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Group 3

Design and Heat Treatment of Cam Follower

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01. INTRODUCTION TO CAM FOLLOWER

1.1 WHAT IS CAM FOLLOWER?

A cam-follower mechanism is a basic machine component that converts a cam's uniform rotary motion into a follower's predetermined, non-uniform linear or oscillating motion. The follower's movement is determined by the surface profile of the cam, a rotating component with a unique contour. The follower rises, stays, or returns in accordance with the cam's shape as it rotates.

In devices that need precise timing, automated control, and repeated motion cycles, this mechanism is crucial. By simply shaping the cam profile, designers can program precise movement patterns. Cam-follower systems are widely used in automation equipment, precision control systems, textile and printing machines for synchronized motions, and engines to operate valves. Their ability to convert simple rotation into complex motion makes them versatile and essential in mechanical engineering [1],[2].

The cam follower is the small contact element that directly touches the cam surface and transfers the cam's profile into motion. Its shape whether flat, spherical, roller, or knife-edge determines how the follower interacts with the cam, how much friction is generated, and how contact stresses are distributed. Because it experiences intense Hertzian pressure, sliding or rolling contact, and continuous cyclic loading, the tip must be made from a high-hardness, wear-resistant material and finished to a very smooth surface. Essentially, this is the functional point where all force, motion, and wear in the cam–follower mechanism are *concentrated.*

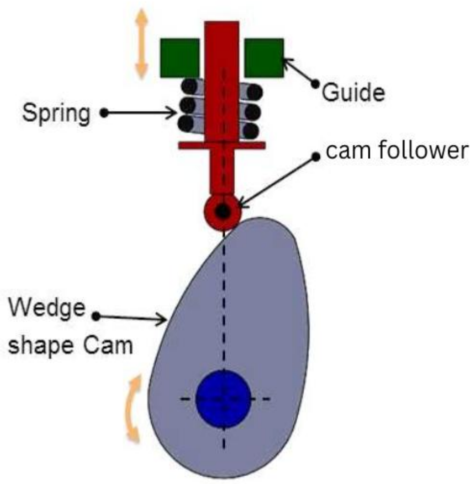


Figure 1:Cam and follower

1.2 COMMON APPLICATION OF CAM FOLLOWER.

Cam followers are widely used in mechanical and automated systems where controlled, repeatable motion is required. Their applications can be categorized as follows:

• Valve and Pump Mechanisms

Cam followers play a critical role in systems that require precise timing and high-frequency cyclic motion. In internal combustion engines, they convert the camshaft rotation into accurate valve opening and closing sequences, ensuring proper air–fuel intake and exhaust removal. In fuel injection pumps, the follower is driven by a cam to generate the high pressures needed for efficient fuel delivery, making reliability and wear resistance essential in these components.

• Industrial Machinery and Automation

Cam followers are widely used in industrial machines where synchronized mechanical motion is required. Textile machinery uses followers to generate repetitive weaving and knitting motions, while printing machines depend on cam-driven mechanisms for coordinated paper feed and roller movements. Packaging machines utilize cam followers to drive cutters, sealers, pushers, and labeling arms, ensuring precise timing in high-speed production lines. In CNC and automated systems, cam followers support controlled actuation for positioning, feeding, and tool indexing.

• Motion-Control and Robotics

In motion-control applications, cam followers provide reliable mechanical actuation without the need for complex electronic control. Robotic arms use cam followers in certain compact, low-cost mechanisms to achieve smooth and repeatable motion. Indexing tables and rotary positioners also rely on cam-follower pairs to convert continuous rotation into discrete, accurate positioning steps, making them essential in automation and assembly processes.

1.3 TYPES OF CAM FOLLOWERS

Classification of Cam Followers by Contact Shape

Cam followers can be categorized based on the geometry of the contact surface that interfaces with the cam profile. The shape of this contact element strongly influences friction, wear behavior, allowable load, and the follower's suitability for high-speed or misalignment-prone applications [3].

a. Knife-Edge Cam Follower

The knife-edge follower incorporates a sharp, pointed tip that provides very precise point contact. While simple and inexpensive, it experiences extremely high localized stresses and rapid wear on both the follower and the cam surface. Therefore, it is suitable only for very light loads and low-speed applications.

