification create package issue crankshaft cannot fit into its place therefore same technical drawing is used only tolerances are changed due to different tolerances of forging and casting processes. Details of the 2D techincal drawing of the crankshaft's side and top view is given in below Figure 9.1 and 9.2.

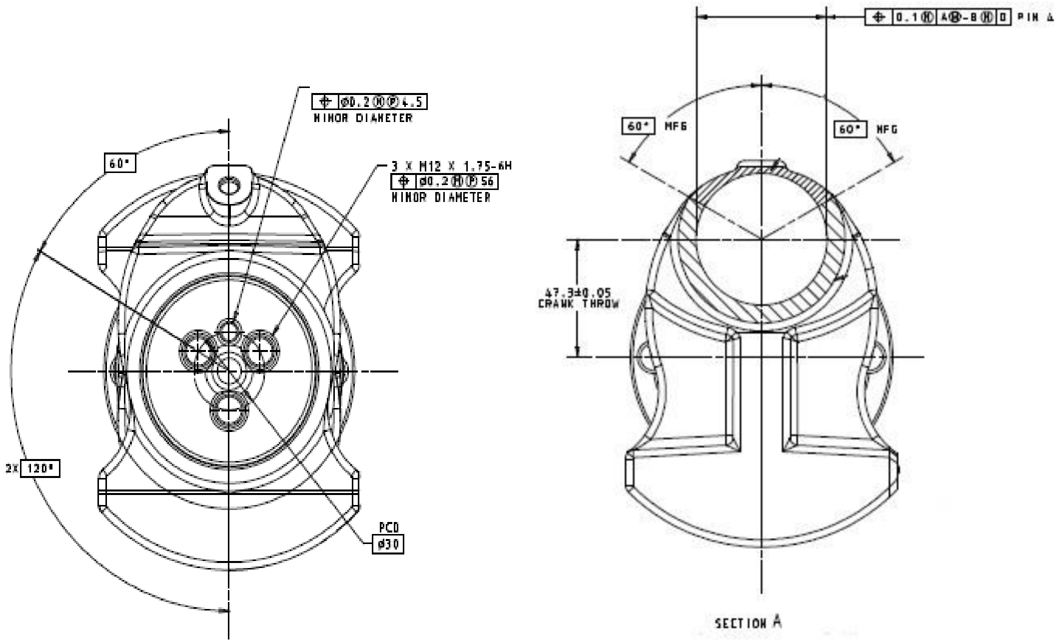


Figure 9.1 : Technical drawing of the cast crankshaft (side view)

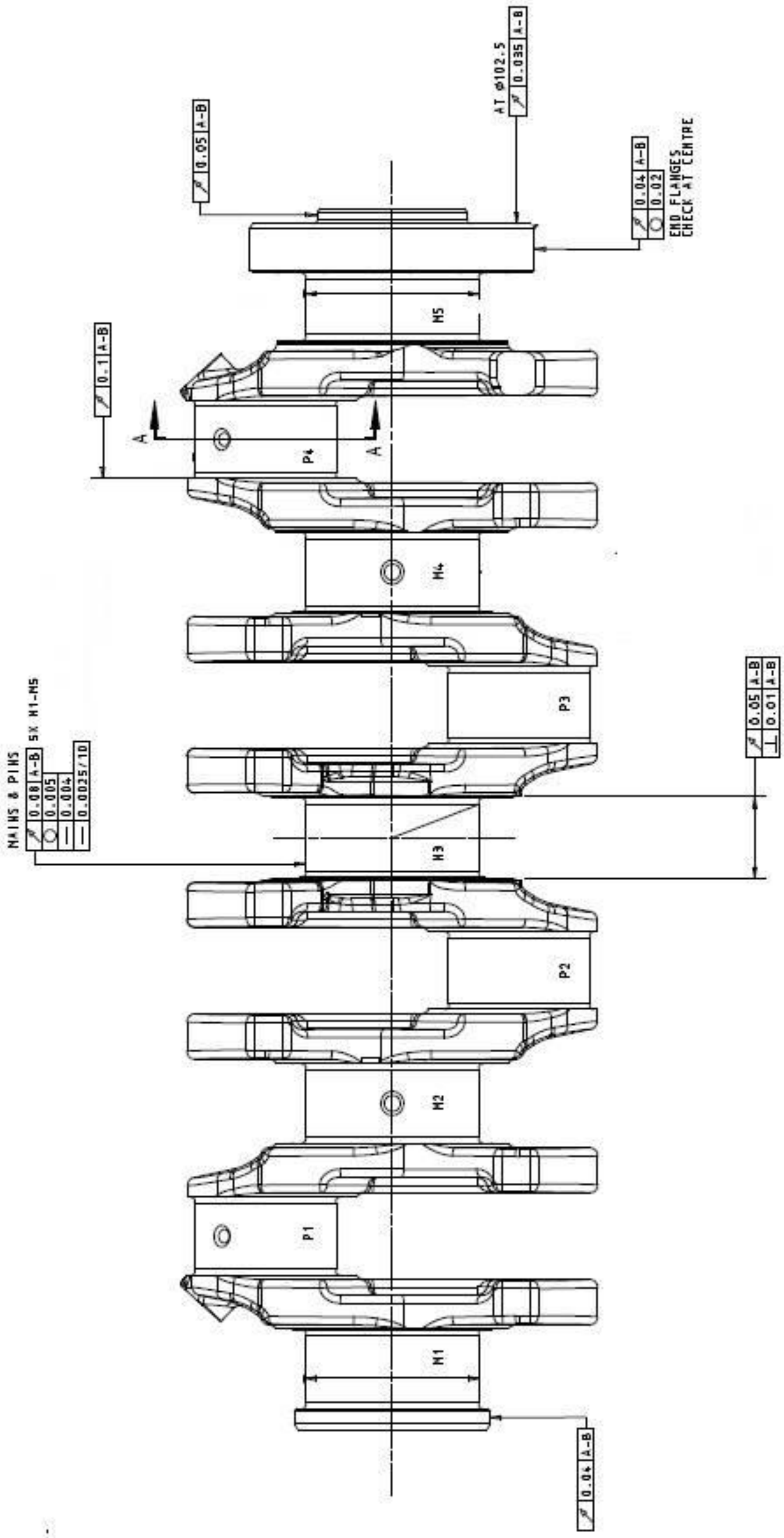


Figure 9.2 : Technical drawing of the cast crankshaft (top view)

9.2 Manufacturing Day of the Cast Crankshaft

Casting is a fabrication process whereby a totally molten metal is poured into a mold cavity having the desired shape. Upon solidification, the metal assumes the shape of the mold but experiences some shrinkage

Casting of crankshaft mainly consists of sub-steps of casting design, pattern making, molding, pouring and riser cutting. After getting the raw crankshaft annealing, fillet rolling, heat treatment processes are applied to get final designed product.

Chemical composition for a casting process is very critical to characterise its mechanical properties.

Designed crankshafts' casting material is as below Table 9.1.

Table 9.1: Chemical composition cast crankshaft

Material	C%	Si%	Mn%	Cr%	Al%	S%	P%	Ni%	Cu%	Mg%
Cast	4	2.3	0.7	0.15	0.03	0.01	0.06	1	1.1	0.025

There is 2.3 % silicon which provides the ferritic matrix with the pearlitic structure. Silicon enhances the performance of ductile iron at elevated temperature by stabilizing the ferritic matrix and forming the silicon reach surface layer, which inhibits the oxidation.

There is 0.70 % manganese. Manganese a mild pearlite promoter, with some required properties like proof stress and hardness to a small extent. As Mn retards the onset of the eutectoid transformation, decreases the rate of diffusion of C in ferrite and stabilize cementite (Fe_3C). However it should be limited up to 1 % not to face embrittlement.

There is 1.1 % copper as it is a strong pearlite promoter. It increases the proof stress with also the tensile strength and hardness with no embrittlement in matrix.

There is 1 % nickel. Nickel increases the U.T.S without affecting the impact values and it strengthens ferrite however there is the danger of embrittlement with the large additions, more then 2 % therefore it is kept at 1 %.

There is 0.15 % chromium in the content as it prevents the corrosion by forming the layer of chromium oxide on the surface and stops the further exposition of the surface to the atmosphere.

Sulphur is kept below 0.010 % although it gains good machinability, higher amount of it may cause the hot shortness.

In the same way phosphorous kept below 0.060 % because it causes cold shortness and so the property of ductile iron will be ruined.

Magnesium is the key element for the composition. Mg has spherodising effect on the graphite structure so that graphite nodules can be formed. There is 0.025 % magnesium in the content.

Sand casting technique is used to produce crankshafts. Sand casting is the most common method; ordinary sand is used as the mold material. Two piece mold is formed by packing sand around the aluminium pattern that has the shape of the crankshaft. A gating system is in-corporated into the mold to expedite the flow of molten metal into the cavity. Also in this way internal casting defects are minimised.

Casting can be summarized in four steps as desulphurisation, nodulising, inoculation and solidification. In desulphurisation step sulphur has removed from the raw material by adding calcium carbide. And it can be kept below than 0.010 %. In nodulising step magnesium is added to bath. This has done when the melt is at 1500 °C however Mg vaporises at 1100 °C. To overcome this problem Ni-Mg alloy is used for nodulising. In inoculation process is addition of small amounts of a material (inoculants) to the molten metal either just before or during pouring. Inoculation is important in maintaining good nodule shape and also high nodule numbers. Ferrosilicon, containing about 75 % silicon and 1 % aluminium is added just before pouring melted material in to the mold. 15 to 20 seconds is the necessary time to fill a mold. The last step is solidification and casted patterns cooled in the room temperature approximately at 20 hours. Initial raw material is get after cooling step. Raw crankshaft is machined after casting to remove excess materials that remain from casting.

Heat treatment process follow the casting, spheroidizing heat treatment has applied. Crankshaft is heated to 700°C, which is just below eutectoid in the $\alpha + Fe_3C$ region of the phase diagram. Duration of the heat treatment process is 15 hours. After the heat treatment grinding process is applied to get the necessary surface and tolerances. Final shape of the crankshaft can be seen in Figure 9.3. After all these steps cast crankshaft is ready for testing. 100 crankshafts were manufactured in this way and 5 of them are used for engine testing. 20 of them are used for tensile testing and rest is used for fatigue testing.

Figure 9.3 : Final shape of the cast crankshaft

10. TESTING OF THE MANUFACTURED CRANKSHAFT

Three different tests have been applied to manufactured crankshafts namely tensile testing, fatigue testing and engine durability testing. Test set-up and purpose of these tests are explained in details in this section;

10.1 Tensile Testing

Mechanical properties of the manufactured cast crankshaft are measured by performing standard tensile testing. Schematic of the tensile test machine can be seen in Figure 10.1. First a specimen is prepared from manufactured crankshaft. Geometric shape of the specimen can be seen in Figure 10.2. Diameter of the specimen is 0.6cm and outer diameter is 1.2 cm, inner length of the specimen, G distance is 3.0cm and fillet radius is 0.6 cm.

Tensile test set-up is available in many research center and universities. Hardest part of the test is to preparing the test material. They have to be machined from whole crankshaft. Parts are manufactured from the crankshafts that have manufacturing defect. According to mentioned drawing tensile testing specimens are manufactured in CNC turning machine by the operators.

