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Establishing Core Hardness by Induction Hardening Process for Crankshaft

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Abstract

The main purpose of this paper is to identify the need for Surface Hardening in Crankshafts and establishing Induction Hardening as the most practically viable process for the same.

Crankshaft is one of the largest components in the internal combustion engine that has a complex geometry consisting of cylinders as bearings and plates as the crank webs. Geometry section changes in the crankshaft cause stress concentration at fillet areas where bearings are connected to the crank webs. In addition, this component experiences both torsional and bending load during its service life. The crankshaft must be capable of withstanding the intermittent variable loads impressed on it.

The principal purpose of Surface Hardening is to increase the hardness, wear resistance and endurance limit of the surfaces of metal components. The core remains tough and can withstand impact loads.

Prior to the advent of Induction Hardening methods such as furnace hardening, flame hardening and liquid nitriding were used. However each of these processes presented problems such as inadequate or non-uniform hardening and distortion. Induction Hardening overcomes many of these problems through rotation of the part during heat-treating and selection of frequency and power to obtain adequate case depth and uniform hardness.

Keywords: Induction Hardening, Crankshaft, Heat Treating, Materials, Failures

Introduction

A crankshaft (i.e. a shaft with a crank) is used to convert reciprocating motion of the piston into rotatory motion or vice versa. The crankshaft consists of the shaft parts which revolve in the main bearings, the crankpins to which the big ends of the connecting rod are connected, the crank arms or webs (also called cheeks) which connect the crankpins and the shaft parts.

A crankshaft is a highly stressed component in an engine that is subjected to bending and torsional loads. The crankshaft must be designed to last the life of the engine due to the catastrophic damage to the engine which would result if failure did occur. Considering the life of an engine in an automobile, for example, this results in requirement for an infinite life fatigue situation. Because of the long life and high stresses, as well as the need for weight reduction, material and manufacturing process selection is important in crankshaft design.

Surface Hardening is used to improve the wear resistance of ferrous parts without affecting the softer, tough interior of the part. The combination of a hard surface and softer interior is of inestimable value in modern engineering practice. By the use of high-quality alloy steels, great strength and toughness in the core can be combined with extreme surface hardness, resulting in a composite structure capable of withstanding certain kinds of stress to a high degree.

High frequency induction heating is ideal for localized surface hardening of crankshafts and a wide variety of machine parts. There is practically no distortion or scale formation. Time cycles of only a few seconds are maintained by automatic regulation. The usual and expensive pre-treatment, such as copper plating and carburizing, is eliminated. The transformation of pearlite into austenite is extremely rapid. A fine nodular and more homogeneous martensite results from induction hardening. Carbide solution rates of less than one second and higher hardness than are obtainable with conventional methods are inherently characteristic.

Function of Crankshafts in IC Engines

The crankshaft, connecting rod, and piston constitute a four bar slider-crank mechanism, which converts the sliding motion of the piston (slider in the mechanism) to a rotary motion. Since the rotation output is more practical and applicable for input to other devices, the concept design of an engine is that the output would be rotation. In addition, the linear displacement of an engine is not smooth, as the displacement is caused by the combustion of gas in the combustion chamber. Therefore, the displacement has sudden shocks and using this input for another device may cause damage to it. The concept of using crankshaft is to change these sudden displacements to a smooth rotary output, which is the input to many devices such as generators, pumps, and compressors. It should also be mentioned that the use of a flywheel helps in smoothing the shocks. A crankshaft contains two or more centrally-located coaxial cylindrical ("main") journals and one or more offset cylindrical crankpin ("rod") journals. The two-plane V8 crankshaft pictured in *Figure I* has five main journals and four rod journals, each spaced 90° from its neighbors.

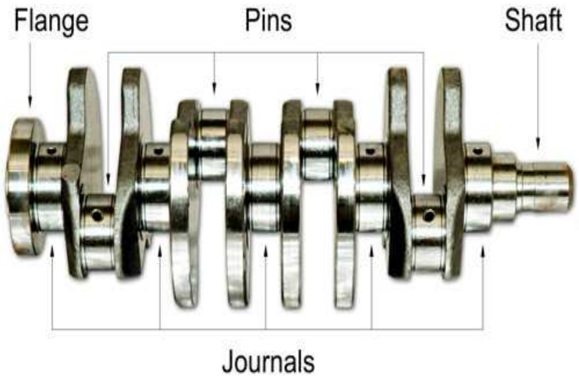

Figure I: CRANKSHAFT

Performance Requirements

Crankshafts require the following characteristics:

- High strength and stiffness to withstand the high loads in modern engines, and to offer opportunities for downsizing and weight reduction
- Resistance to fatigue in torsion and bending
- Low vibration
- Resistance to wear in the bearing areas

Service Loads and Failures Experienced by Crankshafts

Crankshaft experiences large forces from gas combustion. This force is applied to the top of the piston and since the connecting rod connects the piston to the crankshaft, the force will be transmitted to the crankshaft. The magnitude of the force depends on many factors which consist of crank radius, connecting rod dimensions and weight of the connecting rod, piston, piston rings and pin. Combustion and inertia forces acting on the crankshaft cause two types of loading on the crankshaft structure; torsional load and bending load.

There are many sources of failure in the engine. They could be categorized as operating sources, mechanical sources, and repairing sources (Silva 2003). One of the most common crankshaft failures is fatigue at the fillet areas due to bending load caused by the combustion. Even with a soft case as journal bearing contact surface, in a crankshaft free of internal flaws one would still expect a bending or torsional fatigue crack to initiate at the pin surface, radius, or at the surface of an oil hole. Due to the crankshaft geometry and engine mechanism, the crankshaft fillet experiences a large stress range during its service life.

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

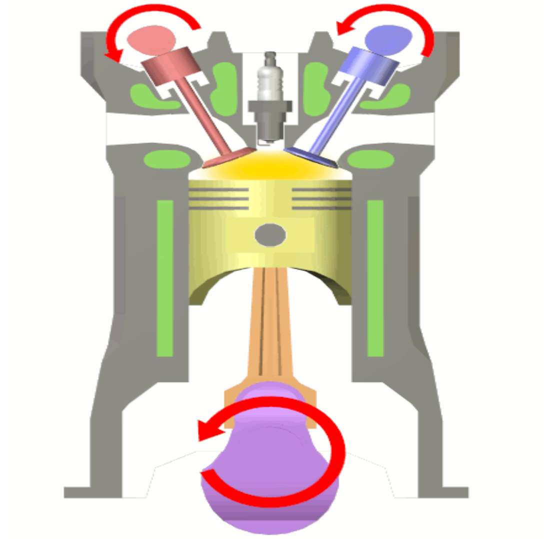

Figure II: Side View Of The Engine Block At The Time Of Combustion

Materials and Manufacturing Processes

There are several ways to manufacture a crankshaft, including machining from a billet, forging, and casting. Due to cost and time, machining a crankshaft from a billet is seldom used except in very low production applications. The two most common types of crankshafts are made of cast iron and forged steel.

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Comparison of Forging and Casting Processes

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

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

- Castings cannot obtain the strengthening effects of hot and cold working. Forging surpasses casting in predictable strength properties, producing assured superior strength consistently.

- A casting has neither grain flow nor directional strength and the process cannot prevent formation of certain metallurgical defects. Pre-working forge stock produces a grain flow oriented in directions requiring maximum strength. Dendritic structures, alloy segregations and like imperfections are refined in forging.

- Casting defects occur in a variety of forms. Because hot working refines grain pattern and imparts high strength, ductility and resistance properties, forged products are more reliable. And they are manufactured without the added costs for tighter process controls and inspection that are required for casting.

- Castings require close control of melting and cooling processes because alloy segregation may occur. This results in non-uniform heat-treatment response that can affect straightness of finished parts. Forgings respond more predictably to heat treatment and offer better dimensional stability.

- Some castings, such as special performance castings, require expensive materials and process controls, and longer lead times. Open-die and ring rolling are examples of forging processes that adapt to various production run lengths and enable shortened lead times.

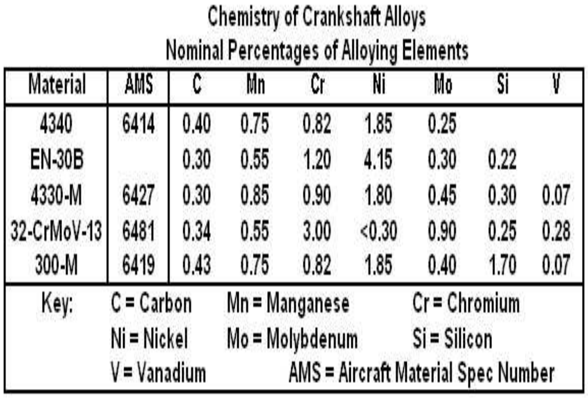
In spite of the aforementioned advantages of forgings over castings, castings may be an economical alternative, depending on part functionality requirements, production volume, and other considerations.