b. Roller Cam Follower

A roller follower uses a rotating cylindrical roller at the contact point, which significantly reduces sliding friction and promotes predominantly rolling contact. This design minimizes wear, supports higher speeds, and provides smooth motion transfer, making it ideal for high-performance and high-cycle applications.

c. Flat-Faced Cam Follower

A flat-faced follower uses a planar surface to engage the cam profile. This increases the contact area, allowing it to handle higher loads and steep cam slopes without edge failure. However, misalignment can generate high surface stresses and uneven wear, requiring careful design and proper guiding.

d. Spherical Cam Follower

A spherical follower features a curved, ball-shaped contact surface that distributes stress more uniformly and avoids edge loading. Its geometry accommodates minor misalignment while reducing sliding friction compared to a flat follower. This design is preferred in systems where slight angular deviations or variable contact conditions occur.

1.4 COMPARISON OF CAM FOLLOWER

Feature	Knife-Edge	Flat-Face	Roller	Spherical-Face
Contact Type	Point or line	Flat surface sliding	Rolling	Curved spherical surface
Friction	Very high because of sliding	High due to large sliding area	Very low because of rolling	Medium because sliding still exists
Wear Rate	Extremely high sharp edge wears quickly	High sliding causes material removal	Very low rolling avoids wear	Medium curved surface reduces wear
Load Capacity	Very low sharp edge can fail	High large surface supports load	Very high roller bearings carry load	Medium better than knife-edge but less than flat
Speed Capability	Very low Due to friction & heating	Medium sliding limits speed	Very high rolling is efficient	High
Stress Concentration	Very high at sharp point	Moderate (good load distribution due to large surface)	Low	Low (curved surface spreads stress)
Side Thrust	Moderate	High side thrust	Very low	Very low
Durability	Very poor	Moderate	Excellent	Good
Manufacturing Cost	Cheapest	Medium	Highest	Medium
Best Application	Light-duty low-speed	Heavy loads at moderate speeds	High-speed high-load precision	High-speed with misalignment
Worst Application	High speed/high load	High speed	Poor lubrication or heavy shock	Extremely heavy sliding loads

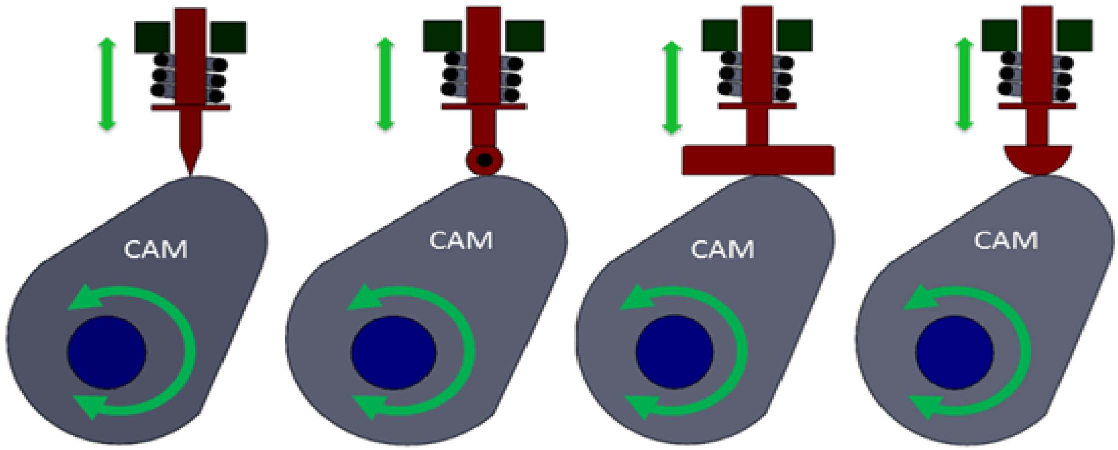


Figure 2: a. Knife-Edge Cam Follower, b. Roller Cam Follower, c. Flat-Faced Cam Follower, d. Spherical Cam Follower

02.SPHERICAL CAM FOLLOWER

2.1 SPHERICAL CAM FOLLOWER AND DIMENSIONAL DEPENDENCIES

2.1.1 Physical Dimensions of the Follower.

- Spherical Radius (R_f): The radius of the curved "dome" or surface that contacts the cam. Unlike a flat follower, this is a finite radius.

