MATERIALS OF THE CAMSHAFTS

Subject: Materials Science

MSc presentation
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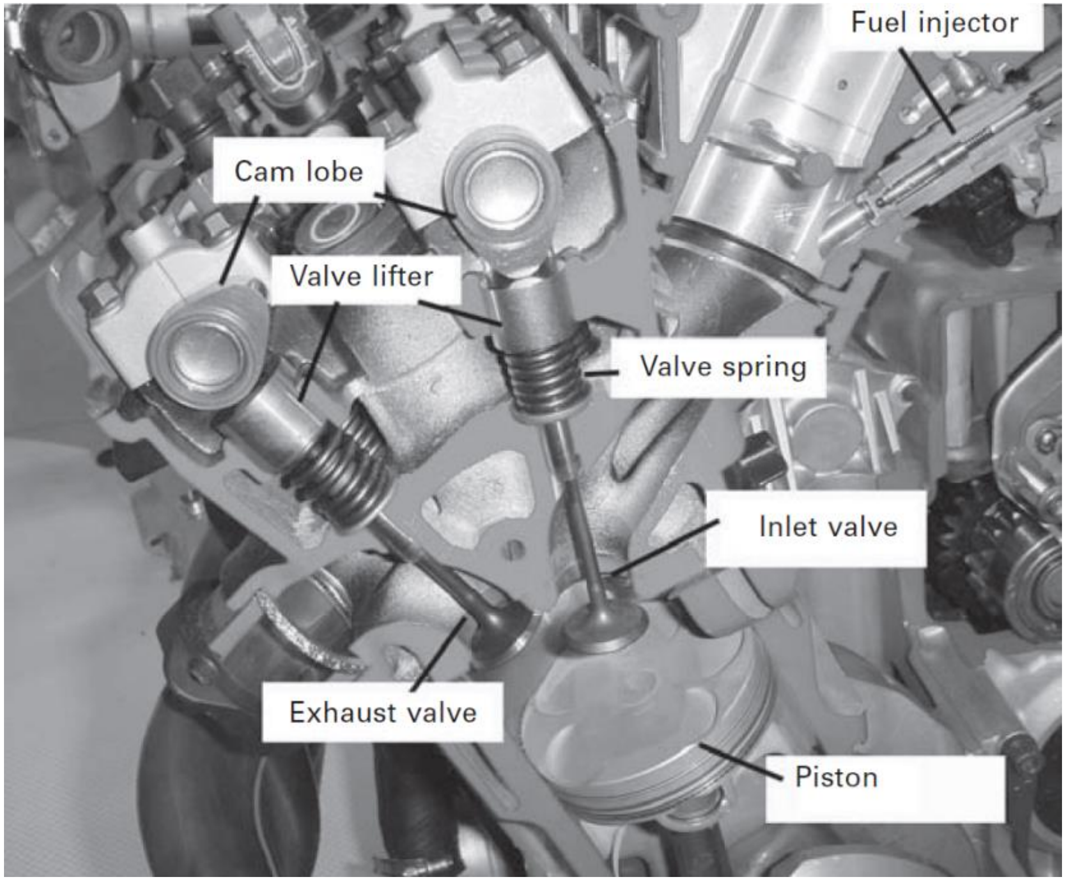
FUNCTION

Combustion gases in four-stroke engines are controlled by the **valve mechanism**, a complex structure, often referred to as a **valve train**, of which **the camshaft is an integral part**.

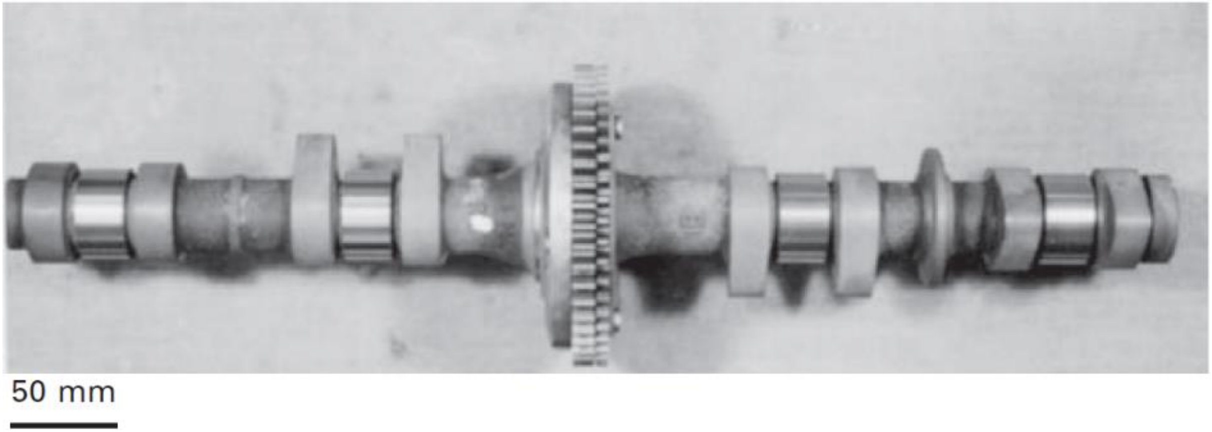
The valve train determines overall engine performance.

The figure shows a photographic representation of a valve train.



FUNCTION

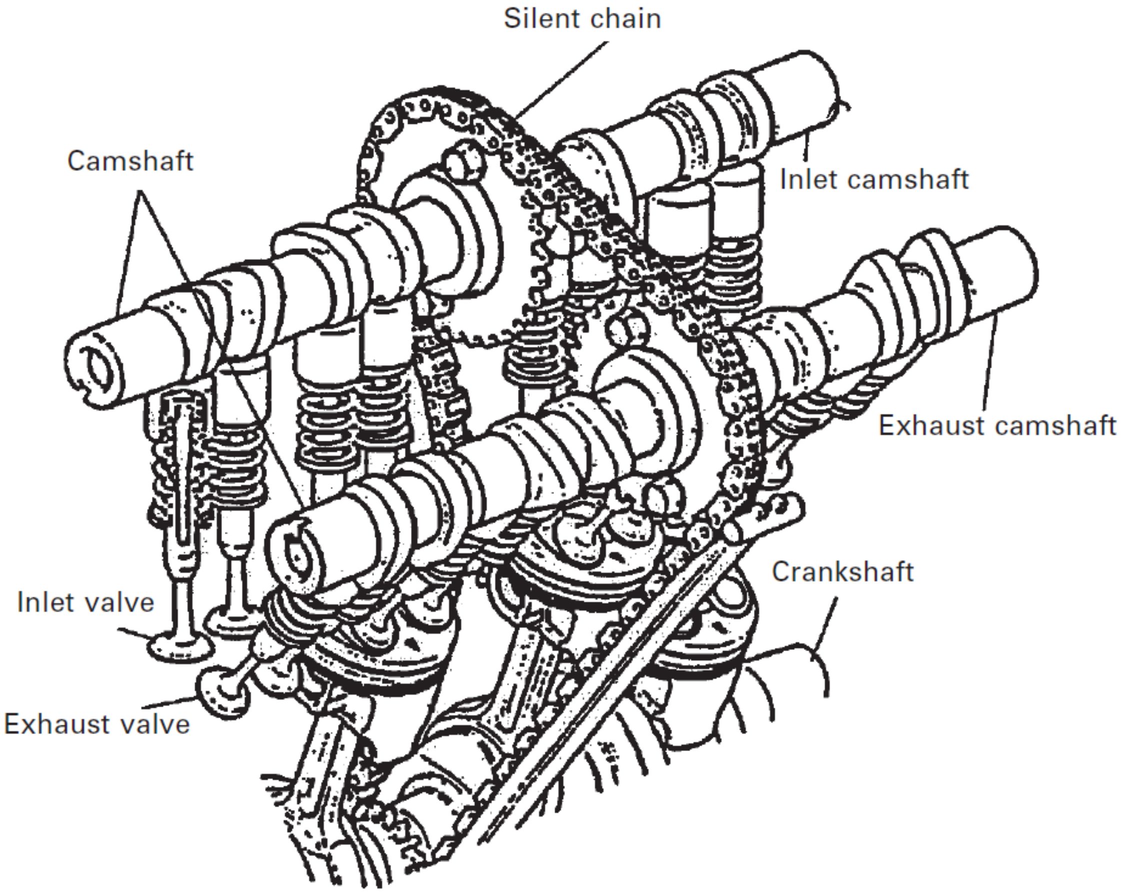
Several types of valve trains have been developed.
The **overhead camshaft** is the most popular mechanism used in high-speed engines. There are two types, the **double overhead camshaft** (DOHC) and **single overhead camshaft** (SOHC).
The figure shows an example of the DOHC type, which uses five valves per cylinder (two exhaust and three inlet valves). This mechanism uses two camshafts, one camshaft drives the three inlet valves and the other drives two exhaust valves through the valve lifters.