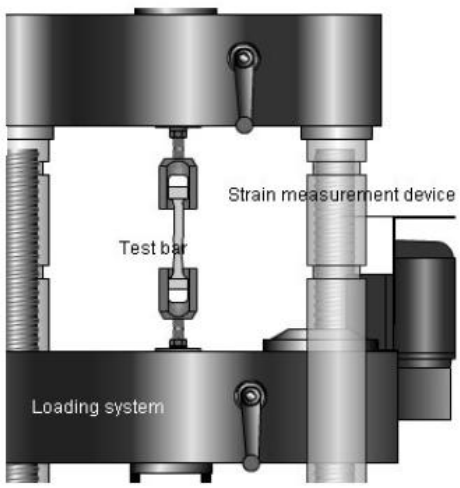


Figure 10.1 : Tensile testing machine

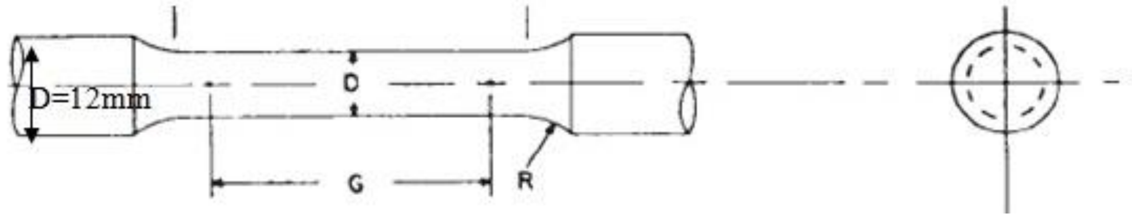


Figure 10.2 : Drawing of the specimen

These specimens are taken from below marked position of the crankshafts in Figure 10.3. First main bearing and fifth main bearing are used as shown.

Figure 10.3 : Location of the test specimen

10.2 Fatigue Testing

Fatigue performance of crankshafts is very important parameter to understand their performance. According to size and highest power and torque of the engine working condition of the crankshaft is understood. Fatigue test result indicates that whether crankshaft can resist to calculated dynamic load.

10.2.1 Fatigue test rig set-up and test cycle

Crankshafts are tested with dynamic loading with special machines. In order to fix the crankshaft to these machines fixtures are needed. A fixture is designed according to the technical drawing of the crankshaft.

Fixture is designed by me and it is created in Catia. Related 2D drawings are given to fixture supplier and parts are manufactured. As seen in the Catia drawing crankshaft is cut in into its one piece for fatigue testing.

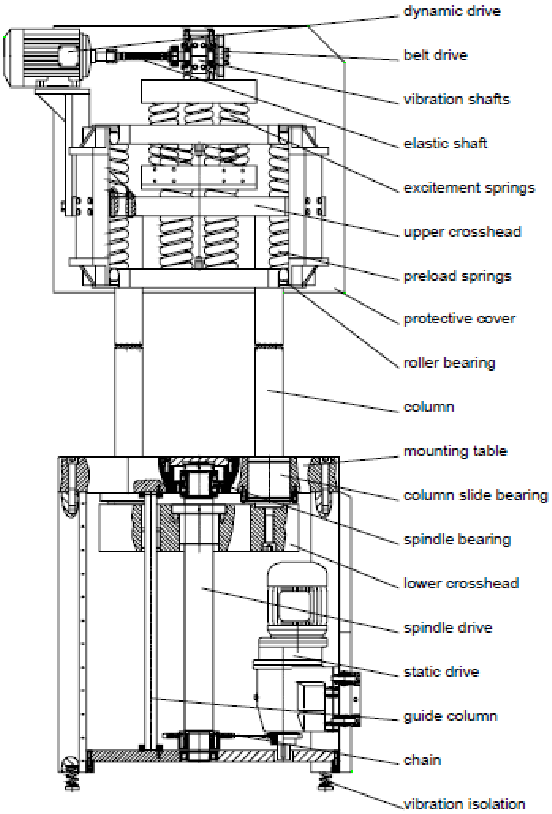


Figure 10.4 : Fatigue testing machine layout

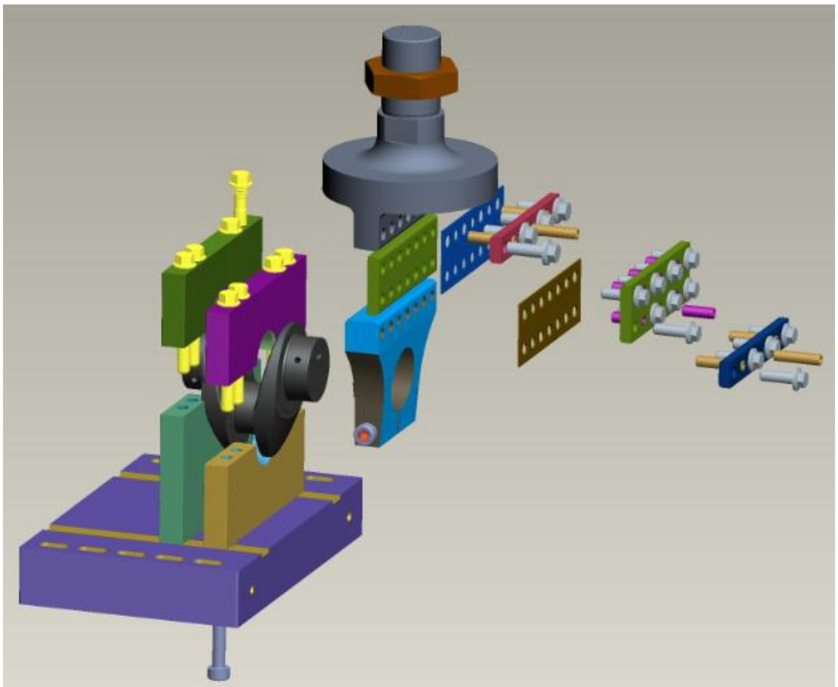


Figure 10.5 : Catia drawing of the fixture

Fatigue test has started with higher load than the estimated fatigue strength of the crankshaft. When the crank has failed load is lower 0.5kN and test is repeated. Test continues while crankshaft can resist up to 10000000 cycles. Finding fatigue strength of a crankshaft may continue two weeks. For cast crankshaft test started with 28kN dynamic load whereas it started from 32kN for forged crankshaft.

10.3 Engine Durability Test

Engine durability test is quite long, expensive and group study work. Operators build the engine with new crankshaft according to engine build guide. All necessary instrumentations are done by the operators. Location of the instrumentations are defined and showed by me to the operators. As evaluation is done according to these measurements locations are very important. During the test operators stay in the test room and in any strange condition test was stopped and they call me to investigate the root cause of the problem. After fixing the problems test has restarted and operators continue to look after the test. Achieving successful measurements from instrumentations and completing the test according to requirements is under my responsibility.

10.3.1 Test set-up

Manufactured crankshafts are tested for long hours on whole engine to give confirmation about their use, instead of their forged equivalent

Cast crankshafts are manufactured for 2 litter diesel engine. Testing engine has maximum power of 102kW and maximum torque of 350Nm. Engine is tested in performance and emission dynamo-meter. Set-up of the test cell can be seen below photo and lay-out.

Engine is rotated with electrical motor with an external controller. These testing systems are used to develop new engines and to test developed engines. Similar set-up exists in our university, ITU, at OTAM.

There are several instrumentation on the engine some of them for test cell and engine's safe running for example; water inlet pressure and temperature, turbine outlet pressure, test call room temperature parameters. Some of the instrumentations are to understand whether environmental conditions are OK and test is acceptable for example; compressor inlet temperature and pressure, inlet manifold temperature. Some other instrumentation is to protect hardware and supply necessary testing conditions such as fuel inlet outlet temperatures and pressure. Several parameters are measured to calibrate them for certain limits such as exhaust smoke value turbine inlet temperature, compressor outlet temperature, and specific fuel consumption. Photographic view and test layout with all measurement points are shown in Figure 10.6 and Figure 10.7 respectively.

In the engine durability test all these channels recorded however results of the important parameters are shown in this study.

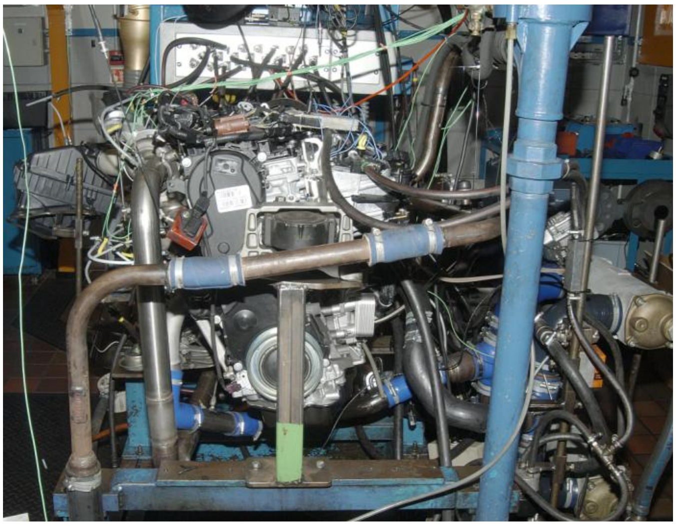


Figure 10.6 : Photo of test set-up

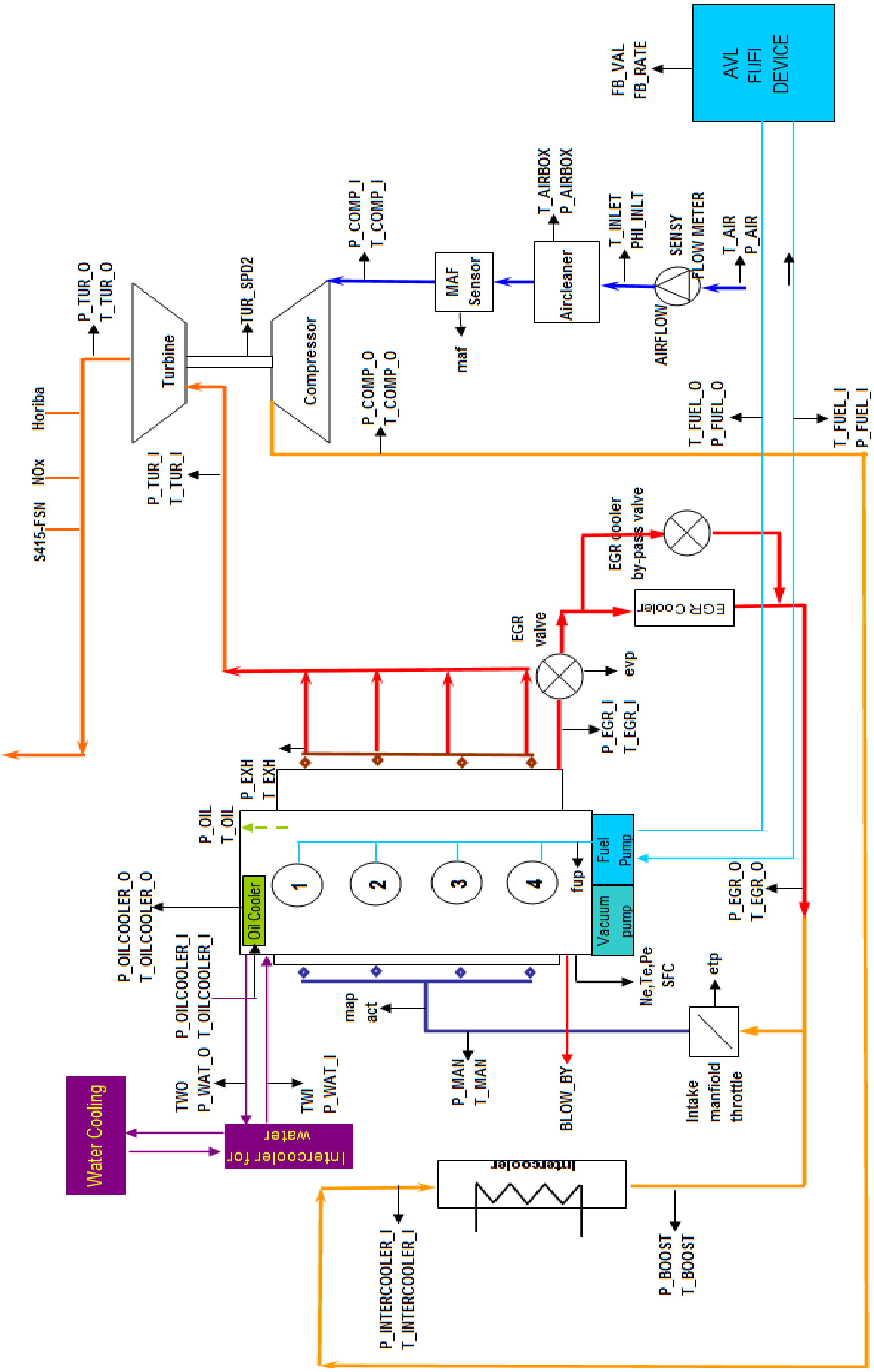


Figure 10.7 : Layout of the test set-up with measurement points

10.3.2 Purpose of the engine durability test

Manufactured crankshafts are tested for long hours on whole engine to give confirmation about their use, instead of their forged equivalent.