- Face Width (W): The physical width of the follower tip (or roller) along the axis of rotation. Even though contact is a single point, the width ensures the contact point doesn't "fall off" the edge if the follower tilts or slides sideways.

- Stud/Stem Diameter (d_s): The diameter of the shaft connecting the follower tip to the rest of the mechanism.

2.1.2 Functional Dimensions (System Geometry)

These definitions relate to how the follower interacts with the cam.

- Base Circle Radius (R_b): The radius of the smallest circle that can be drawn tangent to the cam profile from the cam center.
- Prime Circle Radius (R_b): The radius of the circle drawn from the cam center to the center of the follower (for a spherical/roller follower) when it is at its lowest position.

Formula: $R_p = R_f + R_b$

2.1.3 Effect of Dimensional Changes of Performance

The table below defines these dimensions and details how incrementing or decrementing them impacts the system's mechanical behavior.

Dimension & Definition	Effect of Increment	Effect of Decrement
Spherical Radius (R_f)	• Smoother: Filters surface roughness. • Lower Stress: Increases the effective contact area (larger Hertzian ellipse), reducing surface fatigue. • Risk: Increases risk of undercutting (cannot fit into concave cam curves).	• Trace Accuracy: Can follow sharper, tighter concave curves on the cam. • Higher Stress: Shrinks the contact point, drastically increasing pressure and wear. • Risk: Higher likelihood of surface pitting/failure.
Stud Diameter (d_s)	• High Stiffness: Resists bending from side loads	• Lightweight: Low inertia allows for faster acceleration/cam speeds.

	(friction/pressure angle forces). • Stable: Keeps the contact point in the correct position. • Heavier: Adds moving mass, limiting high speed performance.	• Flexible: Stem may bend under load, causing "lift error" (follower doesn't rise as much as intended).
Face Width (W)	• Safety: Allows for greater misalignment/tilt without the contact point slipping off the edge. • Wasted Mass: Since contact is just a "point," extra width adds unnecessary weight.	• Compact: Fits into tighter spaces; lower weight. • Risk: If the mechanism vibrates or tilts, the contact point might slip off the edge, causing catastrophic failure.
Cam Base Circle (R_b)	• Low Pressure Angle: Reduces side-thrust on the follower stem (less friction/jamming). • Geometry: Allows you to use a larger Follower Radius (R_f) without undercutting.	• Compact System: Reduces the overall machine size and weight. • High Pressure Angle: Steeper cam slopes create massive side-loads on the follower stem, leading to wear or jamming.
Prime Circle (R_p)	• Smoother Force: Generally, correlates with a larger system that handles force transmission better. • Space: Requires larger housing.	• Compact: Tighter packaging. • Aggressive: Often correlates with steeper acceleration curves.

Table 1: performance change with dimension

2.2 MATERIAL SELECTION FOR SPHERICAL TYPE CAM FOLLOWER

2.2.1 TYPICALLY USED MATERIALS

Machine Type & Examples	Functions	Desired Material Properties	Suitable Material & How It Satisfies Properties	Heat Treatment	Surface Treatment & Enhancement
Automotive Valve Train Systems Engines (OHV, OHC), Motorcycles	• Convert cam profile into follower • Motion under high-frequency cyclic loading	• Very high surface hardness (58–66 HRC) • Contact fatigue resistance • Dimensional stability • Low wear under sliding + rolling contact	AISI 52100 Bearing Steel High carbon chromium steel provides very high hardness and excellent rolling-contact fatigue life	Austenitize 830–860°C → Oil quench → Low-temperature tempering (150–200°C)	Superfinishing & lapping for low Ra; optional DLC/TiN coating for friction reduction
High-Precision Automation Systems Robotic actuators, Indexing mechanisms	Smooth motion transfer with minimal friction	High dimensional accuracy Smooth contact High wear resistance Low distortion during heat treatment	Nitriding Steel (e.g., Nitralloy 135M) Thin, extremely hard nitride layer forms with minimal distortion	Core harden to ~30–35 HRC → Gas/Plasma Nitriding @ 500–530°C	Plasma nitriding gives 900–1200 HV surface hardness; polishing for smooth contact
Industrial Cams & Packaging Machines High-speed rotary cams	Continuous rolling–sliding contact under moderate impact	Hard case + ductile core Shock resistance Good wear & pitting resistance	20MnCr5 / AISI 8620 Carburizing Steel Carburized case provides hard martensitic surface with tough core	Carburizing 900–950°C → Oil/polymer quench → Temper 150–200°C → Case depth 0.8–1.2 mm	Shot peening improves fatigue life; surface grinding & lapping for precision
Hydraulic & Injection Systems Cam-driven pumps	High contact pressure + frequent cyclic loading	Deep case hardness High compressive strength Fatigue resistance under high Hertz stress	Case-Carburized 20MnCr5 (Preferred for heavy loads) Deep case resists pitting; strong core resists impact	Carburizing to 1.0–1.2 mm case → Hardness 58–62 HRC → Temper	Phosphate or DLC coating to reduce scuffing under boundary lubrication
Precision Motion Control & CNC Machines	Precision profile following + minimal vibration	Dimensional stability Hard, wear-resistant surface Ability to finish to low roughness	AISI 4140 (Induction Hardened)	Through-hardening + localized induction hardening of sphere → Temper	Polishing to Ra < 0.4 µm; optional nitriding for extra wear resistance