FUNCTION

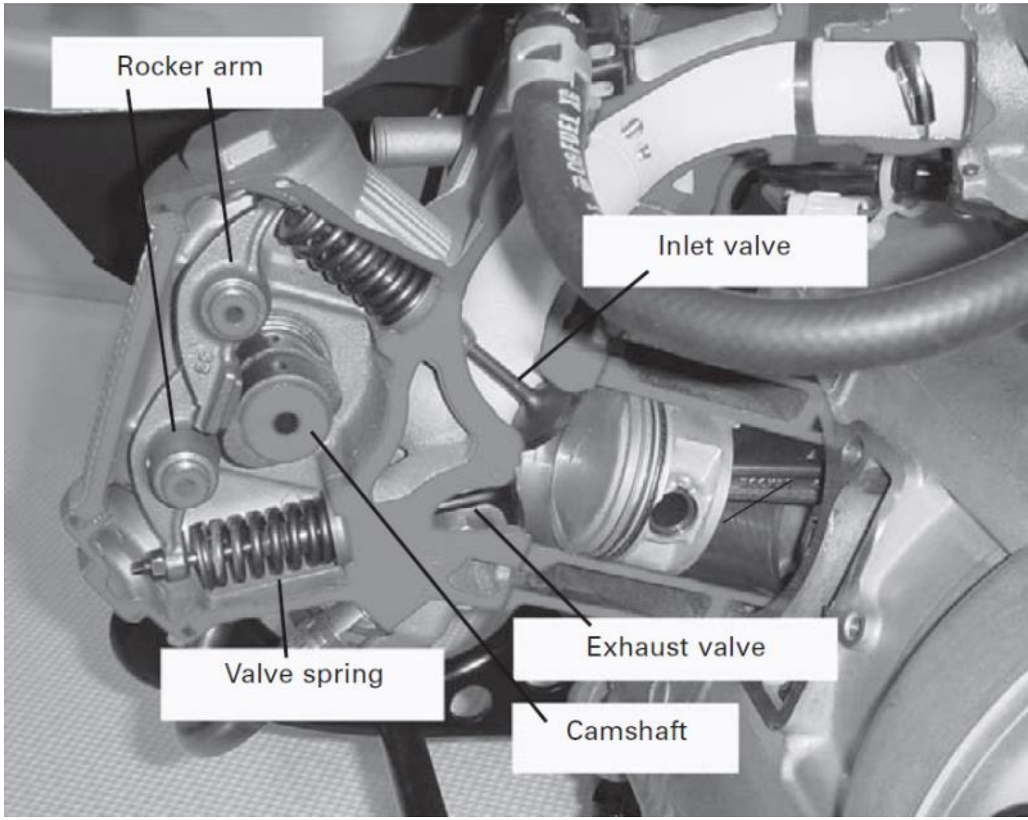
The figure gives a schematic representation of a **typical DOHC drive mechanism**.

The chain or timing belt transmits the rotation of the crankshaft to the camshaft, which is turned by the camshaft drive mechanism.



FUNCTION

The figure shows the **SOHC type**. This mechanism uses **one camshaft**, which **drives a pair of inlet and exhaust valves via the rocker arms**.



FUNCTION

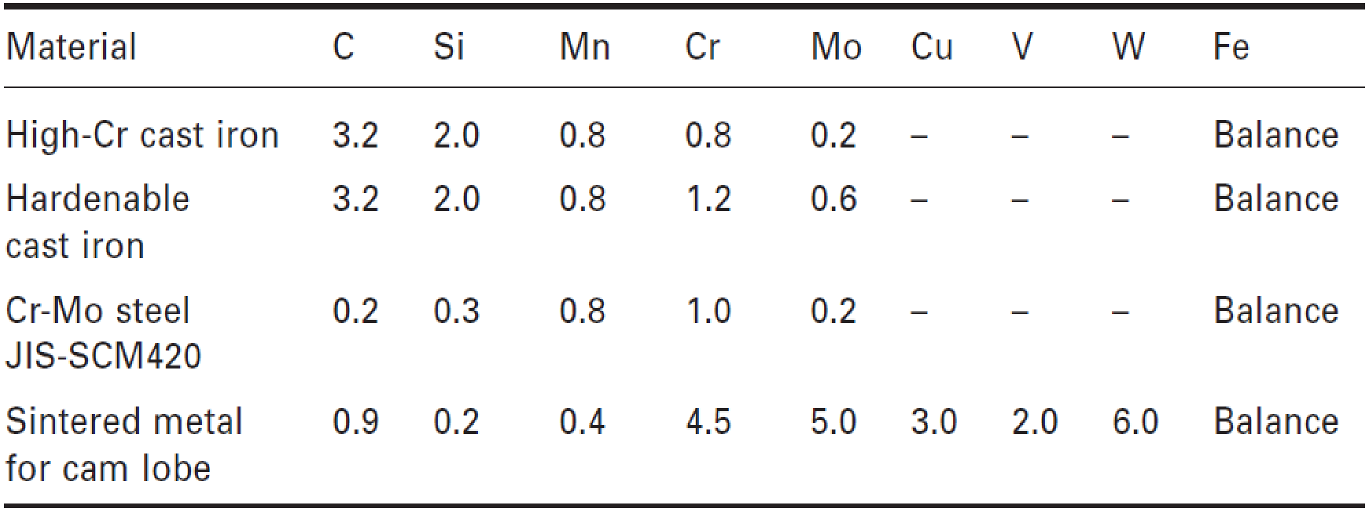
The **oval shape of the cam lobe determines the lift** (displacement) **of** inlet and exhaust **valves**.
The valve itself has an inertial mass. If the curved shape of the cam lobe surface is not designed appropriately, then the valve cannot accurately follow the contour and this will result in irregular motion.

It is essential that **adequate amounts of lubricating oil are supplied to the cam lobe**. The contact between the curved surface of the cam lobe and the flat face of the valve lifter generates high stress, and therefore both parts require **high wear resistance where contact occurs**.