Crankshaft Materials

The crankshafts are subjected to shock and fatigue loads. Thus material of the crankshaft should be tough and fatigue resistant. The crankshafts are generally made of carbon steel, special steel or special cast iron. In industrial engines, the crankshafts are commonly made from carbon steel such as 40 C 8, 55 C 8 and 60 C 4. In transport engines, manganese steel such as 20Mn2, 27Mn2 and 37Mn2 are generally used for the making of crankshaft. In aero engines, nickel chromium steel such as 35Ni1Cr60 and 40Ni2Cr1Mo28 are extensively used for the crankshaft.

The steel alloys typically used in high strength crankshafts have been selected for what each designer perceives as the most desirable combination of properties. *Table I* shows the nominal chemistries of the crankshaft alloys discussed here.

Medium-carbon steel alloys are composed of predominantly the element iron, and contain a small percentage of carbon (0.25% to 0.45%, described as '25 to 45 points' of carbon), along with combinations of several alloying elements, the mix of which has been carefully designed in order to produce specific qualities in the target alloy, including hardenability, nitridability, surface and core hardness, ultimate tensile strength, yield strength, endurance limit (fatigue strength), ductility, impact resistance, corrosion resistance, and temper-embrittlement resistance. The alloying elements typically used in these carbon steels are manganese, chromium, molybdenum, nickel, silicon, cobalt, vanadium, and sometimes aluminium and titanium. Each of those elements adds specific properties in a given material. The carbon content is the main determinant of the ultimate strength and hardness to which such an alloy can be heat treated.



Chemistry of Crankshaft Alloys
Nominal Percentages of Alloying Elements

Material	AMS	C	Mn	Cr	Ni	Mo	Si	V
4340	6414	0.40	0.75	0.82	1.85	0.25		
EN-30B		0.30	0.55	1.20	4.15	0.30	0.22	
4330-M	6427	0.30	0.85	0.90	1.80	0.45	0.30	0.07
32-CrMoV-13	6481	0.34	0.55	3.00	<0.30	0.90	0.25	0.28
300-M	6419	0.43	0.75	0.82	1.85	0.40	1.70	0.07

Key:
C = Carbon
Mn = Manganese
Cr = Chromium
Ni = Nickel
Mo = Molybdenum
Si = Silicon
V = Vanadium
AMS = Aircraft Material Spec Number

TABLE I

In addition to alloying elements, high strength steels are carefully refined so as to remove as many of the undesirable impurities as possible (sulfur, phosphorous, calcium, etc.) and to more tightly constrain the tolerances, which define the allowable variations in the percentage of alloying elements. The highest quality steels are usually specified and ordered by reference to their AMS number (Aircraft Material Specification). These specs tightly constrain the chemistry, and the required purity can often only be achieved by melting in a vacuum, then re-melting in a vacuum to further refine the metal. Typical vacuum-processing methods are VIM and VAR.

Vacuum Induction Melting (VIM) is a process for producing very high purity steels by melting the materials by induction heating inside a high-vacuum chamber.

Vacuum Arc Remelting (VAR) is a refining process in which steels are remelted inside a vacuum chamber to reduce the amount of dissolved gasses in the metal. Heating is by means of an electric arc between a consumable electrode and the ingot.

Operating Conditions and Failure of Crankshafts

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

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

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

Another common failure in the crankshafts is mechanical crack nucleation at the fillet radius of journal bearings.

Many studies, including the one conducted by Jensen (*figure IV*) on the V-8 automotive crankshaft, identify the critical location of the crankshaft as the fillet connecting the crank-pin to the web of the crankshaft.

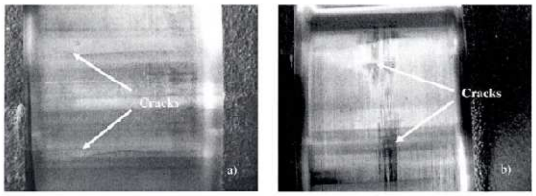


Figure III Detail Of A Journal Of A Crankshaft In The Study By (Silvia, 2003)