Fine actuation cams			Localized hardening suits spherical surfaces while core remains tough		
Small Engine Components & Lightweight Mechanisms Portable tools, scooters	Reliable operation under moderate cyclic stress	Low weight Adequate surface hardness Cost-effective	Medium-Carbon Steel (1045) with Induction Hardening Provides moderate hardness and low cost	Induction hardening of spherical cap → Temper to 50–55 HRC	Basic surface finishing; optional black oxide for corrosion resistance
Wear-Critical, High-Speed Contacts Precision cam followers in machine tools	Sustained rolling contact under high speed	Extreme wear resistance Smooth surface Stable microstructure	AISI 52100 or Nitrided Alloy Steel depending on load	Through-hardening (52100) or nitriding for high fatigue resistance	Superfinishing, micro-polishing, DLC coating for extreme wear control
Textile Machinery Cam followers operating under oscillating or misaligned motion.	Convert rotary motion into precise reciprocating/oscillating motion	High Surface Hardness High Contact Fatigue Strength	Bearing Steels (AISI 52100) Carburizing Alloy Steels (AISI 8620, AISI 9310)	Case hardening Induction Hardening	DLC Coating Phosphate Coating

Table 2: Applications of Cam followers

2.2.2 PROPERTY REQUIREMENTS

Valve trains, high-speed industrial cams, and automated machinery are the applications with the highest global usage of spherical cam followers. According to those applications these are the primary and secondary requirements for spherical cam follower materials.

<u>Primary Requirements for Spherical Cam Follower Material</u>

These are mandatory for reliable operation:

1. High surface hardness
    - 58–65 HRC needed to resist Hertzian contact stresses.
2. High rolling + sliding wear resistance
    - Spherical contact patch experiences mixed contacting.
3. High contact fatigue resistance
    - Prevents micro-pitting, spalling, and flaking.
4. Tough and ductile core
    - Needed to withstand shocks during high-speed actuation.
5. Good hardenability
    - Must develop required hardness at sufficient depth (case).
6. Dimensional stability after heat treatment
    - Spherical geometry must remain precise.
7. Good grindability / machinability
    - Spherical follower requires finishing to low roughness ($Ra < 0.4$ µm).

<u>Secondary Requirements</u>

These improve manufacturability & service life but are not mandatory:

1. Corrosion resistance
2. Low coefficient of friction (can be achieved via coatings)
3. Resistance to temper softening
4. Compatibility with lubricants / additives
5. Cost effectiveness and availability
6. Ability to accept surface engineering (DLC, TiN, nitriding)
7. Low distortion for precision applications
8. Environmental friendliness in heat treatment