MATERIALS OF THE CAMSHAFT

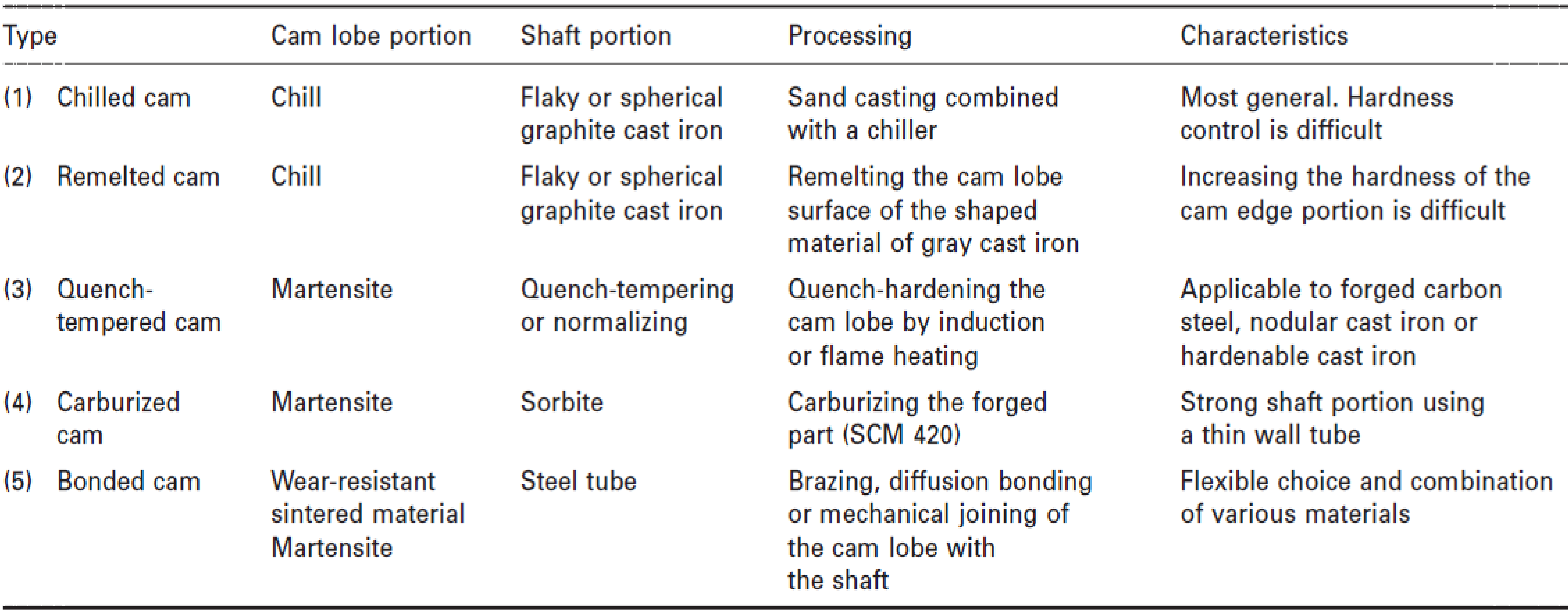
Compositions of camshaft materials are shown in the table:

- The **high-Cr cast iron** is used for chilled camshafts. The chromium concentration is slightly raised to obtain hard chill.
- The **hardenable cast iron** generates a **martensitic microstructure** through quench-tempering.
- The **Cr-Mo steel** is forged and carburized.
- The **sintered metal** has a martensitic microstructure dispersing Cr and Fe carbide.



Material	C	Si	Mn	Cr	Mo	Cu	V	W	Fe
High-Cr cast iron	3.2	2.0	0.8	0.8	0.2	–	–	–	Balance
Hardenable cast iron	3.2	2.0	0.8	1.2	0.6	–	–	–	Balance
Cr-Mo steel JIS-SCM420	0.2	0.3	0.8	1.0	0.2	–	–	–	Balance
Sintered metal for cam lobe	0.9	0.2	0.4	4.5	5.0	3.0	2.0	6.0	Balance

MATERIALS OF THE CAMSHAFT

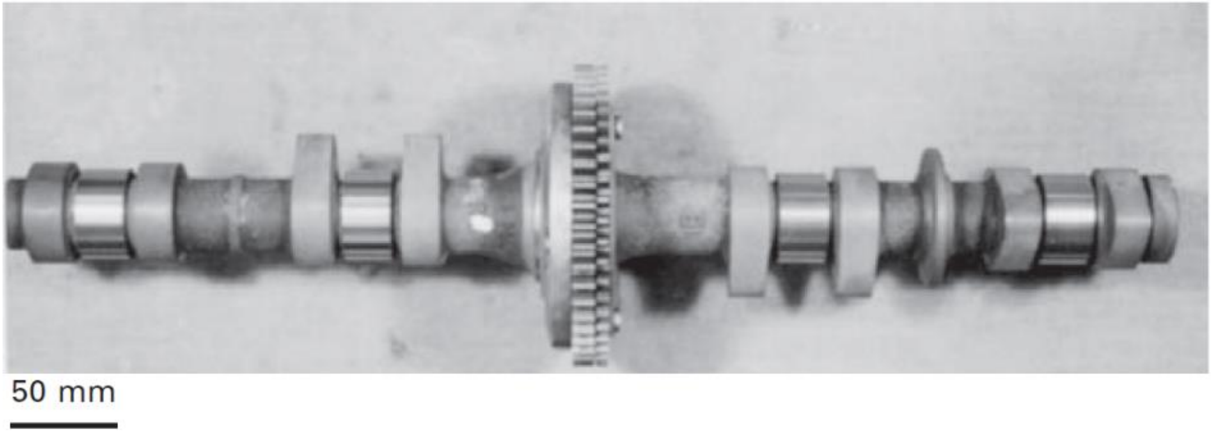


Type	Cam lobe portion	Shaft portion	Processing	Characteristics
(1) Chilled cam	Chill	Flaky or spherical graphite cast iron	Sand casting combined with a chiller	Most general. Hardness control is difficult
(2) Remelted cam	Chill	Flaky or spherical graphite cast iron	Remelting the cam lobe surface of the shaped material of gray cast iron	Increasing the hardness of the cam edge portion is difficult
(3) Quench-tempered cam	Martensite	Quench-tempering or normalizing	Quench-hardening the cam lobe by induction or flame heating	Applicable to forged carbon steel, nodular cast iron or hardenable cast iron
(4) Carburized cam	Martensite	Sorbite	Carburizing the forged part (SCM 420)	Strong shaft portion using a thin wall tube
(5) Bonded cam	Wear-resistant sintered material Martensite	Steel tube	Brazing, diffusion bonding or mechanical joining of the cam lobe with the shaft	Flexible choice and combination of various materials