Whole engine is tested to understand reaction of the contacting components inside the engine such as connection rods, pistons. Crankshafts own performance is not necessary to confirm it because it may cause excess amount of vibration which result in failure of other components. Testing all parameters together allow to understand the effect of the modification to all components.

Moreover this test is 825 hour really long test that allow simulating whole life of the engine. There are approximately 4000 thermal cycle which is really tough test for a crankshaft. With high speed durability testing not only mechanical fatigue is tested also thermal fatigue resistance of the crankshaft is tested.

825 hour test is single test but it have to be observed by an operator due to safety of the test and the test equipment. Therefore engine run only daily working hours and it longs 3 months with 12 hour working everyday.

In addition to 825 hour high speed durability testing, 3 times 225 hour high speed tests were performed. These experiments are run just to confirm contacting parts are successfully complete test

No component failure during the test mean engine is capable to run 250,000km, which is whole life of the engine, without any part failure.

10.3.3 Testing method

There are different testing methods to evaluate the crankshafts. Some of these described in the Intermet Corporations studies which are; machinability test, crankshaft fatigue test and vehicle test.

In the machinability test, the machining performance and durability of cutting tools are investigated. According to tooling life a comparison matrix can be achieved.

In the crankshaft fatigue test, fatigue life of the different crankshafts is found and they are compared. This is a very critical test which is the main criteria while giving decision about the crankshafts.

In the vehicle test, crack analyses were done and performances of the cranks are evaluated under high performance condition. In addition to this noise level of the crankshaft is another comparison method. Generally better for forged ones however for this case it is not critical due to use area.

For the cast crankshaft engine test method is used for evaluation. The purpose of the engine durability testing is to investigate the system-to-system interaction durability of a diesel engine (and/or component parts) at maximum rated engine power. During the test measurement are logged from pre-defined locations. After completing the full test cycle, recorded test results and tear down reports are investigated. If results are in the acceptable limit than sign off can be given to overall engine with its all modifications.

This is a control test and can be used to qualify vehicles or components throughout the world. The test may be conducted at any location having the necessary equipment and facilities.

10.3.4 Test cycle

Engine durability test has duration of 225 hours and can be up to 875 hours. This means test will take from three weeks to nine weeks and approximate cost of such a test is 14,000 dollars to 40,000 dollars. For 225 hours test cycle 1,500 times thermal cycle applied to engine where as 4,500 cycle for nine weeks test. There is not a cold start requirement for high speed test. A complete test cycle is 740seconds. 1 minute of idle followed by 10 minutes of 100 % load maximum power speed. One cycle of the engine durability test can be seen at below Figure 10.8.

Mechanical development tests are performed in the Eskisehir. There are 4 test bed tin Eskisehir which are capable to complete these kinds of long and advanced tests.

Maximum power speed change from engine to engine and for this application it is 3500rpm. Ramp time from idle to maximum power is selected 20 seconds. It is calculated from cylinder head damage model and customer time at max power ramp time 20 seconds. During the test engine water coolant and oil temperature should not increase 105°C and 125°C respectively. Engine oil has to change every 55 hours.

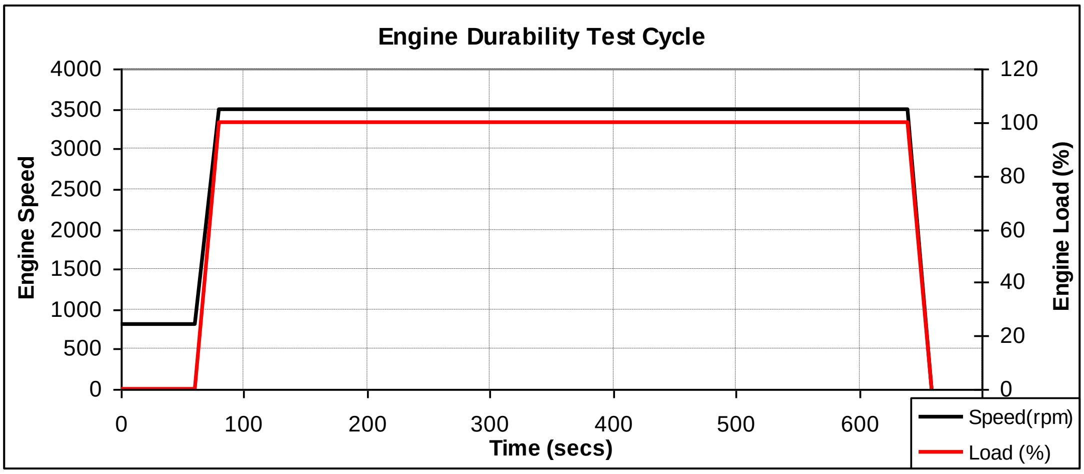


Figure 10.8 : One cycle of engine durability test

10.3.5 Preparation of the engine test cycle

Engine is a plant consists of air system, exhaust system, fuel system. All these systems affect the performance of the engine therefore during the test all components of this system have to be in defines specification limits.

Instrumentation is key procedure for a test. All decisions are given according to the instrumented sensor results. Therefore position of these sensors and correct installation of them are very important. Installation of the necessary instrumentation to measure engine data for high speed test with idle is listed Table 10.1.

Air box, exhaust gas recirculation module, exhaust lay out, turbocharger, injectors, fuel filter and other sub components have to be vehicle representative. In addition to these electrical control unit has to be latest level and calibration also very important as it can change all parameters. If vehicle level part are not available such as exhaust lay out and air box and pipes, it is possible to design components that can fulfil their functions. However these components set the inlet depression and exhaust back pressure values. Change in these parameters may harm the engine and test may fail because of un-representative conditions

Table 10.1: Instrumentation names

Parameter	**Units**	**Tolerance**
Engine torque TORQUE	Nm	+/-10%
Engine power POWER	Nm	+/-10%
Engine coolant outlet temperature (TWO)	ºC	+/- 2
Test Cell Temperature (T_AIR)	ºC	+/- 2
Inlet manifold air temperature T_MAN	ºC	+/- 2
Inlet manifold air pressure Boost_pr	mbar	
Exhaust manifold gas temperature T_EXH	ºC	+/- 2
Lubricant temperature T_OIL	ºC	
Lubricant pressure P_OIL	bar	
Fuel pump Inlet/outlet pressures P_FUEL_I & P_FUEL_O	mbar	+/-1%
Fuel pump Inlet/outlet temperatures T_FUEL_I & T_FUEL_O	mbar	+/-1%

10.3.6 Testing process

All operating systems have special conditions that have to be checked before testing. From daily life car users know some of these parameters such as check oil level, coolant water.

There are some differences from the vehicle to test cell. One of them is the cooling system. Engine water is cooled in the test cell out side of the engine. This is regulated according to vehicle cooling targets. Another one is the engine cooling fans. Engine can be cooled in the vehicle due to the air flow results in vehicle speed. However in test cell external fans are used to keep room temperature at 25°C. In addition to these intercooler of the engine is not vehicle representative. External cooler used to cool the compressed air. This is also adjusted according to pre defined intercooler efficiency target.

All preliminary check parameters can be seen in Table 10.2.

Table 10.2: Preliminary check table

Preliminary Check Table		
1	Electronic control unit and calibration is the latest level	☑
2	Air Filter is new and vehicle representative	☑
3	Check if the oil is new and it is at its maximum level	☑
4	Check the belt tension	☑
5	Check coolant water and system pressure	☑
6	Check dyno cooling fans	☑
7	Check exhaust gas recirculation module valves	☑

Moreover before the engine start to test, some prevention parameters should be defined in the computer that controls the test. It is possible to define a warning and than safe shutting down of the engine to prevent any serious fire or accident. Following parameters have to be set into a limit; engine speed, torque, engine coolant temperature, oil temperature and pressure, exhaust temperature, fuel pressure and temperature, intake manifold pressure and temperature. For example if the engine coolant temperature go beyond the 105 °C system will give alarm and if the temperature go beyond the 110 °C engine directly will go to idle and than shut down after a minute. If such prevention not used engine may fail after 20 minutes run at 110 °C as it is very high for all components.

Test can be started when all preliminary checking parameters are defined. However first five cycle have to be observed. Exhaust bask pressure, inlet depression values and all sensor measurements should be monitored. If any sensor is not measuring or miss measuring it should be replaced.

Engine test is a long process that continues nine weeks; therefore there are some criteria that have to be followed.

All mentioned measurement channels have to be recorded. Recording have to be continuous and the sampling time is 1 hertz. Test cell computer is capable for this recording. In addition to these measurements smoke value is recorded. This is special device that can only measure steady state points not allow continuous measurement. It is used while logging engine performance curve. An opacity meter measures the blackness of the exhaust flow and scales it from zero to ten.

Maintenance check and part changes are also available. For every 60 hours following items are applied;

- Check oil level and restore to its maximum level.
- Change the lubricant filter
- Check coolant level and top up if necessary.
- Stop the continuous test cycle and record full-load curve. Check if the curve in the 5 % of the nominal power rating.
- Examine all boost, oil, water exhaust pipe for any leak
- Visually inspect crankshaft damper for signs of cracks in the rubber.
- Check EGR function at idle by measuring air flow.
- Check fuel filter and fuel system for leakage and record if detected.
- Change air filter inside the air box

In addition to these this at the end of the test;

- Check lubricant pressure and temperature by logging for at full-load curve.
- Check crankcase blow-by level. Blow-by is the amount of unburned fuel and exhaust gases escape around the piston rings and enter the crankcase. If the amount of these gases is uncontrolled, there will high amount of gas in the oil pan. When these gases are condensed, oil would become diluted and it can’t lubricate the engine.

This measurement is done for selected engine speed’s all pedal positions and filled in to a table. All values have to be lower than the accepted maximum level.

- Log a final full-load curve.
- Remove drive cover and inspect chain
- Tear down the engine and inspect all sub-components. If there is any failed part, send to supplier for detailed analyses.