2.2.3 COMPARISON BETWEEN MATERIALS

Pros and cons of materials

Material	Pros	Cons
Case-Carburizing Steels Examples: 20MnCr5, AISI 5120, AISI 8620	Excellent combination of hard case + tough core High contact fatigue resistance (deep case) High impact strength (ductile core) Very good wear resistance Adjustable case depth (0.5–2 mm) Most commonly used industrial choice for cam followers Good dimensional stability after grinding	Requires carburizing furnace (long cycle times) Carburizing can cause distortion → requires finishing More expensive heat treatment than through-hardening Carbon gradients must be controlled
High-Carbon Chromium Bearing Steel Examples: AISI 52100 / EN31 (through hardened)	Very high hardness (60–66 HRC) Excellent rolling contact fatigue performance Extremely wear-resistant Standard bearing steel → reliable & well-characterized Good for small spherical followers needing high precision	Brittle compared to carburized steels Lower core toughness → not ideal for impact loads Requires precise heat treatment → risk of cracking Dimensional changes during quenching Not suitable for large followers (poor through-hardenability)
Medium-Alloy Quenched & Tempered Steels Examples: AISI 4140 / 4142	Easy to machine before heat treatment Very good balance of toughness & strength Induction hardening possible on spherical surface Economical Less risk of distortion than 52100	Surface hardness (55–60 HRC) lower than bearing steel Induction hardening a spherical surface is difficult Fatigue resistance lower than carburized steels Not ideal for extremely high Hertz contact stresses
Nitriding Steels Examples: Nitralloy 135M, Cr-Mo-Al steels	Extremely hard surface (900–1200 HV) Very low distortion (no quench) High wear resistance under sliding	Nitrided layer is thin (0.1–0.6 mm) not ideal for very high Hertz pressure

	Excellent dimensional precision (ideal for spherical surfaces) High fatigue life due to compressive surface stresses	Not suitable for heavy impact loads Long nitriding cycle expensive Core usually medium hardness (~30–40 HRC)
Martensitic Stainless Steels Examples: AISI 420, AISI 440C	Good corrosion resistance High hardness (up to 58 HRC for 420, 60 HRC for 440C) Good wear resistance in corrosive or wet lubrication environments	More brittle than carburized steels Poor toughness compared to 4140 or 8620 Expensive Distortion risk during quenching 440C is prone to cracking at high hardness
Cr–Mo Low Alloy Steels Examples: 4130, 4140 (general), 4145, 4320	Good core toughness Accept both carburizing and nitriding Good fatigue strength Well balanced + economically attractive	Lower achievable surface hardness compared to 52100 Not ideal for the highest wear applications unless carburized Distortion control needed for precision spheres
Ni–Cr–Mo Low Alloy Case Hardening Steels Examples: 3310, 4320, 9310	Excellent deep hardenability Very tough core + high hardness case Superior shock resistance + fatigue resistance More stable than simple Cr–Mo steels One of the best for high-load, precision cam followers	More expensive alloys Carburizing cycle is long Requires controlled atmosphere Grinding after heat treatment required

Table 3 Materials Used in Cam followers and it pros and cons

Property comparison between materials

Material Category	Examples	Surface Hardness Potential	Core Toughness	Wear Resistance	Contact Fatigue Resistance	Distortion During Heat Treatment	Cost	Suitability for Spherical Cam Follower
1. Case-Carburizing Steels	20MnCr5, AISI 5120, AISI 8620	+++++ (58–63 HRC) (If carburized)	+++++	++++	+++++	++ (Carburizing causes distortion)	Low - Medium	Excellent - industry standard choice
2. High-Carbon Chromium Bearing Steel	AISI 52100, EN31	+++++ (60–66 HRC)	++ (brittle)	+++++	++++	++	Medium	Good for small precision followers, lower impact tolerance
3. Medium-Alloy Q&T Steels	AISI 4140, 4142	+++	+++++	+++	+++	++++	Low	Moderate loads only; needs induction hardening
4. Nitriding Steels	Nitralloy 135M, Cr-Mo-Al steels	+++++ (III—1200 HV)	+++	++++	+++ (Thin layer)	+++++ (very low distortion)	High	Excellent for precision, NOT for high Hertzian loads
5. Martensitic Stainless Steels	AISI 420, AISI 440C	++++	++	+++	++	++	High	Useful only if corrosion a major factor
6. Cr–Mo Low Alloy Steels	4130, 4145, 4320	++++ (if carburized)	++++	+++	++++	+++	Low–Medium	Good alternative, but lower performance than 20MnCr5
7. Ni–Cr–Mo Case Hardening Steels	3310, 4320, 9310	+++++	+++++	+++++	+++++	+++	High	Superior performance but high cost; used in aerospace