CHILLED CAST IRON

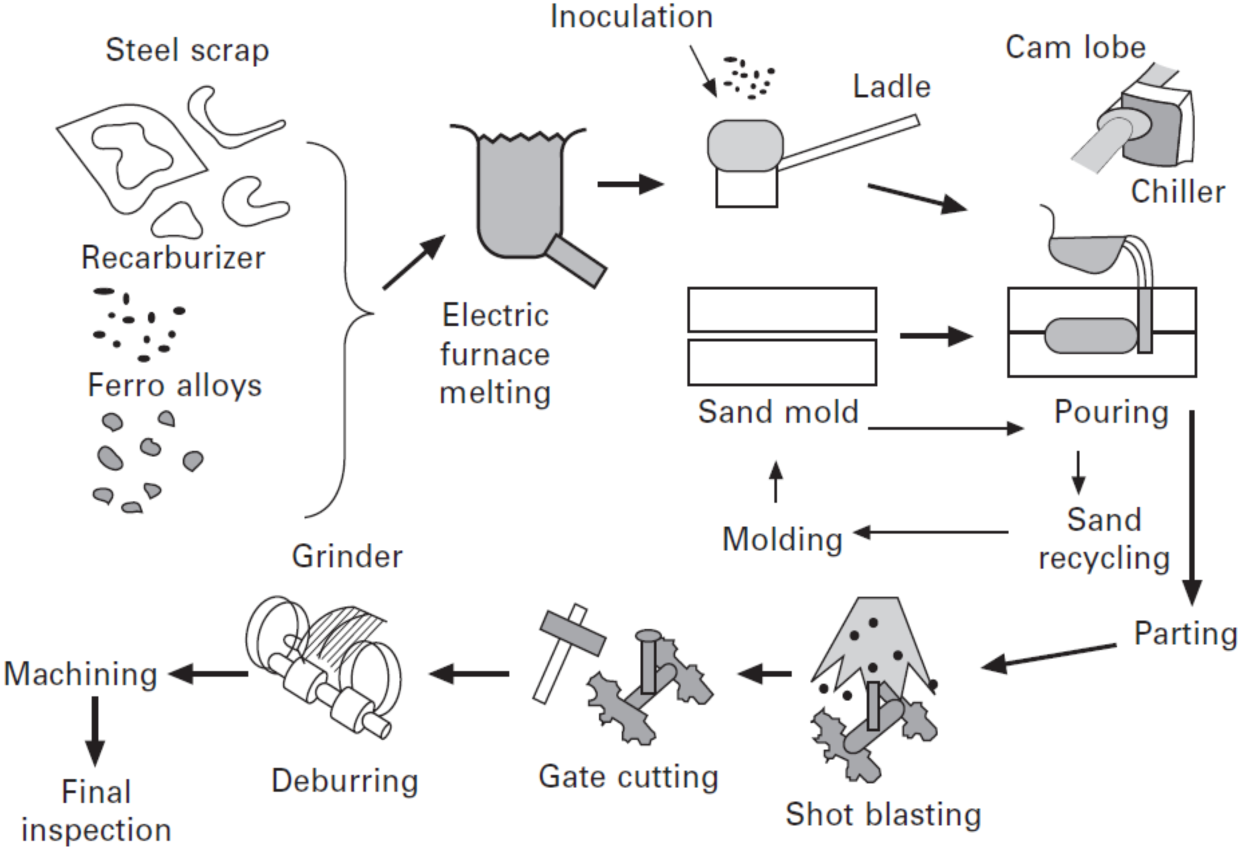
The camshaft should combine a strong shaft with hard cam lobes.

The **most widely used material** for camshafts at present **is chilled cast iron**, using a **high-Cr cast iron**.
This type of camshaft is shown in the figure, and has **hard cam lobes with a strong but soft shaft**.



CHILLED CAST IRON

The extremely rational production process (casting process):

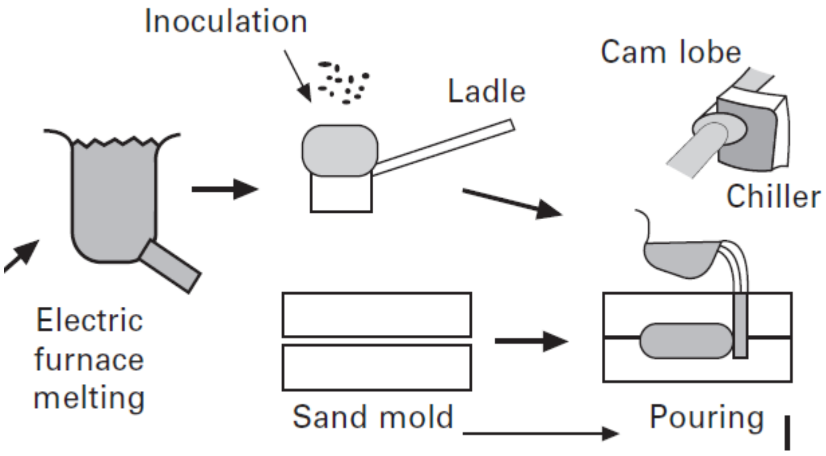


CHILLED CAST IRON

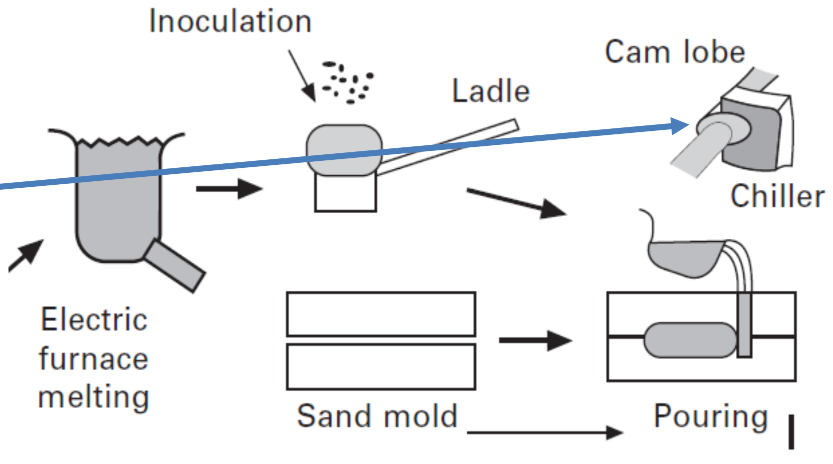
Molten iron is **transferred from furnace to molds** using a ladle **covered with a heat-insulating lining**.

In manual pouring, one ladle of molten iron can be **poured into several molds** one after another, which **takes around five minutes**.

If the solidification temperature of the metal is high, then the pouring must be finished within a very short period of time otherwise the molten iron will solidify in the ladle. Hence, with a **lower solidification temperature there is more time for pouring**.



CHILLED CAST IRON



The **cam lobe portion should be cooled rapidly** in order to generate hard chill.

An **iron lump called a chiller** is used for this purpose.
The **chiller is positioned at the cam lobe** and **takes heat away from the casting, giving a rapid solidification rate**.

The **chiller is normally made of cast iron**. The chiller has a **cam lobe-shaped cavity** and is **inserted into the sand mold prior to casting**.

Except for the chiller, the **master mold consists of compacted sand**. The shape and volume of the chiller determine how effective it is at absorbing heat, and it must be designed carefully to give the optimum cooling rate.

CHILLED CAST IRON

The mold is a **sand mold**.
After solidification, the sand mold is broken and the **camshaft is taken out**.
The **sand mold contains a binder** and appropriate **water content**. It should be breakable after solidification without break during pouring. **The sand is reused**.