During the test an operator is monitoring the test from test cell computer. Any strange noise or alarm can be detected by the operator engine stopped. Test requesting engineer is informed about the situation. If any failure has happened, photo of the failure is captured. After prolonged shut downs, warm engine before staring the test cycle at 2000rpm 50 % load for five minutes. In addition to these there may be torque or power decrease during the test. If toque drops 30 % of its nominal specification, test has stopped and test requesting engineer will informed.

10.3.7 Evaluation and presentation of the test results

Hot speed with idle test is continuously monitored by an operator. All events should be logged by the operator. In the final report all modified and replaced components have to be mentioned with their timing according to the operator’s records. If there is any failed component, its analyses have to be in the report. Tear down observations with photographs are put in to report.

Recorded channel data is plotted for the following parameter; torque, power, specific fuel consumption, ambient temperature, inlet manifold temperature and pressure, exhaust temperature, fuel pressure and temperature, coolant temperature, lubricant temperature and pressure, smoke value, fuel consumption, inlet depression and exhaust back pressure. All these parameters are plotted vs. engine speed. In addition to these blow-by map is investigated that should be logged at the end of the test.

11. RESULTS of the TESTS

All performed tensile, fatigue and engine durability test results are presented in this section.

Crankshaft is manufactured to have high nodule count geometry and heat treatment is also performed to have spheroidized matrix which improve the mechanical properties of the ductile iron. Achieved crankshaft has a similar metallographic matrix given in the Figure 11.1

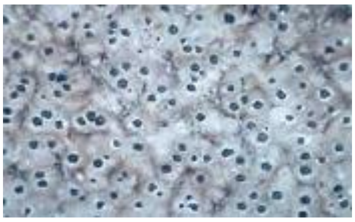


Figure 11.1 : Metallographic view of nodular cast iron matrix

11.1 Results of Tensile Testing

A pre-load of 50N/mm^2 is applied and velocity of the experiment is 10mm per minute. Flow rate is 7mm per minute. In this way five different specimens are tested. First main bearing and fifth main bearing show different characteristics and average of the results are given in Table 11.1 and 11.2. One of the crankshafts the tensile testing graph is shown in Figure 11.1 and Figure 11.2.

Table 11.1: Mechanical properties of first main bearing

Diameter of the Specimen	Area of the section	Rm	Fmax	Fracture Elongation %	Toughness N/mm^2
6	28.26	910.38	24.22	0.1	940.35

Table 11.2: Mechanical properties of fifth main bearing

Diameter of the Specimen	Area of the section	Rm	Fmax	Fracture Elongation %	Toughness N/mm^2
5.8	26.41	815.42	21.56	4.4	280.15

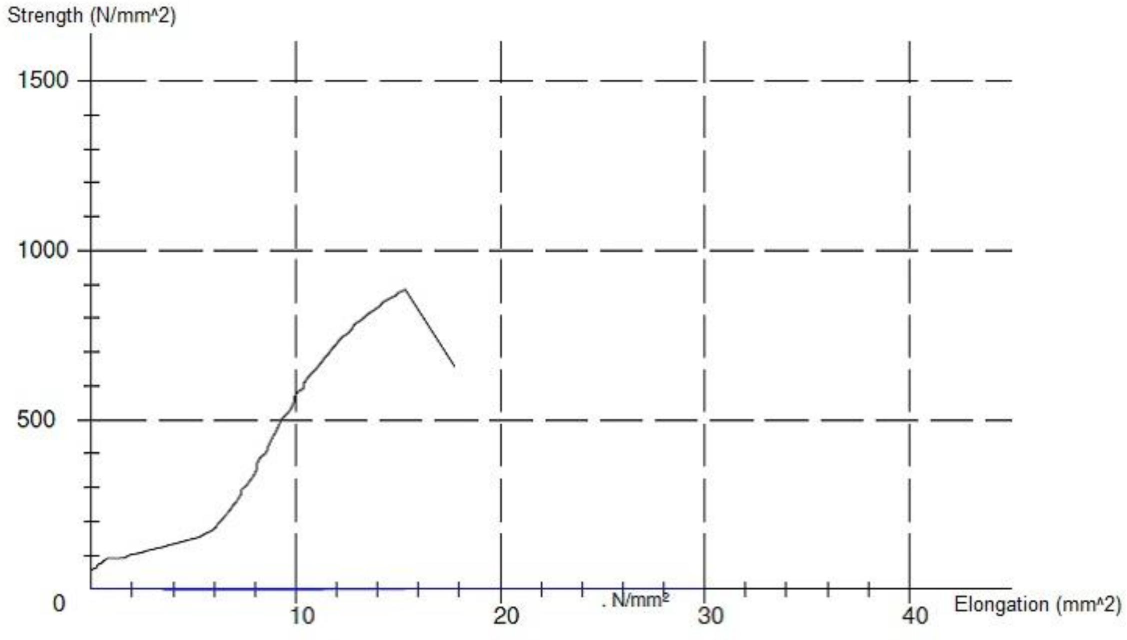


Figure 11.2 : Tensile testing graphic of first main bearing

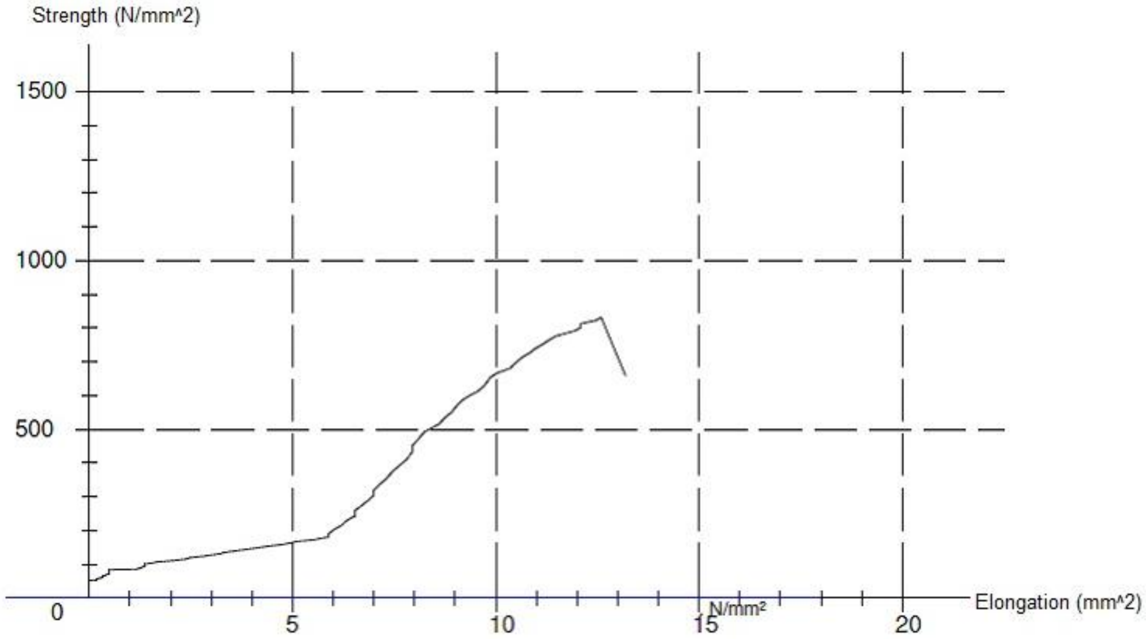


Figure 11.3 : Tensile testing graphic of fifth main bearing

11.2 Results of Fatigue Testing

Fatigue test result of the both cast and forged crankshaft are plotted in the same graph and can be seen in below Figure 11.3. As seen in the figure cast crankshaft has approximately 20 % lower fatigue strength than forged crankshaft.

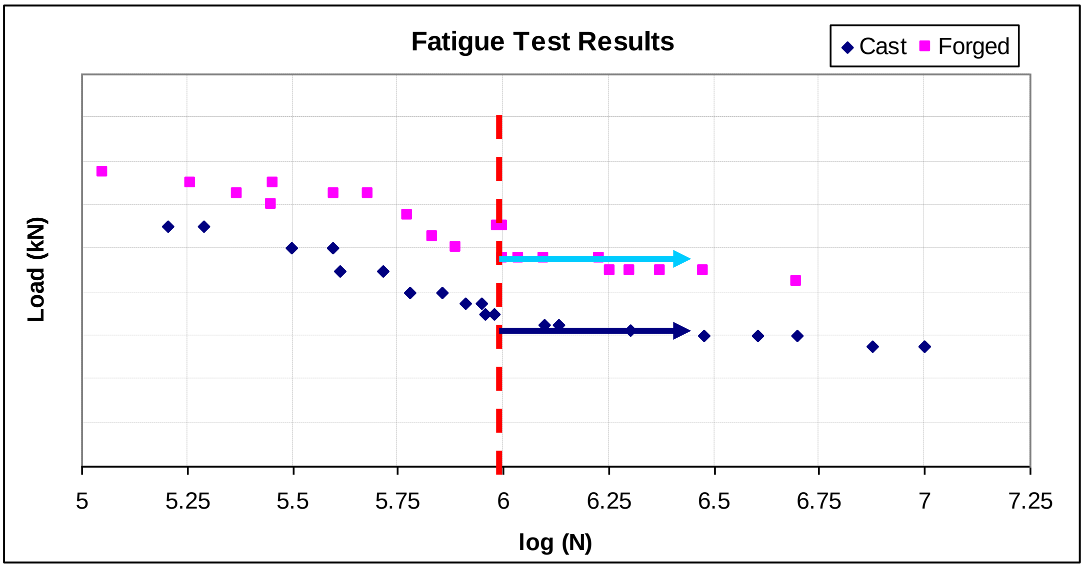


Figure 11.4 : Fatigue test result comparison

11.3 Results of Engine Durability Test

825 hours high speed test is completed with success and none of the components failed during the test. Test was performed with latest level vehicle calibration and components and all important parameters were monitored during the test, none of them pass the limits

11.3.1 Engine component update and failure reports

Some minor failure happened during the test which can be faced all tests. Record of all applications can be found in table. Mainly oil filter change and, oil addition was done during the test as instructed. And for checking engine power curve data is recorded at pre-defined points. Details of the logged report during the whole test are in Table 11.3.