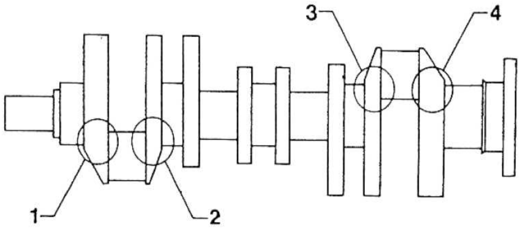


Figure IV V-8 Crankshaft Critical Sections

Crankshaft Hardening

When we specify the material for the crankshaft, we need to be careful not only to specify the composition of the material, but also the level of mechanical properties that we can expect. In general, we do this by ordering the material with a given property or combination of properties within a range that we are happy with. We may deem that we want a certain level of ultimate tensile strength (UTS), or yield strength, or elongation etc. Particularly with reference to UTS, there is a very well understood relationship between this mechanical property and hardness. This allows us to specify a level of hardness for the material which has the advantage that the test can be carried out with (relatively) inexpensive equipment on any reasonably clean flat or round surface.

The method by which we achieve this desired level of hardness or strength is by the processes of hardening and tempering.

The hardening process involves getting the steel very hot indeed – each grade of steel will have a given temperature above which the entire structure is known as ‘austenite’. This is generally above 900 degrees C (>1650 degrees F) and depends on the grade of steel and the properties desired. In general, for most steels, austenite is not an equilibrium phase, and over time (in some cases a very long time) will change into something else. Austenite is a relatively soft phase and not many steels used in engine components use these types of steel (although poppet valves are a notable exception). However, in the controlled process of hardening, we ensure that this change happens by quenching the steel. Where the grade of steel requires that the temperature change is very rapid, the steel may be submerged in water, oil or a polymer quenchant. However, for some steels which are quite highly alloyed, the quenching can be done in air, which leads to less distortion. Generally, what is produced (or desired at least) is a phase called martensite.

Martensite is an equilibrium phase, but is extremely hard and brittle and requires a further process to make the steel usable as a crankshaft. This process is called tempering, and involves getting the steel moderately hot in the case of a crankshaft (somewhere between 500 and 700 degrees C (approximately 930 – 1300 degrees F)). Steels for other applications will temper at higher or much lower temperatures (for example, common gear steels are tempered at around 150 degrees C). As for stabilization (stress-relief), tempering depends on a combination of time and temperature. If the temperature in service (or during the rest of the manufacturing process) exceeds the tempering temperature, there is a danger of loss of mechanical properties.

Induction Hardening

Induction hardening is one of the advanced processes, which saves lot of energy and time. In this process a coil known as inductor coil is used to heat the surface layers of the material. The energy given to this inductor coil is electrical energy

According to the physical law of induction an alternating magnetic field is generated around each electrical conductor through which an alternating current is flowing. By considerably increasing these magnetic fields, metals brought into close proximity will be heated by eddy currents produced within the metal. Heating by induction makes use of the capability of the magnetic field to transmit energy without direct contact.

Comparison of The Induction, Flame, Case and Nitride Hardening Processes

Induction hardening

I) Advantages:

- Uniform heating of the component
- Short heating times
- Low Distortion
- The space requirement is low
- Easy and clean operation with no health hazards.

II) Disadvantages:

- High Initial Cost
- Different inductors have to be used for the different processes.
- Hardening components with large changes in sections can be difficult

Flame hardening

I) Advantages:

- Low capital costs
- Short heating times
- Low Distortion
- Selective hardening of specific areas is possible
- Low space requirements and simple operation

II) Disadvantages:

- Heating flame temperature is not always constant causing the hardening depth to vary
- Different burners have to be used for the different components.

Case hardening

I) Advantages:

- Uniform Hardened Layer
- Core strength is increased at the same time when the surface is hardened
- Selective hardening of specific areas is possible

II) Disadvantages:

- High operating costs

- Long annealing times
- Severe distortion can occur as the whole component will be heated

Nitride hardening (gas nitriding)

I) Advantages:
- Uniform hardness depth irrespective of the shape of the component
- As the process temperature is low (approx. 500 °C), distortion on stress-relieved annealed components is insignificant.
- High Wear Resistance

II) Disadvantages:
- High operating costs
- Long annealing times
- Only special steels can be used.
- The hardened layer is thin.
- The surfaces do not withstand high surface pressure as they tend to collapse under pressure.

Conclusion

Induction heating provides a heat source which is very easily controllable, can be limited to partial heating zones and creates reproducible heat-up processes. Multiple components can be processed by changing the inductor. This provides the opportunity to build heating equipment with a high level of automation which allows to be integrated in a production line. These factors establish Induction Hardening as the most practically viable hardening process for the same.

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