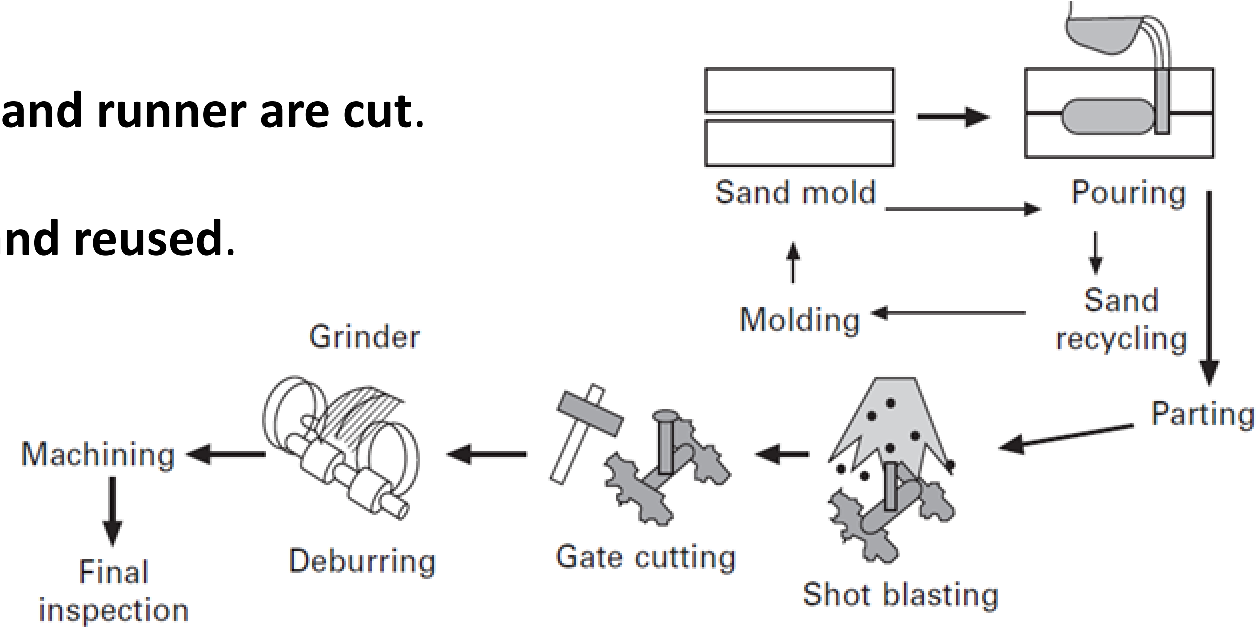
The iron **shots blast the shaped material to remove the sand**.

The **unnecessary gate, sprue and runner are cut**.

The **remnants are remelted and reused**.

Grinding deburrs the shaped material.

Then it is directed to the **final machining**.



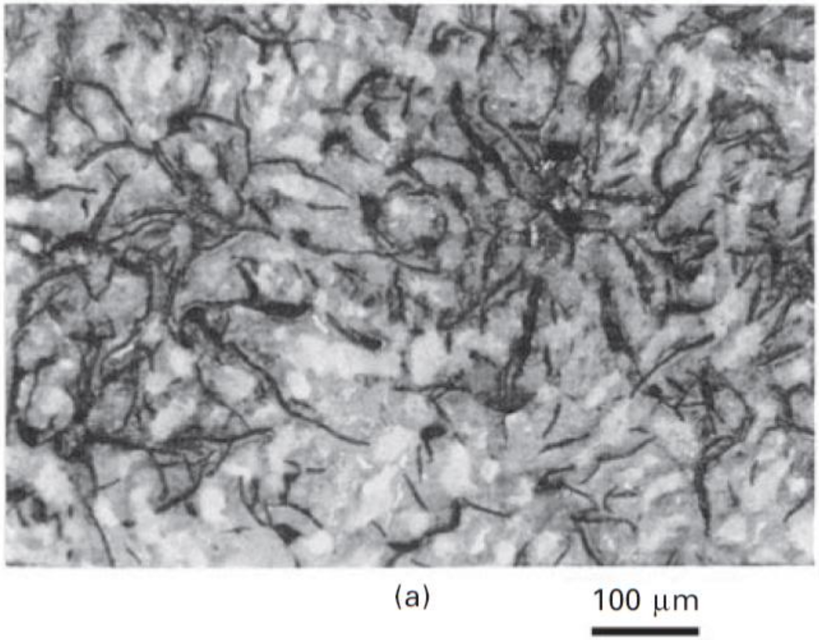
CHILLED CAST IRON

Sand molds produce a slow solidification rate because the insulating effect of the sand slows cooling.

Under these conditions, the **carbon** in the cast iron **crystallizes as flaky graphite** (see the figure) and the **casting expands**.
This **expansion ensures** that the **casting fits the mold shape** very well.

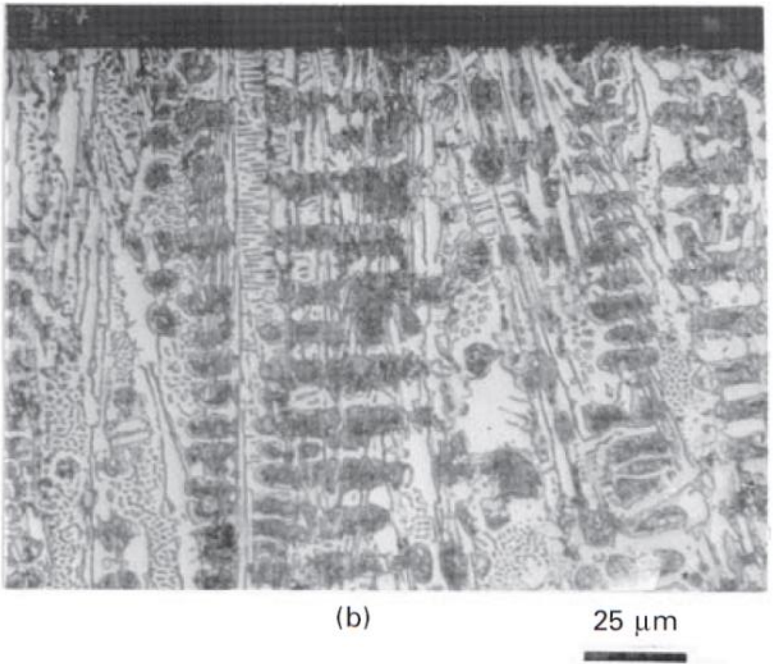
The resultant microstructure of the **iron matrix becomes pearlite**.

The microstructure of **flaky graphite cast iron has sufficient strength** for the shaft portion.



CHILLED CAST IRON

By contrast, the **cam lobe needs high hardness to provide good wear resistance**. If the rate of **solidification of cast iron is fast**, the included carbon forms into **hard cementite** (Fe_3C).
Iron combines with carbon to form cementite because graphite is difficult to nucleate at high solidification rates.
The structure **is very hard and is highly suitable for the hardness requirements of cam lobes**.