Table 4 materials and it's properties

Summary of Suitability Ranking

Rank	Material	Reason
1	20MnCr5 / AISI 5120 / AISI 8620 (Carburizing Steels)	Best combination of hardness, toughness, fatigue resistance, and cost
2	Ni–Cr–Mo Case Hardening Steels	Highest performance, but expensive
3	AISI 52100	Exceptional hardness, suitable for precision but brittle
4	Nitriding Steels	Best dimensional stability, but thin hardened layer
5	Cr–Mo Steel (4130/4140)	Affordable and decent performance but inferior to carburized steels
6	Martensitic Stainless Steels	Only beneficial if corrosion is a major issue
7	Medium-alloy Q&T steels alone	Insufficient wear resistance for high Hertzian contact

Justification Based on Ferrous Alloy Characteristics

Exploring material options for spherical cam followers requires meeting operation specific performance demands related to rolling-sliding interaction, substantial Hertzian stress values and repetitive impacts and pressure load as stated in the project specification.

Evaluation of seven material families reveals 20MnCr5 case-carburizing steel as the best solution because it produces a high-hardness martensitic case alongside a resilient ductile core necessary for components that run under repeated heavy contact pressure. The carburization of steels like 20MnCr5 can achieve surface hardness of 58–62 HRC to a depth of 0.8–1.2 mm, thus producing better wear resistance and longer rolling/sliding fatigue life than other low-alloy steels [6], [7]. Experimental data suggests that the martensitic carburized surface enhances resistance against micro-pitting and adhesive wear together with subsurface fatigue cracking found typically in personalized cam-follower interfaces [8].

Multiple materials were carefully assessed, but none matched the required performance specifications. AISI 52100/EN31 bearing steel achieves exceptional rolling contact fatigue life alongside high hardness (60–66 HRC) values yet its core toughness limitations and brittleness put followers at serious risk of spalling and fractures when faced with shock-driven impacts [9], [10], [11], [15]. The material's performance as a spherical follower diminishes when used in sizes bigger than the ones found in both valve train and industrial cam applications. Nitralloy 135M among nitriding steels can form highly resistant surfaces with a hardness level between 900 and 1200 HV at minimal surface distortion but the small nitride layer size of usually less than 0.4 mm (about 0.02 in) prevents them from managing deep cyclic stresses present in spherical contact applications [12].

The induction hardening process fails to produce the same surface hardness and fatigue lifetime reduction achieved by carburized low-alloy steels in AISI 4140 and other medium-alloy steels [13], [14]. Martensitic stainless steels in grades 420 and 440C deliver corrosion protection but become too brittle above 55–58 HRC to maintain good fracture toughness, so they fail when used for impact service in cam follower components. The Ni–Cr–Mo case-hardening steel 9310 excels mechanically, but heavy alloying costs and specialized heat-treatment procedures make it suitable only for aerospace power transmission components which show few extra benefits compared to 20MnCr5 steel.

The 20MnCr5 alloy delivers the greatest combination of hardness and fatigue strength and impact toughness and dimensional retention and affordability after evaluating mechanical and metallurgical and economic factors. The alloy's ability to undergo carburizing followed by quenching and tempering methods supports the assignment's objective of enhancing ferrous alloy heat treatment performance for sliding and rolling contact applications.

Among the available materials 20MnCr5 shows full technical validity and industry support to develop high quality spherical cam followers that maintain dependable operation during valve train and high-speed cam mechanism cyclic loads.

2.2.4 CHOOSING 20MNCR5 CARBURIZING STEELS

Key Properties of 20MnCr5 for a Spherical Cam Follower

20MnCr5 material belongs to low-alloy case-carburizing steels and stands developed to serve components exposed to rigorous sliding and rolling contact, therefore precisely fitting the requirements for spherical cam follower applications. The application benefits from the following key material characteristics:

1. High Surface Hardness (58–62 HRC after carburizing)

The hardened case can withstand the high Hertzian stresses that develop at the small, curved contact area of a spherical follower. High hardness significantly reduces abrasive wear, adhesive wear, and micro-pitting.

2. Excellent Contact Fatigue Resistance

The carburized case forms a deep martensitic layer (0.8–1.2 mm) which resists **s**ubsurface fatigue cracking, flaking, and spalling, ensuring long service life under cyclic loads.

3. Tough, Ductile Core (28–40 HRC)

The low-carbon core remains tough after heat treatment and provides resistance to impact and shock loads, which occur when the cam follower engages rapidly at high speed.