Table 11.3: Updates during engine durability testing

Record of the 825 hour high speed test	
Test Hours	**Reason for Update/Description of Failure**
0	Power curve recorded, test started
10	Transmission replaced
	New oil pick fill up pipe installed
18	Transmission shaft replaced
33	Clutch and transmission was replaced
	Exhaust manifold stud bolt was replaced
	Exhaust gas temperature sensor was replaced
70	Oil filter was replaced
100	Oil dipstick pipe bracket was removed
	Oil pressure sensor was placed to the oil pan
120	Power curve recorded
150	Oil filter was replaced
225	Oil filter was replaced, Power curve recorded
300	Oil filter was replaced, Power curve recorded
360	Power curve recorded
375	Oil filter was replaced, Power curve recorded
420	Power curve recorded
450	Oil filter was replaced
465	Oil filter was replaced
480	Power curve recorded
510	Oil filter was replaced
540	Power curve recorded
570	Oil filter was replaced
600	Power curve recorded
630	Oil filter was replaced
660	Power curve recorded
690	Oil filter was replaced
720	Power curve recorded
750	Oil filter was replaced
825	End of test, Power curve and blow-by recorded

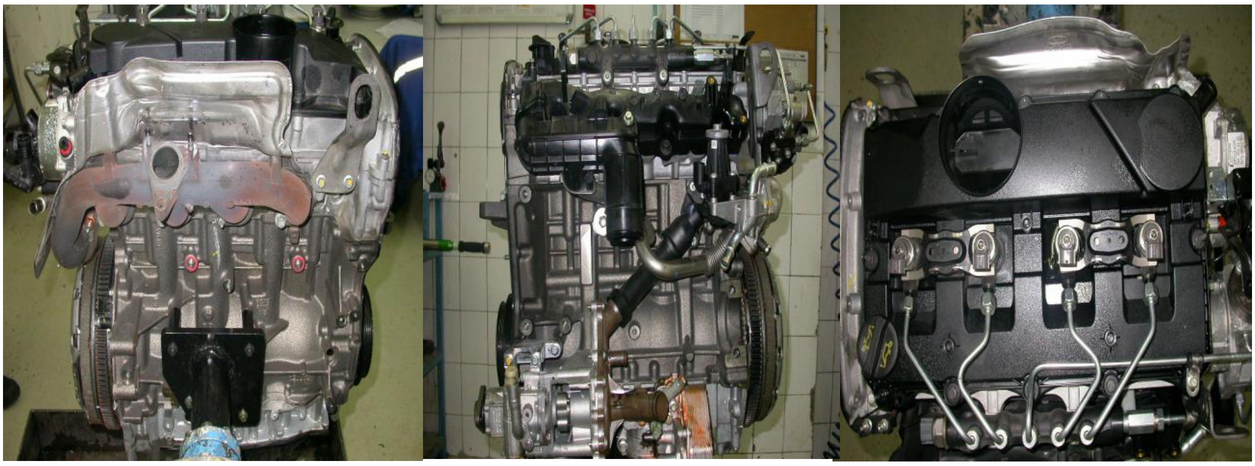
11.3.2 Engine component investigation

Engine can run smoothly up to the end of the test. None of the critical components fail for the period of the test. However tear down results are also important, critical cracks failure indications can be found.

During the test an operator is monitoring the test from test cell computer. Any strange noise or alarm can be detected by the operator engine stopped. Test requesting engineer is informed.

After finishing the test all components of the engine is tear downed to investigate whether there is any crack or disturbed area.

General outer view of engine is fine. No serious issue is found on engine. Exhaust, intake and top photos can be seen in Figure 11.4.



Exhaust side Intake side Top view

Figure 11.5 : General view of the engine

Gear and pulley system of engine is in good condition. Guides have no mechanical damage and no serious wear over chain sliding surfaces as seen in Figure 11.5.

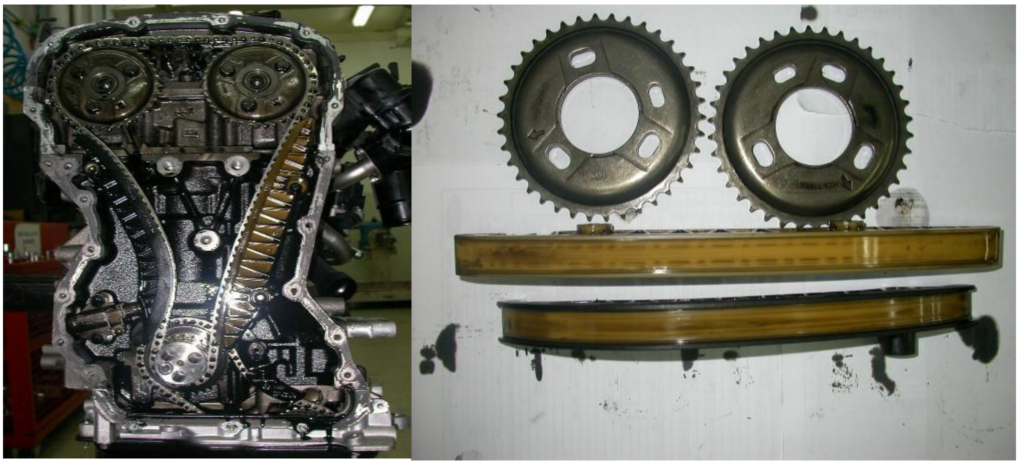


Figure 11.6 : Gear and pulley system

Injector tips are coated with partial carbon layer which can be considered thick according to running time of engine however they can inject fuel at an acceptable level. Injectors are shown in Figure 11.6.

Figure 11.7 : Injectors of the engine

Connecting rod big end bearings are in good condition No score caused by debris or foreign material observed on inner surfaces. Conrod side bearings are more polished. Debris embedment is not found. Score was not observed on *main bearing* surfaces. Distinctive polishing was seen on middle section of cap side bearings. Debris embedment was not found. Details can be seen in Figure 11.7

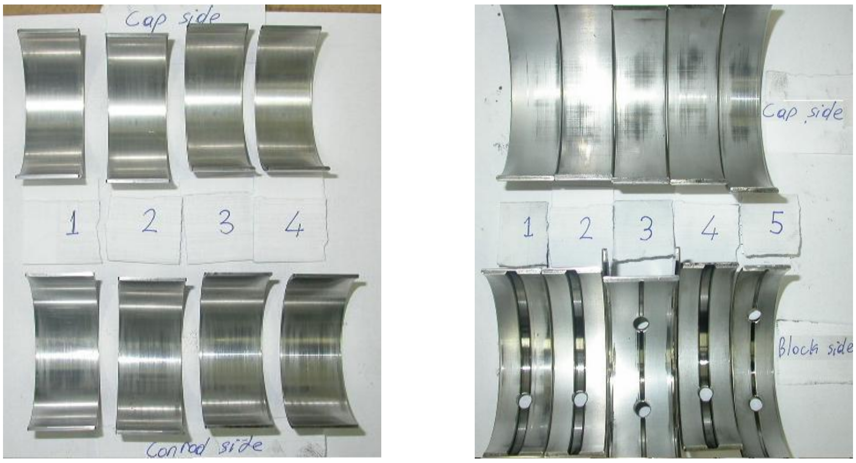


Figure 11.8 : Connecting rod big end bearings and main bearings

Pistons are generally in fine condition as shown in Figure 11.8. Top faces of pistons have no mechanical damage. No crack was detected at piston crown area. Injection signs are normal. Carbon contamination at top, first and second lands are in normal levels. 1st and 2nd compression rings are free in groove and wear is in acceptable levels. Oil rings are also ok.

1st piston top view | 1st thrust side view | 1st antitrust side view

Figure 11.9 : Overall view of piston

Connection rods have no damage or crack as it can be seen in Figure 11.9.

Figure 11.10 : Connection rods

Both thrust and antitrust sides of *cylinder wall* is in good condition. No scuff or score is observed on cylinder walls. Honing lines are visible. Cylinder wall is shown in below Figure 11.10.

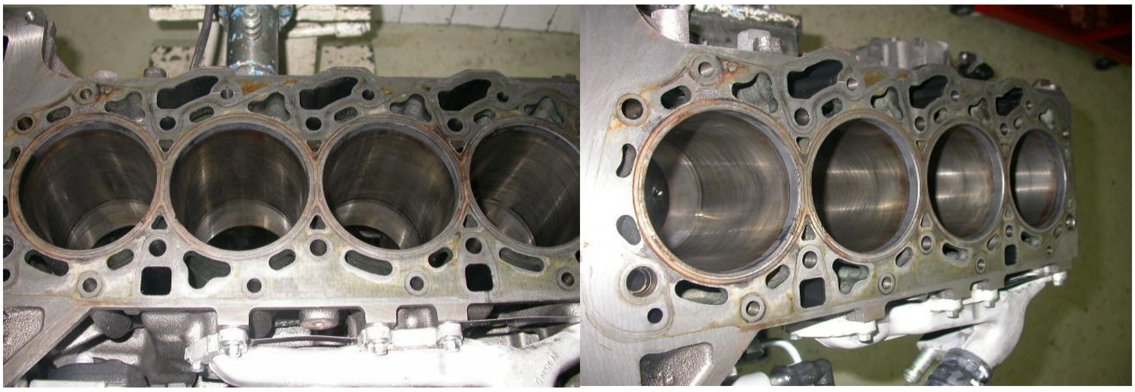


Figure 11.11 : Cylinder wall

Both *exhaust and intake camshaft* is in good condition. No scuff or score is observed as observed in Figure 11.11.

Figure 11.12 : Exhaust (above) and intake (below) camshafts

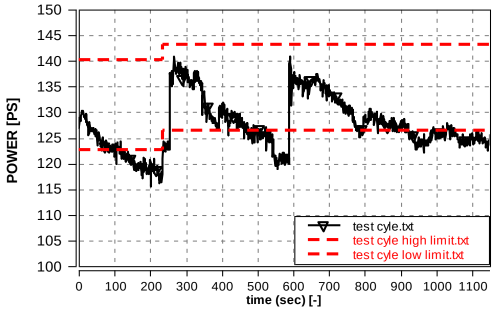
General condition of crankshaft is good. No deep score or debris embedment is found on 1st and other main and conrod journals. Crack is not observed on whole shaft. Photo of the crankshaft can be seen in Figure 11.12.

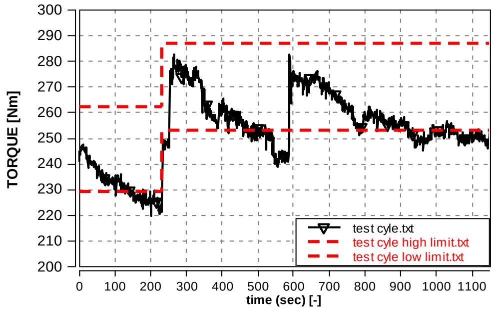
As a conclusion for the tear down observation engine is in good condition. No crucial mechanical damage is observed. The aim of the test is to validate the die cast crankshaft and crankshaft and the relevant components are in good condition and no problem related with cast structure was found.

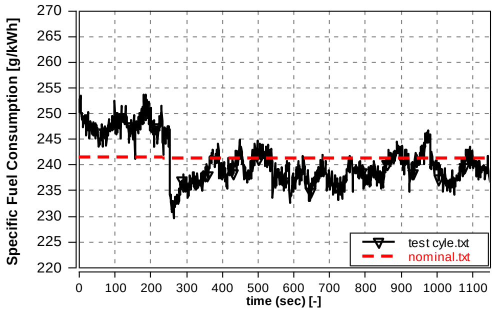
Figure 11.13 : Crankshaft photo

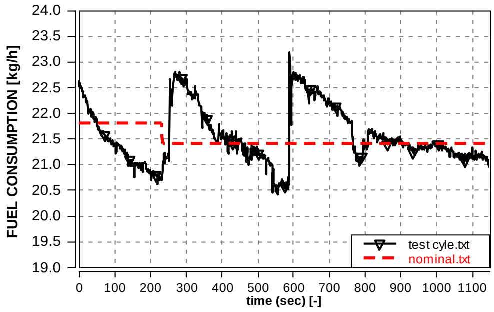
11.3.3 Engine evaluation parameters and plots

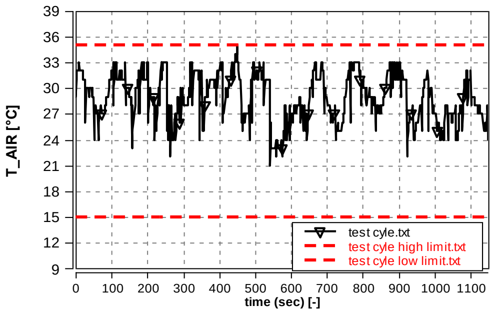
Engine durability test consist of continuous test cycle as defined earlier. During these tests power and torque should not drop the 30 % of the nominal values. During the hall test none of the observed parameters exceeded the limits. One cycle's graphs are given below in the following sequence; power, torque, specific fuel consumption, fuel consumption, ambient temperature, inlet depression, exhaust back pressure, smoke, oil pressure, oil temperature, inlet manifold pressure, inlet manifold temperature, engine coolant temperature, blow-by, fuel pressure and fuel temperature vs. time scale.