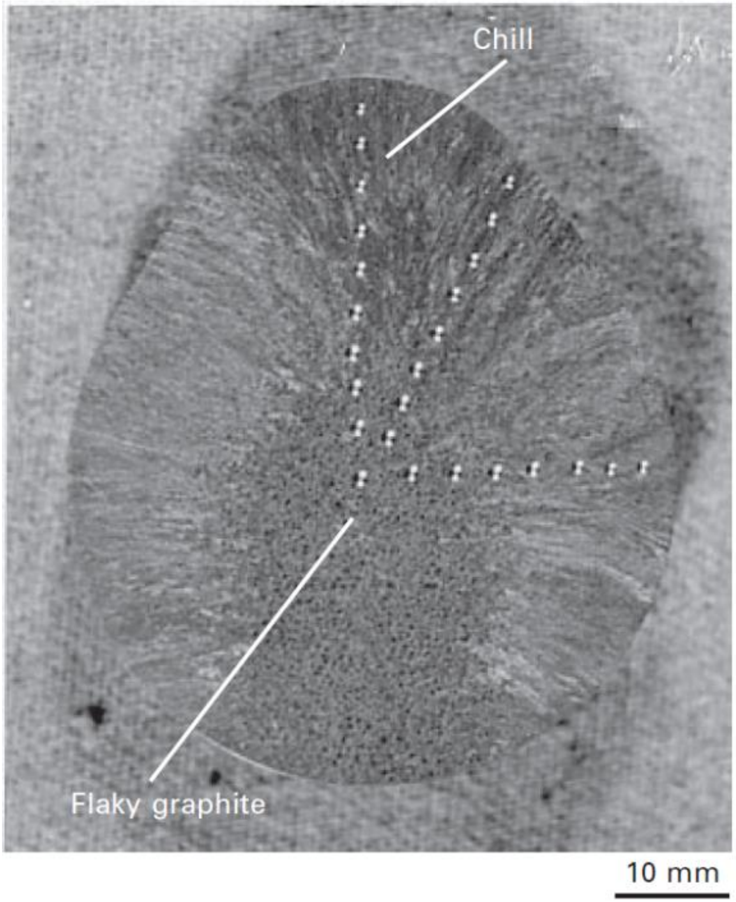
Chill has a mixed microstructure of cementite (white portion) and pearlite (gray portion). The hardness is around 50 HRC. Austenite and cementite appear simultaneously by eutectic solidification. The austenite portion transforms to pearlite during cooling. The eutectic solidification is called Ledeburite eutectic reaction. The additional quench-tempering changes pearlite to martensite. This heat treatment raises the hardness to 63 HRC.

CHILLED CAST IRON

The figure shows the **microstructures** correspond to the **chill and the flaky graphite**, respectively.

The **hardness** was measured **along three different radial directions**.

The small points are the places of the hardness measurements.



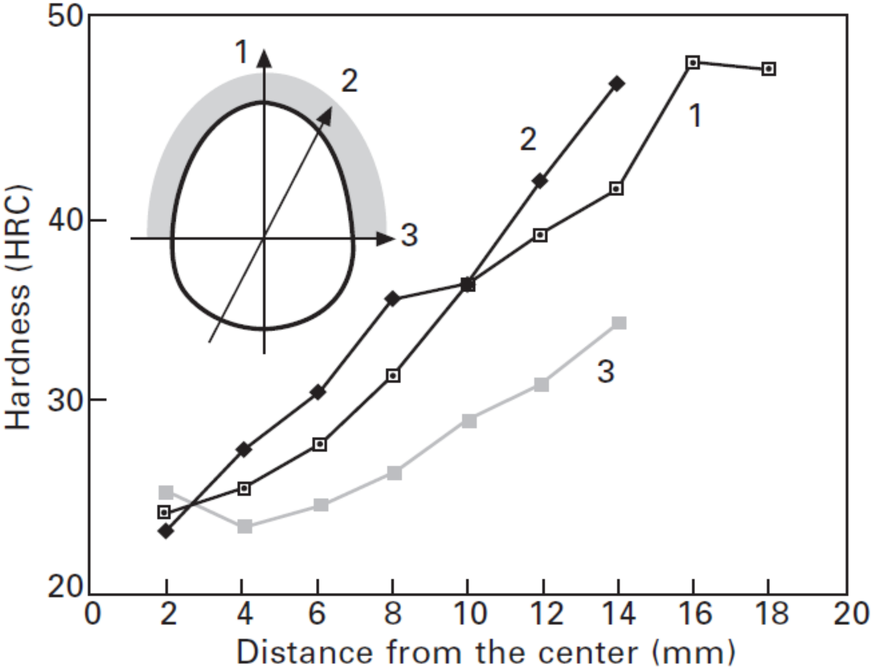
CHILLED CAST IRON

The figure shows the **distribution of hardness** at a cam lobe section.

Generally, **solidification starts from the surface**, **where the cooling speed is faster**. **Solidification in the central portion is slow due to the slow heat discharge rate**.

The **surface shows a high hardness** around 50 HRC **because of rapid quenching by the chiller**.
The chiller has contacted the molten cast iron only at the gray part in the illustration.

The **central portion is softer** at 25 HRC.



CHILLED CAST IRON

It is not easy to produce hard chill without any graphite in mass production.
A chill microstructure including graphite is soft and defective.

The manufacturing process must control the chill hardness of the cam lobe to achieve the required value (45 HRC), while avoiding hard chill in the shaft portion.

Hard chill in the shaft portion can break an expensive gun drill in subsequent machining operations.

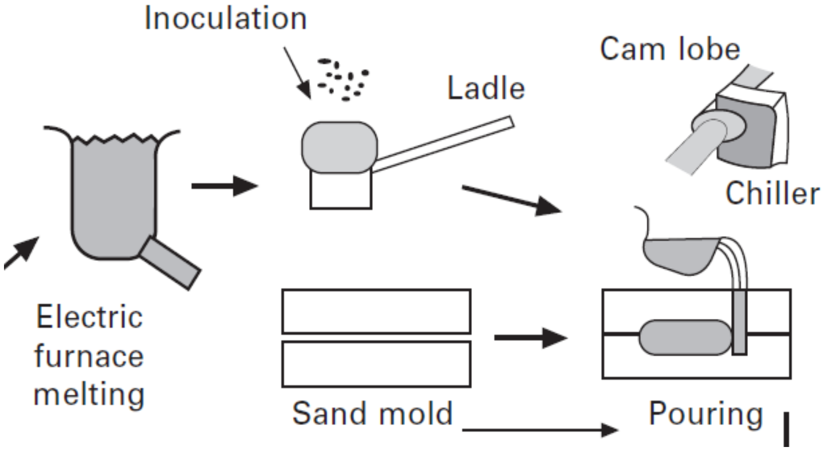
Generally, insufficient concentrations of C and Si are likely to cause chill even at slow solidification rates.

CHILLED CAST IRON

Inoculation is a procedure aimed at **solving the paradox that the hard chill and soft but strong shaft go together**. The **inoculant is placed** in the ladle **before pouring.**

The inoculant **adjusts the graphite shape, preventing chill where it is not required**. The inoculant is an **alloy powder**, such as Fe-Si, Ca-Si, or an alloy containing rare earth metals.

The inoculation effect lasts for a limited period of time and gradually disappears after the inoculation (known as fading), thus it is important to time the inoculation accurately.



CHILLED CAST IRON

An **alternative process to ensure hard chill at the cam lobes is remelting**.

This process controls casting and chilling separately. The material is **first cast to produce the flaky graphite** microstructure. Then **the surface of the cam lobe is partially remelted and then solidified rapidly to generate chill**.