4. Good Hardenability and Case Depth Control

Alloying elements Mn and Cr enhance hardenability, enabling:

- uniform case depth

- deeper hardened layer under high load
- minimized risk of surface soft spots

5. Good Machinability and Grindability

Before heat treatment, 20MnCr5 machines easily, and after carburizing it can be ground and polished to the low surface roughness (Ra ≤ 0.4 µm) required for spherical followers.

Chemical Composition Of 20MnCr5

Element	% Composition
Carbon (C)	0.17–0.22%
Manganese (Mn)	1.10–1.40%
Chromium (Cr)	0.80–1.10%
Silicon (Si)	0.15–0.35%
Phosphorus (P)	≤ 0.025%
Sulfur (S)	≤ 0.035%
Iron (Fe)	Balance

Table 5 Composition of 20MnCr5

Microstructural Benefits

The microstructure after full heat treatment consists of:

Carburized Martensitic Case

- Extremely hard (58–62 HRC)
- Fine, high-carbon martensite with retained austenite
- High compressive residual stresses → improved fatigue life
- Good resistance to abrasive and adhesive wear

Tough, Low-Carbon Martensitic/Bainitic Core

- Lower carbon content ensures toughness and ductility
- Prevents brittle fracture when the follower experiences impact
- Supports the hardened surface during high-contact loads

Chromium & Manganese Effects

- Cr improves hardenability and wear resistance
- Mn enhances toughness and hardenability
- Both elements help form a stable martensitic case with consistent depth

Resulting Microstructural Advantage

This combination of hard case and tough core is exactly what a spherical cam follower requires for durability, load distribution, and reliability in high-speed cam systems.

Reasons for Choosing 20MnCr5 for the Spherical Cam Follower

Spherical cam followers operate under mixed rolling and sliding contact thus requiring the combined properties of high surface hardness and wear resistance together with core toughness which 20MnCr5 delivers effectively. 20MnCr5 forms a martensitic case with 58-62 HRC hardness after carburizing and quenching to standardize case depth between 0.8 and 1.2 mm which provides the follower resistance for high Hertzian stresses at the cam follower join [6], [7]. The hardened depth suppresses adhesive and abrasive wear together with micropitting and rolling contact fatigue.the main failure mechanisms in spherical cam followers [8].

The core of low carbon remains ductile and tough after heat treatment so the material can effectively absorb impact shocks and cyclic loads without breaking and this quality is crucial during quick cam lobe to follower surface engagement. 20MnCr5 achieves better overall property balance than alternative materials. AISI 52100 bearing steel attains extremely high hardness levels but its impact toughness stays low and its brittleness increases which results in surface spalling under shock and misalignment conditions [9], [10], [11], [16]. Dynamic loading conditions make 52100 unsuitable as a material for follower mechanisms.

Hard nitriding treatment in steels reaches exceptionally high hardness levels with negligible distortion but synthesizes shallow nitride layers only about 0.1–0.4 mm thick thereby unable to maintain the intense subsurface stresses of spherical contacts [12]. Both AISI 4140 as well as comparable quenched and tempered steels demonstrate substantial toughness but reach neither equal case hardness nor durable contact fatigue resistance without induction hardening this latter treatment displays weak performance when applied to spherical components producing unsteady hardness distribution [13], [14].

20MnCr5 presents remarkable heat treatment and finishing dimensional stability in addition to its capability for precision grinding and polishing to low roughness levels necessary for effective cam–follower performance. The manufacturing of accurate spherical surfaces is more challenging since high-carbon through-hardening steels experience greater distortion during their quenching process. Ni–Cr–Mo carburizing steels like AISI 9310 produce excellent fatigue resistance, but their high cost alongside specialized manufacturing demands restrict their use for general industrial cam follower applications. Spherical cam followers achieve optimal performance through the investigated materials properties at 20MnCr5 because it provides technical suitability and cost efficiency with proven reliability in industrial applications. The deep case hardness together with the core toughness and excellent fatigue resistance plus dependable manufacturing results enable 20MnCr5 to maintain extended durability and dependable operation under repetitive high-speed cam loads [6]–[8].