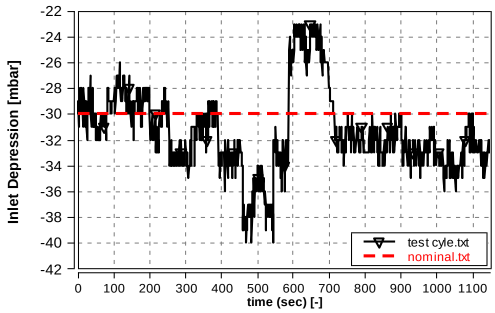


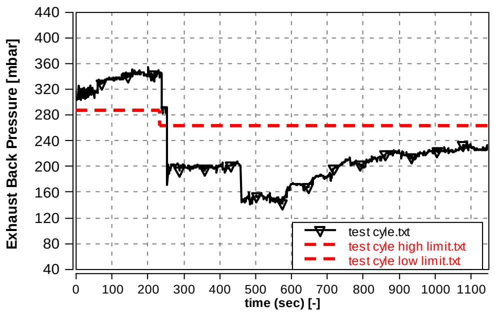


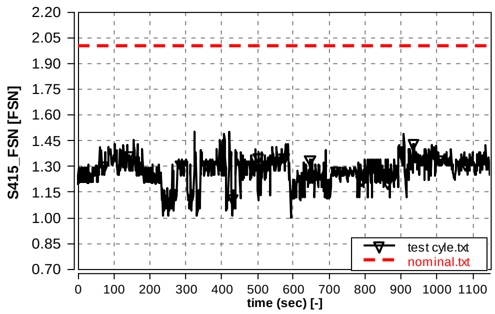












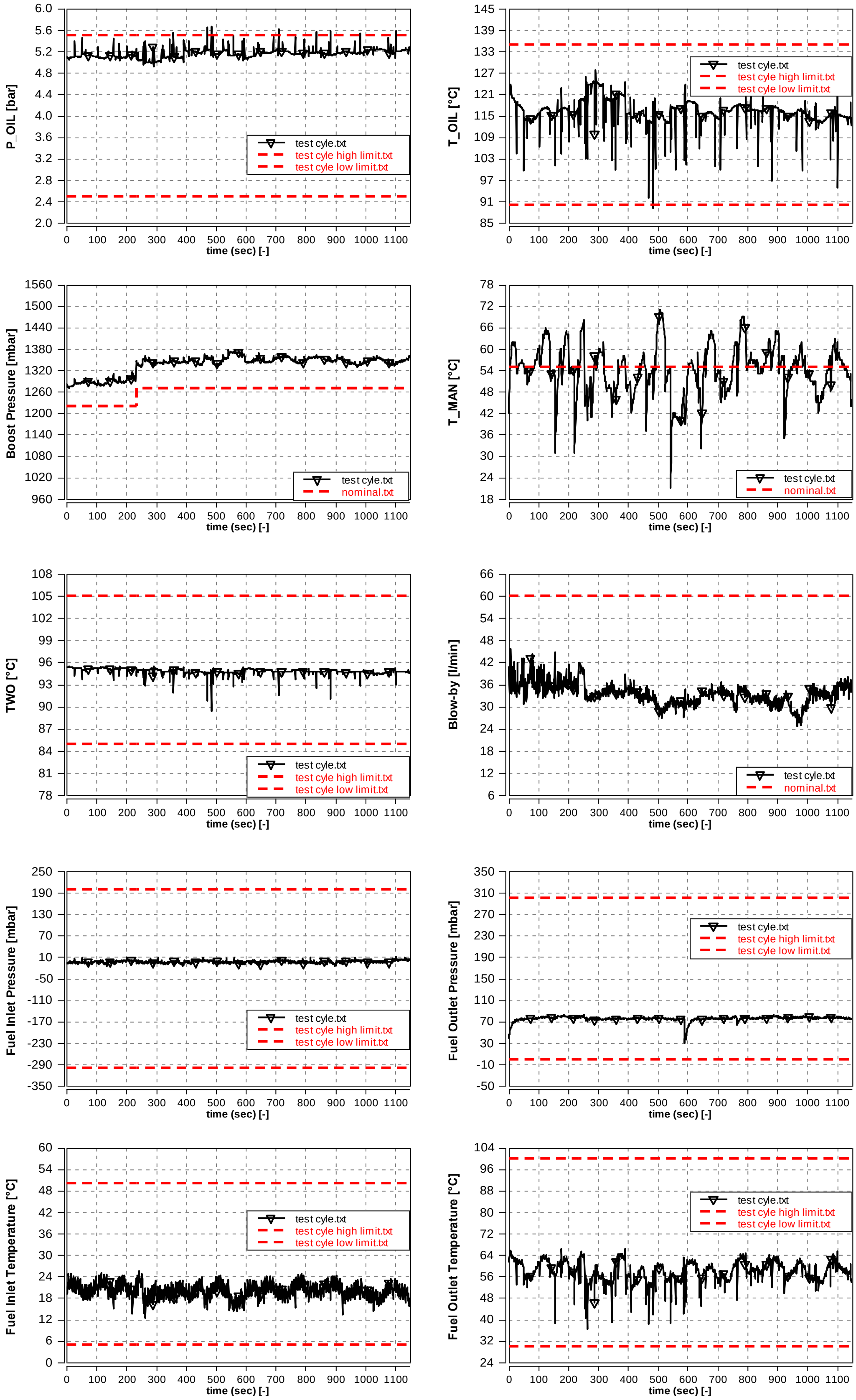


Figure 11.14 : Record of the decision parameters during one cycle

In addition to these power curve data was logged at pre defined points of the 825 hour test. Approximately every 60th hour of the test power curve was logged. This curve has to be the 5 % of the nominal power curve. Otherwise there was problem at one of the components; however such a condition was not seen throughout the test.

Plots of the recorded data according to engine speed can be seen below figures in the following sequence; power, torque, specific fuel consumption, fuel consumption, ambient temperature, inlet depression, exhaust back pressure, smoke, oil pressure, oil temperature, inlet manifold pressure, inlet manifold temperature, engine coolant temperature, blow-by, fuel pressure and fuel temperature vs. engine speed.

Figure 11.14 show the labels colour and type of the each recorded data.

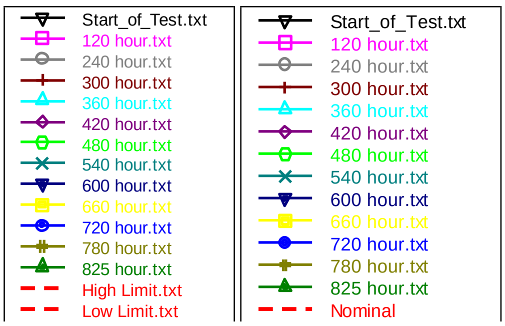
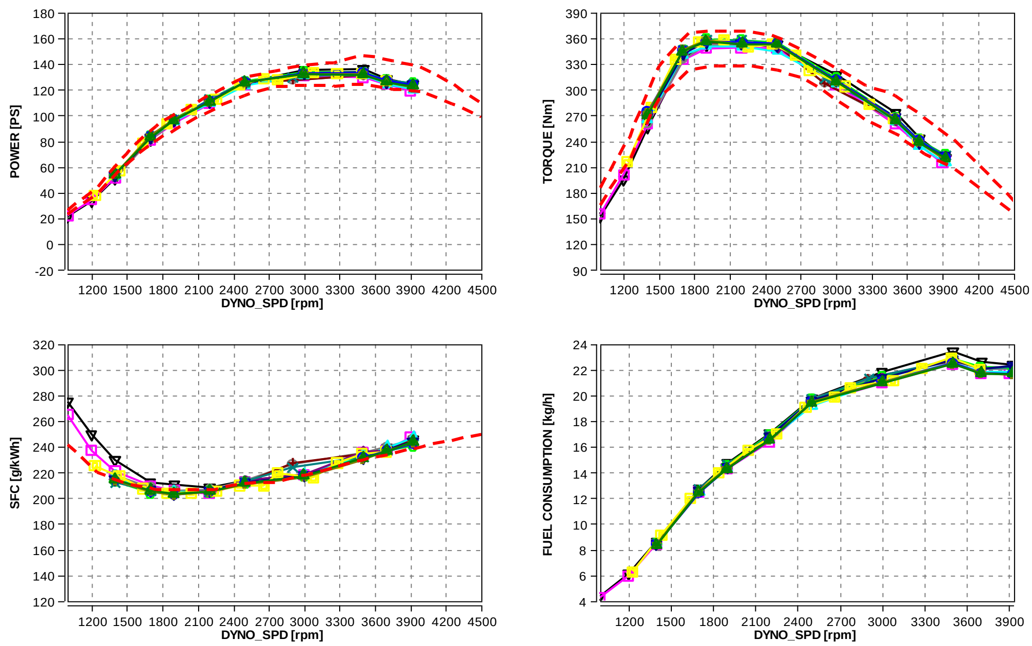
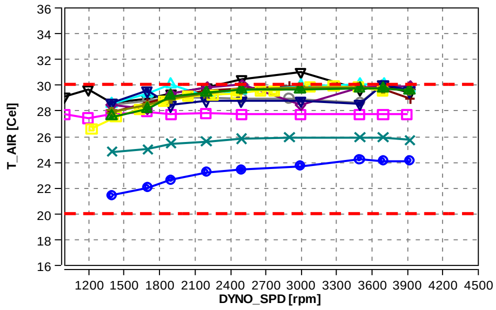
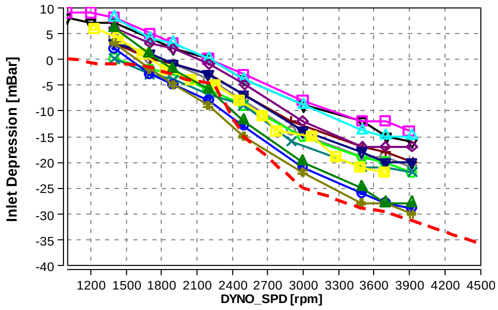
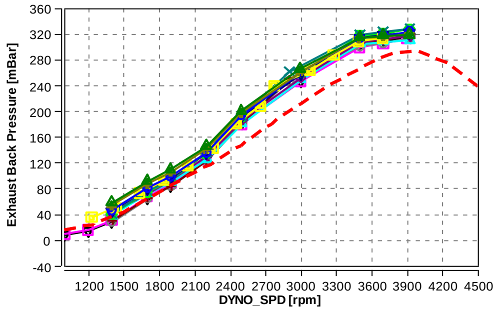


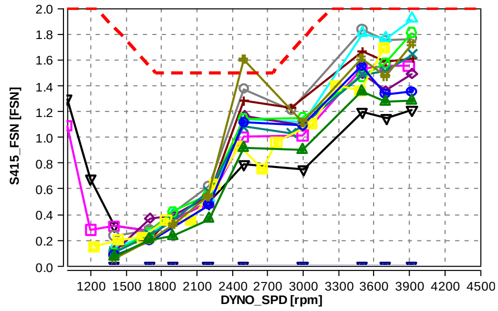
Figure 11.15 : Legends of the pre-defined point measurements