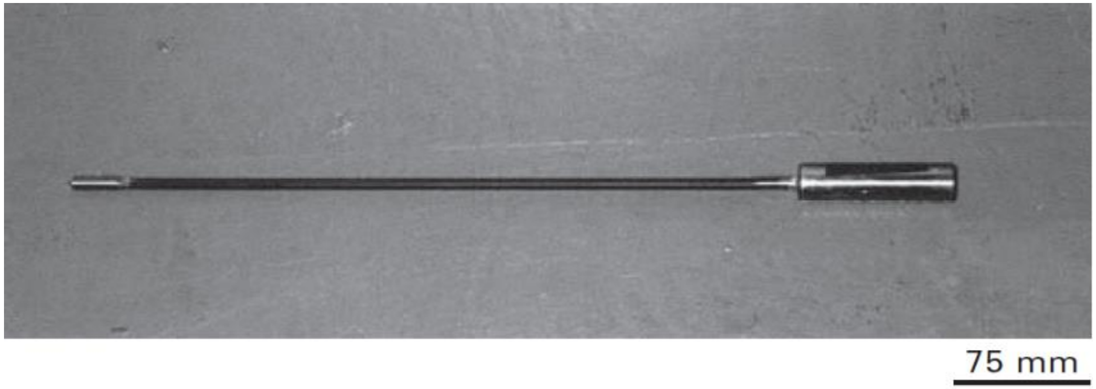
Although **it requires an additional process**, this method **provides better control of the hardness**. However, if remelting is too slow, it can cause the shaft section to melt, so a **high-energy heat source**, such as a **tungsten inert gas (TIG) torch**, is used. The concentrated heat melts the surface of the cam lobe instantaneously.

CHILLED CAST IRON

The camshaft needs a **continuous, longitudinal central hole for the passage of oil**. This also serves **to reduce the weight**.

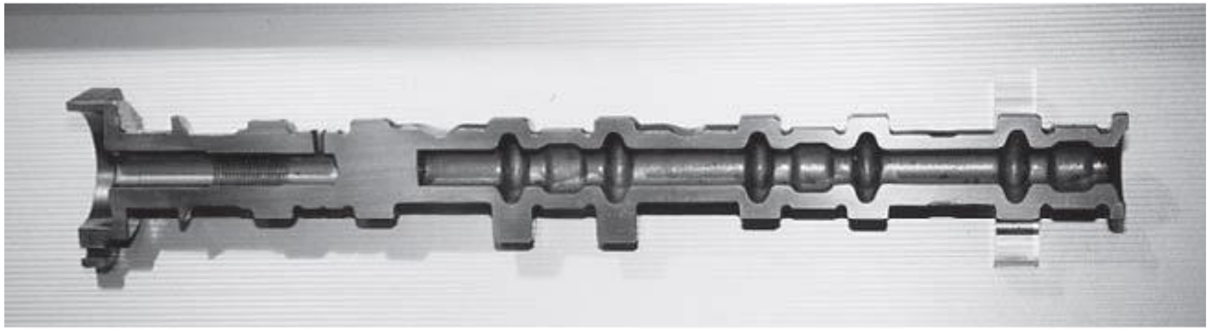
The hole is made using a **gun drill** (see figure), which was originally developed for boring guns. The drill consists of a long pipe shaft with a cutting bit at the end.

Machining oil is transmitted through the pipe to the bit during the drilling process. If hard chill has occurred in the central portion of the camshaft, this prevents the drill from boring effectively.



CHILLED CAST IRON

It is possible to **eliminate the boring process** by making the hole in the camshaft during the **initial casting process**. Figure shows an example in cross-section. Excess metal is cut away using a long shell core.



CHILLED CAST IRON

The **shape of the cam lobe has a direct influence** on engine performance.

A **copy-grinding** machine is used to **finish the cam lobe**. The grindstone traces a predetermined master cam.

The hard chill means that each cam lobe has to be ground in small stages.

Machine **finishing is often followed by gas nitriding** or manganese-phosphate conversion coating. These improve how the cam lobe adapts to the rocker arms during the running-in period.

FORGED CAMSHAFTS

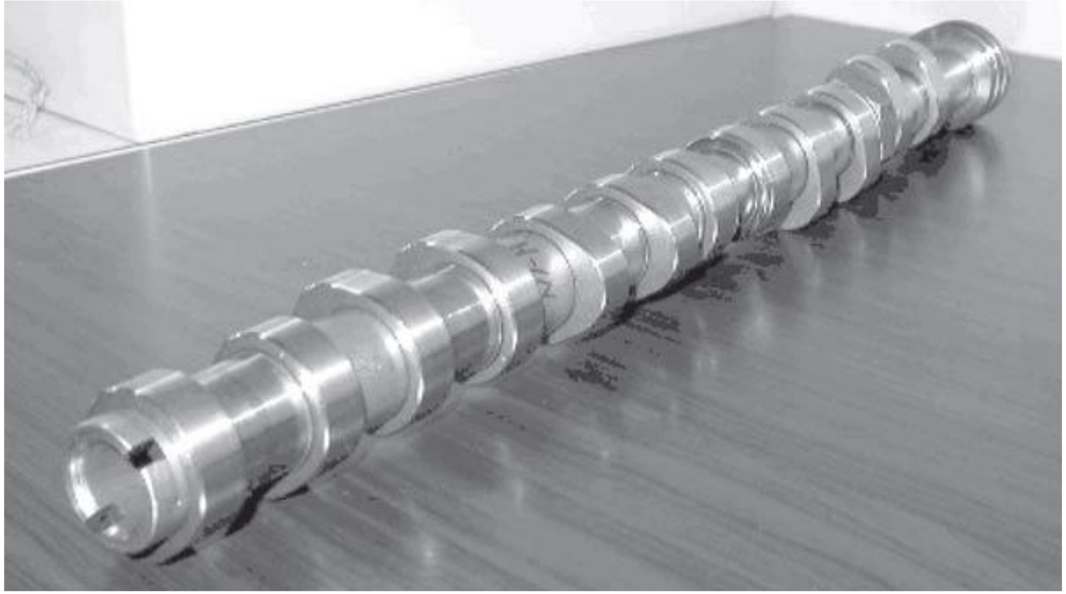
Camshafts can also be **forged from Cr-Mo steel**. The entire camshaft is carburized and quench-tempered.

The **multivalve engine** employs a greater number of valves, and the **gap between these valves is consequently narrow**, particularly in the small-bore-diameter engine, requiring short intervals between cam lobes.

Chill hardening cannot be used where the gap between the cam lobes is narrow because of the difficulty in using the chiller, so **forged camshafts are used**.

COMPOSITE STRUCTURES

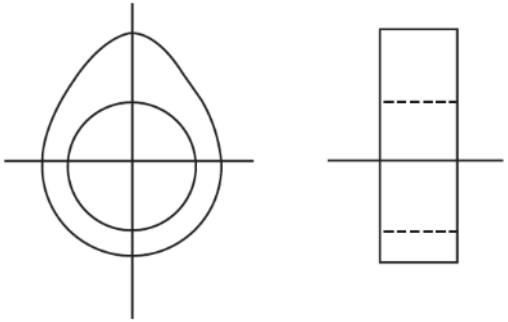
Assembled camshafts consist of a hollow shaft and cam lobe pieces. The figure gives an example.



Assembled camshaft using mechanical joining (hydroforming).

COMPOSITE STRUCTURES

The **cam lobe** piece shown in the figure is made from a **wear-resistant sintered material** or hardened high carbon steel. The shaft portion is a steel tube.