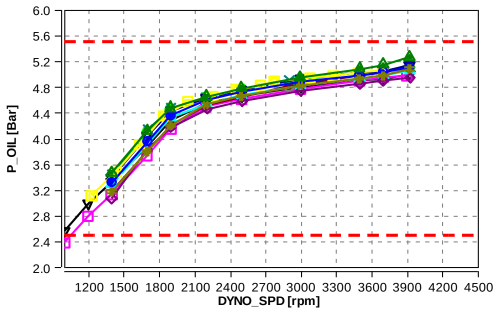


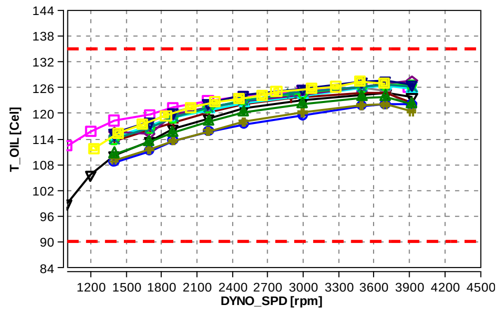

T_AIR [Cel]
DYNO_SPD [rpm]

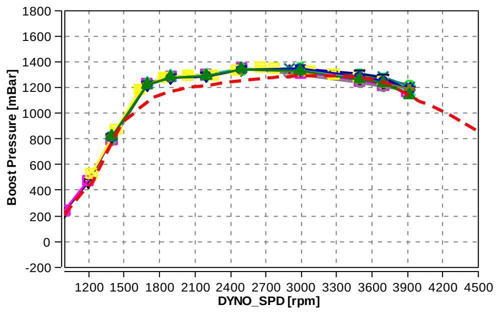

Inlet Depression [mBar]
DYNO_SPD [rpm]

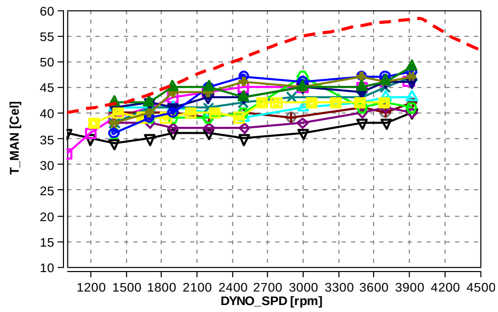

Exhaust Back Pressure [mBar]
DYNO_SPD [rpm]

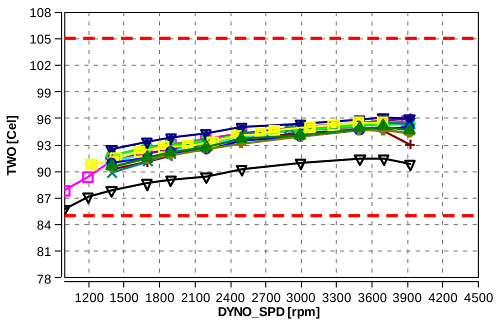

S415_FSN [FSN]
DYNO_SPD [rpm]

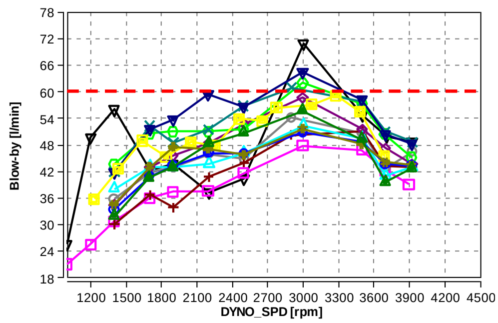

P_OIL [Bar]
DYNO_SPD [rpm]


T_OIL [Cel]
DYNO_SPD [rpm]


Boost Pressure [mBar]
DYNO_SPD [rpm]


T_MAN [Cel]
DYNO_SPD [rpm]


TWO [Cel]
DYNO_SPD [rpm]


Blow-by [l/min]
DYNO_SPD [rpm]

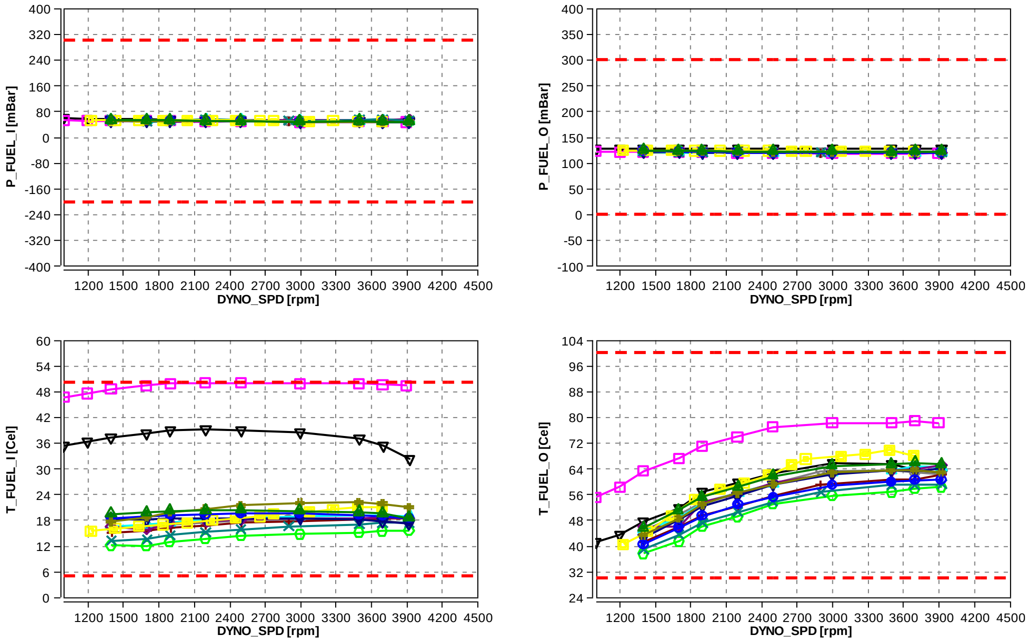


Figure 11.16 : Record of the decision parameters at pre-defined time

11.3.4 Evaluation of engine durability test results

New developed cast crankshaft has lower tensile strength than previous forged crankshaft however it can fulfil the function. Engine durability test results are in the operating range during entire test.

Analysed test results are; power, torque, specific fuel consumption, fuel consumption, ambient temperature, inlet depression, exhaust back pressure, smoke, oil pressure, oil temperature, inlet manifold pressure, inlet manifold temperature, engine coolant temperature, blow-by, fuel pressure and fuel temperature are the

Torque, power are the main performance indications of an engine. These do not go below the target which means engine is operating according to its performance specifications.

Fuel consumption and specific fuel consumption values are an indication about the efficiency of the engine. New developed crankshafts did not affect these parameters and also fuelling parameters are in the acceptable range.

Ambient temperature, inlet depression and exhaust back pressure values are indication of the test environment and condition. Change at these parameters; adjust the performance of the engine. If these parameters are not in the specified range, test will not be valid; however as seen from the plots they are in the specified range.

Smoke is an indication for the combustion efficiency, and sooth propagation. Increase at this value mean that there is not enough air and high amount of fuel. Measured smoke values are also below the target value which is another validation for the engine performance is in specified range and cast crankshaft is acceptable.

Oil pressure and temperature are very important parameters for the evaluation of the crankshaft. Increase in the oil temperature and decrease in the oil pressure mean that there is an oil leak in the engine. If there is a leak, there is a problem at one of the components. Oil pressure and temperature values are in the operating range also oil investigations show that there is not metal particulate in the oil. This is also show that the there is not friction between crankshaft and another component.

Inlet manifold pressure and temperature are both affected from environmental conditions and engine performance. If environmental conditions are not at the determined level, boost pressure cannot be maintained which lower the engine performance. During the test both can be kept in target which is evidence for environmental condition and performance are in the operating range.

Blow-by is another way of monitoring the engine oil level. Increase in this value means that there is an excess amount of oil leak from the engine. This value has to be monitored carefully since it may cause catastrophic failure in the engine. Blow-by value is lower than its target 60 litter per hour during entire test.

Fuel pressure and temperature is another environmental criterion that has to be kept in the specified range. If it is not in the operating range fuel pump can be damaged and supplied fuel may be different than the specified value. In such a condition test cannot be accepted. Both inlet and outlet fuel pressure and temperature values are between the specifications. This can be proved by the fuel consumption however monitoring these values are also important to make it easy to diagnose any failure.

As described all monitored parameters are in the allowable range. Moreover, tear down investigation show that crankshaft has no defect or crack.

All these are approval for the cast crankshaft. 30 % cheaper cast crankshaft can be used instead of forged crankshaft. Fillet rolling is also not necessary as it passed successfully from durability test.

11.4 Cost Analyses of the Cast crankshaft

Cast crankshaft has necessary mechanical properties according to the test results, now its piece cost is compared with forged crankshaft and cost saving can be calculated.

Annual volume of the forged crankshafts is approximately 25,000 which can be found from vehicle market sale statistics and low annual volume is one of the main reasons that make the casting favourable.

Piece cost of the forged crankshaft is approximately 46 units according to Nallichery's study whereas piece cost of cast one is 38 units. In this study as the raw material of the cast one has high amount of carbon and sulphur content not tried to be kept zero. These make cast material relatively cheaper than the forged crankshafts raw material. In addition to the raw material, fillet rolling process is removed as the cast crankshafts can fulfil the required durability condition. As cast crankshaft can pass the durability tests than fillet rolling process will be eliminated otherwise fillet rolling have to be applied to increase the mechanical properties. Elimination of fillet rolling also reduced the piece cost approximately one unit. Nallichery's study was done in 1991 and as it was done for high amount of annual volume, raw material cost was not a major effect on final piece cost. Material cost for the forged crankshaft is 15 units higher than the cast one due to the very low amount of annual volume and chemical content.

In Figure 11.16 cost analyses of the cast and forged crankshaft is given. As described there is cost saving at materials and tooling cost. Where there is a cost increase at labour cost due to manual operations. Also there is cost saving at the surface treatment as fillet rolling process is removed. In overall there is a 30 % cost reduction.

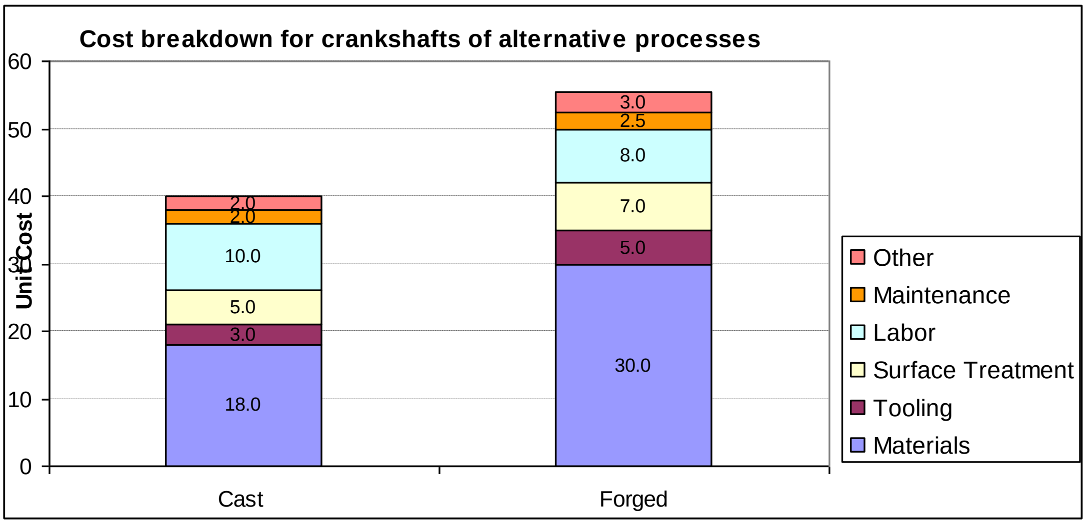


Figure 11.17 : Cost comparison of cast and forged crankshaft

11.5 Summary of the Tests for Alternative Cast Crankshaft Instead of Forged Crankshaft

After completing all tests and results are summarized in below Table 11.4. As seen in the table peak power and torque capability of the engine is compared. With both crankshafts, it is possible to get target peak power and torque. Cast crankshaft is capable to achieve the engine performance criteria. Blow-by is an indication of the oil leakage from the pistons and it has relation with the crankshaft because vibration of the crank has a direct effect on oil leakage. This value has to be lower than 60 litters per minute. Although forged crank has two litters lower blow-by value per minute both crankshafts are in acceptable range. Yield strength, tensile strength, toughness and Fmax values of the cast crankshaft lower than the forged one. Yield strength of cast approximately 20 % lower than forged, tensile strength of cast is approximately 7 % lower than forged. Elongation of forged is very low according to forged crankshaft however 2 % not a very low value for a crankshaft. Toughness of cast crankshaft is also approximately 20 % lower than the forged crankshafts' toughness. Fmax is the maximum applied force before fracture of the specimens during the tensile test. As all other mechanical properties cast crankshaft has 10 % lower Fmax than forged crankshaft. Although cast crankshafts lower mechanical properties it can fulfil the high speed engine durability testing successfully which is an indication of durability approve of 250,000km.