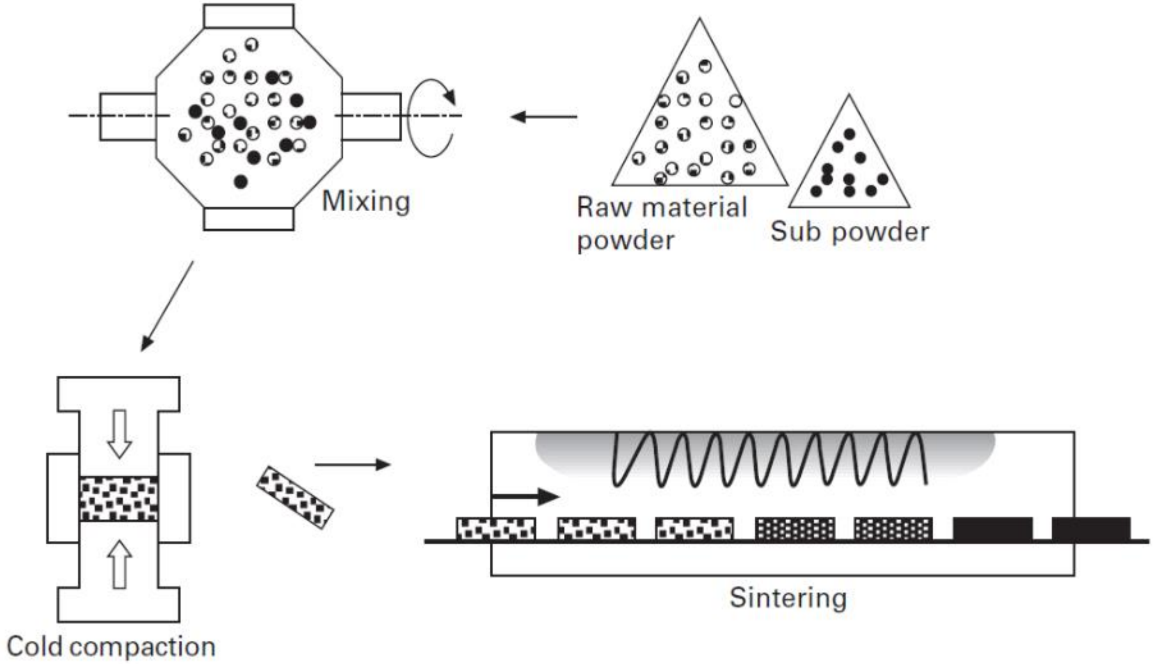


A cam lobe piece for assembled camshaft

COMPOSITE STRUCTURES

The figure is a schematic representation of the **powder metallurgy process** used to shape and harden the cam lobe pieces for assembled camshafts.

A mixture of powders that will produce the desired composition is prepared.

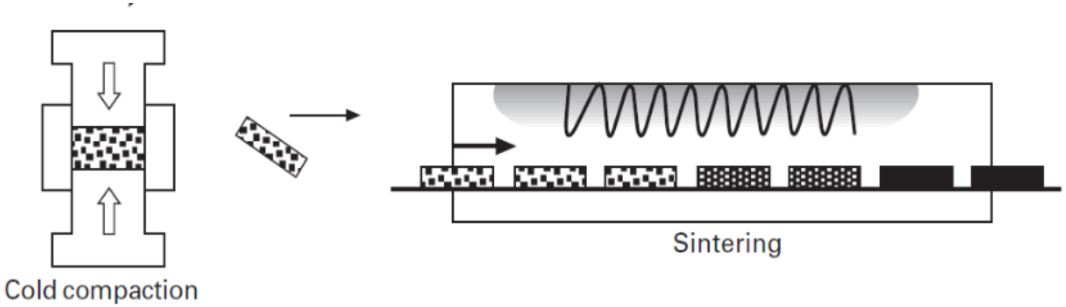


COMPOSITE STRUCTURES

This **mixture is pressed into the die**, which shapes the material in a process called **cold compaction**. The resulting shaped material is **still porous and soft**.

The **sintering process** in the furnace **removes pores** through atomic diffusion and increases the density of the part. Generally, the compacted powder is **heated to a temperature** well below the melting point of the iron, usually **between 1100 °C and 1250 °C**, in continuous furnaces with a **protective atmosphere**. A density of 90% to 95% of the maximum theoretical value is quite normal, leaving between 5% to 10% porosity.

This has some influence on the properties of the part, but the **strength and hardness** that can be achieved range from those of cast iron to those of **hardened and tempered tool steel**.



COMPOSITE STRUCTURES

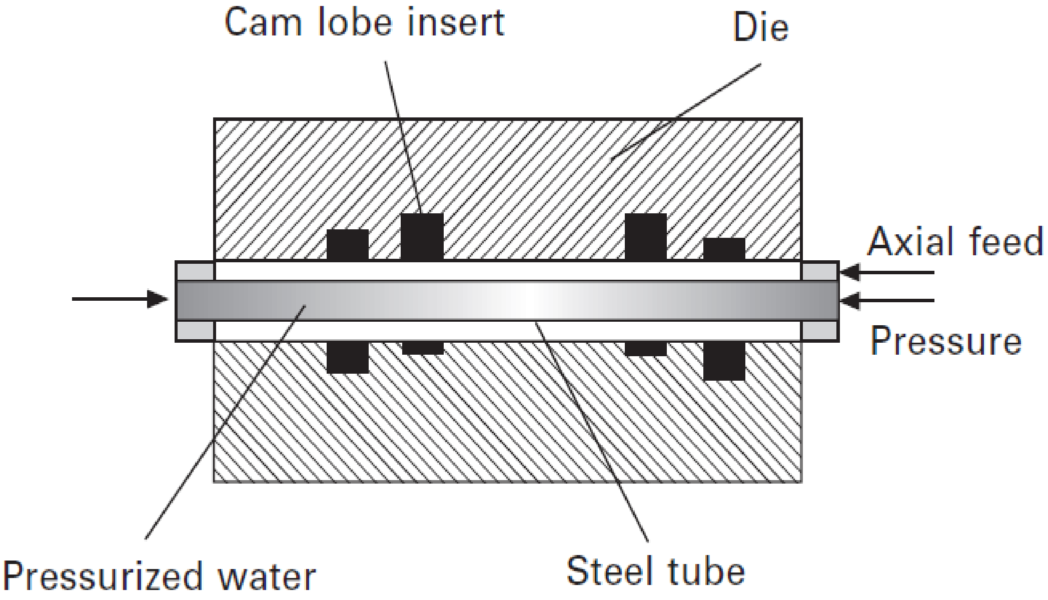
Sintering makes it possible to mechanically **mix several dissimilar powders**. Since sintering does not melt **the powders**, these **can coexist in the sintered** part so that the alloy composition can be very different from that produced during conventional solidification. A **high amount of hard carbide with a fine dispersion**, which **is not possible in the normal casting process**, is thus **obtained and gives the cam lobes good wear resistance**.

In car engine parts, **valve seats**, **main bearing caps** and **connecting rods** are made by this process.

The alloy mixture for sintering contains **small amounts of Cu**. During sintering, the Cu melts and **bonds the iron-alloy powder** particles.

COMPOSITE STRUCTURES

Assembling of camshaft using hydroforming process:
The steel tube is placed in the die where the cam lobe inserts are already positioned. The internal **pressurized water expands the steel tube to fix the cam lobe**. The axial feeding pushes the end of the tube to minimize the wall thinning out.



REFERENCE, SOURCE

Hiroshi Yamagata: The science and technology of materials in automotive engines, Woodhead Publishing Limited and CRC Press LLC, 2005

SUGGESTED VIDEOS

Function:

https://www.youtube.com/watch?v=itE2JWqdTqE
https://www.youtube.com/watch?v=s5n-2gb8yfM

Forging of camshaft:
https://www.youtube.com/watch?v=mj8leWsB4w4