Cost is a very important parameter while giving a decision for a company indeed for every one. Cast crankshaft is approximately 20 % cheaper than the forged crankshaft. As cast crankshaft can fulfil all requirements successfully it is not meaningful to pay more to get high mechanical properties.

Table 11.4: Comparison of cast and forged crankshaft

	Cast	Forged
Power kW	103	103
Torque Nm	345	345
Blow-By lt/min	45	43
Cost TL	80	110
Yield Strength MPa	480	620
Tensile Strength MPa	850	917
Elongation %	2	14
Toughness MPa	280	370
Fmax kN	21.56	24.1

Chemical composition of the both forged and cast crankshaft is also shown in Table 11.5. Chemical compositions are totally different. As described is the manufacturing of cast crankshaft magnesium and aluminium addition to cheap ductile iron allow to increase its ductility and mechanical properties. As mentioned above cast material has much lower cost than forged one and make the casting process favourable.

Table 11.5: Chemical composition of cast and forged crankshaft

Material	C%	Si%	Mn%	Cr%	Al%	V%	S%	P%	Ni%	Cu%	Mg%
Cast	4	2.3	0.7	0.15	0.03	-	0.01	0.06	1	1.1	0.025
Forged	0.4	0.55	1.35	0.16	0.01	0.09	-	-	-	-	-

In conclusion forged crankshaft with a tensile strength of 917MPa can be replaced with a cast crankshaft which has a tensile strength of 850MPa. This can be achieved by the ductile cast iron’s nodular microstructure.

12. CONCLUSION

Manufacturing is continuously developing technology due to the high competition and challenge in the market. Automotive companies always try to lower the cost and improve the quality. Crankshaft, having a complex manufacturing process, and relatively high cost among the automotive components, has an opportunity to gain cost reduction benefit.

One of the automotive companies has forged crankshaft in its 2 litter engine and in order to decrease cost a new crankshaft is developed which can fulfil the forged crankshafts functions. In order to improve mechanical properties all steps of the manufacturing of crankshaft were investigated and cost effect of these steps are thought.

Alternative methods of casting and forging with sub-steps were investigated. Possible surface treatment methods that improve mechanical properties were analysed. Impressive improvements can be achieved by heat treatment processes. Especially fillet rolling implementation is increasing the fatigue life and allows eliminating some of the minor steps. Beyond these new developed materials such as austempered steels can increase the fatigue strength enough to successfully fulfil the necessities of a race car. Moreover nitrocarburizing is a new method to eliminate heat treatment which can reduce the cost.

In addition to all alternative manufacturing methods, material quantity is another effect which is critical both on the cost and weight. As material bought according to volume, increase at the raw material consumption increases the cost.

All materials and methods compared with current manufacturing method. Cost effect of them were analysed via MIT's and Nallicheri's cost model to optimize the cost. These cost models are updated according to local prices and implemented to project successfully.

In the end, ductile cast irons' favourable use seems to provide necessary requirements. Mechanical properties were improved by increasing pearlite percentage in the matrix via use of copper and manganese; moreover, good machinability was achieved by keeping sulphur and phosphorous as low as possible. In addition to all, nodular phase was created by applying magnesium in the alloy form of nickel and magnesium. All these followed with 15 hours heat treatment process and spheroidize matrix is obtained with a tensile strength of 850 MPa.

Testing of the crankshaft is also important while making decision about their performance. Rig tests, component test and engine test are main tests to make decision. In this study tensile test and engine durability test was performed to understand the mechanical properties of new developed cast crankshaft and in this way it was compared with existing forged crankshaft.

Test results show that mechanical strength of the cast crankshaft approximately is 10 % lower then forged crankshaft however successful completion of engine durability test proves its 250,000km use without any warranty concern.

In conclusion, manufacturing of a crankshaft is a challenging process as there are lots of parameters that may affect the final product. Geometric shape, material, heat treatments, surface treatment, manufacturing methods are all change the mechanical properties and final price cost. There is not an optimum design for all applications; optimum design can be done according to necessity of the project. In this project this is proved by changing current crankshaft by a cast one with lower mechanical properties by gaining 20 % cost reduction.

REFERENCES

[1] **Chatterley, T. C. and Murell, P.,** 1998, ADI Crankshafts – An Appraisal of Their Production Potentials, SAE Technical Paper No. 980686, Society of Automotive Engineers

[2] **Çevik G., Tuncalı Z., Duran E. T.,** 2009, A Study on the Diesel Engine Crankshaft Fatigue Performance Optimization, SAE Technical Paper No. 2009-01-0261, Society of Automotive Engineers, Ford Otomotiv San. A.Ş

[3] **Druschitz A. P., Fitzgerald D. C., Hoegfeldt I.,** 2006, Lightweight Crankshafts, SAE Technical Paper No. 2006-01-0016, Society of Automotive Engineers, INTERMET Corporation

[4] **Dubensky, R. G.,** 2002, Crankshaft Concept Design Flowchart for Product Optimization," SAE Technical Paper No. 2002-01-0770, Society of Automotive Engineer, Mechanical Design & Analysis Institute Incorporation

[5] **Fatemi, A., Zoroufi, M.,** 2002, Fatigue Performance Evaluation of Forged versus Competing Process Technologies: A Comparative Study, 24th Forging Industry Technical Conference, Cleveland, Ohio

[6] **Hoffmann, J. H. and Turonek, R. J.,** 1992, High Performance Forged Steel Crankshafts - Cost Reduction Opportunities, SAE Technical Paper No. 20784, Society of Automotive Engineers, Chrysler Corporation

[7] **Kothari K. D., Jhala R. L.,** 2009, Optimization for Cost and Weight of Forged Steel Crankshaft Using Geometry Variables, 2009 ASME Early Career Technical Conference, ASME ECTC October 2-3, 2009, Tuscaloosa, Alabama, USA

[8] **Kubo H. and Mori H.,** 2005: Technical Developments and Recent Trends in Crankshaft Materials. Kobelco Technology Review No. 26 December 2005.

[9] **Matsumura Y., Kurebayashi Y., Konagaya D., Mizuno K.,** 1999, Development of nitrocarburizing steel for crankshafts, SAE Technical Paper No. 1999-01-0601, Society of Automotive Engineers, Daido Steel Co., Ltd., Honda R&D Co., Ltd.

[10] **Mikulec, A., Reams, L., Chottiner, J., Page, R. W., and Lee, S.,** 1998, Crankshaft Component Conceptual Design and Weight Optimization," SAE Technical Paper No. 980566, Society of Automotive Engineers, Ford Motor Company

[11] **Mittal R., Nanda S.,** 2010, Property Enhancement of Spheroidal Cast Iron By Heat treatment, Department of Metallurgical and Materials Engineering National Institute of Technology Rourkela

[12] **Montazersadgh F. H., Fatemi, A.,** 2008, Optimization of a Forged Steel Crankshaft Subject to Dynamic Loading, SAE Technical Paper No. 2008-01-0432, Society of Automotive Engineers, Warrendale, PA, USA.

[13] **Montazersadgh F. H., Fatemi, A.,** 2007, Stress Analysis and Optimization of Crankshafts Subject to Dynamic Loading, A Final Project Report Submitted to the Forging Industry Educational Research Foundation (FIERF) and American Iron and Steel Institute (AISI)

[14] **Nallicheri, N. V., Clark, J. P., and Field, F. R.,** 1991, Material Alternatives for the Automotive Crankshaft; A Competitive Assessment Based on Manufacturing Economics, SAE Technical Paper No. 910139, Society of Automotive Engineers, Warrendale, PA, USA.

[15] **Park, H., Ko, Y. S., and Jung, S. C.,** 2001, Fatigue Life Analysis of Crankshaft at Various Surface Treatments, SAE Technical Paper No. 2001-01-3374, Society of Automotive Engineers, Hyundai Motor Company, R&D Center

[16] **Pye D.,** 2003, Practical nitriding and ferritic nitrocarburizing, pp. 193 – 202

[17] **Qizhou C., Bokang W.,** 2008, Material Processing and Dies & Mould Technology, Huazhong University of Science and Technology, Wuhan 430074, China

[18] **Ren, W., Keyu. L., and Lee, Y. L.,** 2004, Optical Measurement of Residual Stress at the Deep-Rolled Crankshaft Fillet, SAE Technical Paper No. 2004-01-1500, Society of Automotive Engineers, DaimlerChrysler Corporation

[19] **Saidi, M.T., Baghersaee, N., Varahram N., Rao M.H., Rao N. G.V.S.,** 2007, Fatigue Properties of Machinable Austempered Ductile Iron, 22.-24.5.2007, Hradec nad Moravicí

[20] **Şahin Y.,** 2003, İmal Usulleri, Gazi Kitabevi, pp. 121 -123

[21] **Url-1** <*http://www.roymech.co.uk/Useful_Tables/Matter/Cast_iron.html*>, accessed at 01.05.2011

[22] **Url-2 <** *http://www.ductile.org/didata/*>, accessed at 01.05.2011

[23] **Url-3 <** *http://www.differencebetween.net/miscellaneous/difference-between-ductile-iron-and-cast-iron/*>, accessed at 01.05.2011

[24] **Williams, D. and Callister, Jr.,** 2003, Materials Science and Engineering an Introduction, Wiley International Edition, pp. 360

[25] **Williams, J. and Fatemi, A.,** 2007, Fatigue Performance of Forged Steel and Ductile Cast Iron Crankshafts, SAE Technical Paper No. 2007-01-1001, Society of Automotive Engineers, Warrendale, PA, USA.

[26] **Williams, J. and Fatemi, A.,** 2007, Fatigue Performance Comparison and Life Predictions of Forged Steel and Ductile Cast Iron Crankshafts, A Final Project Report Submitted to the Forging Industry Educational Research Foundation (FIERF) and American Iron and Steel Institute (AISI)

[27] **Williams, J. L. and Gary, J. P.,** 2007, Standard Handbook of Petroleum & Natural Gas Engineering, Elsevier

[28] **Zoroufi, M. and Fatemi, A,** 2005, A Literature Review of Durability Evaluation of Crankshafts Including Comparisons of Competing Manufacturing Processes and Cost Analysis, 26th Forging Industry Technical Conference, Chicago, IL.

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