Additionally, 20MnCr5 presents the ideal balance of mechanical features, hardenability and operational cost among case-carburizing steels including 16MnCr5, 20CrMo, 20CrNiMo, 25MoCr, and AISI 8620 for spherical cam followers. 20MnCr5 steel features increased manganese contents between 1.1% and 1.4% percent and chromium contents between 0.8 % and 1.1% percent when compared to other 16MnCr5 carburizing steels which mineralizes the steel to deeper and more uniform hardened cases during the carburizing process. Sectional case hardening of spherical cam followers requires a substantial depth since their contact point undergoes intense Hertzian stress, and a limited case depth will result in early subsurface spalling and fatigue.

2.3 SPHERICAL CAM FOLLOWER DESIGN

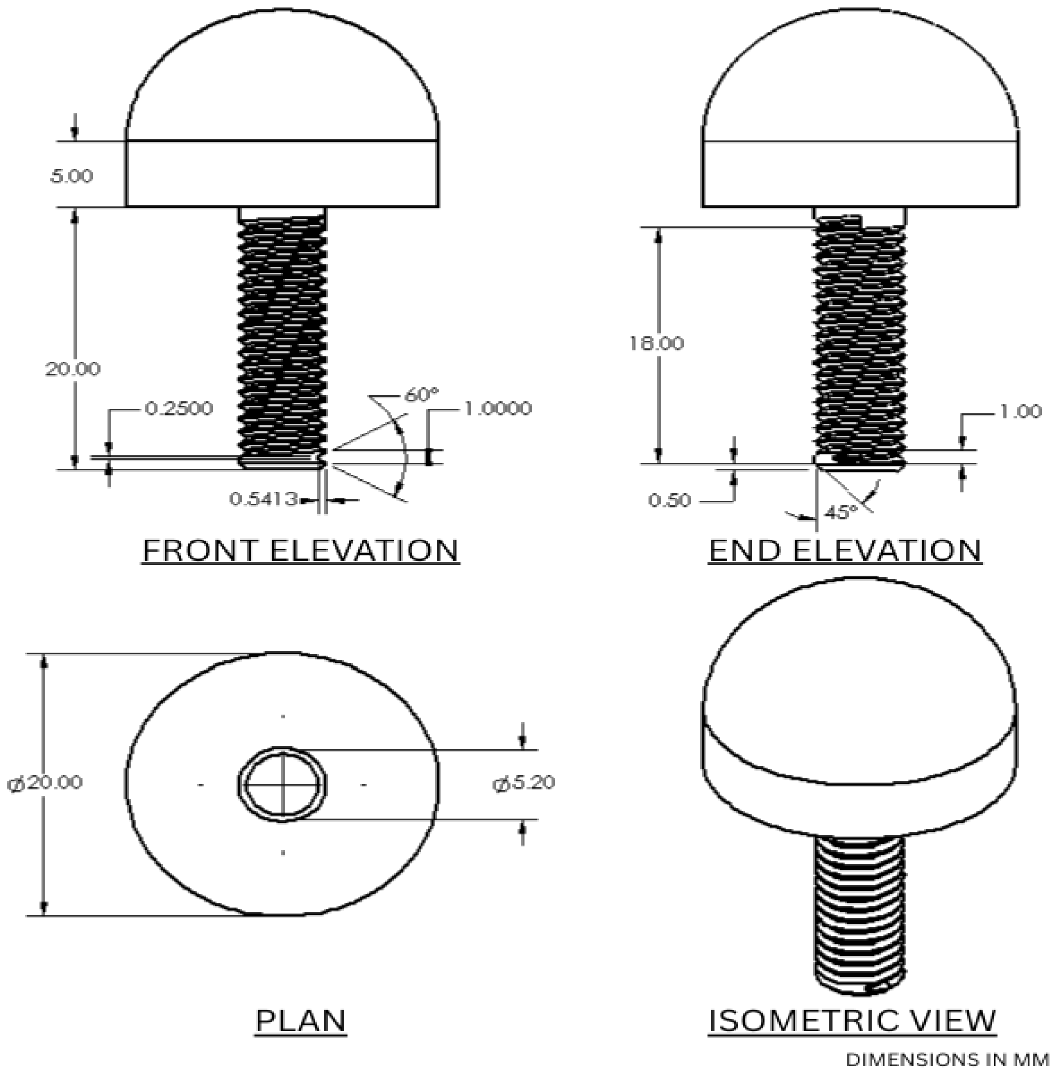


Figure 3 : Design of Spherical Cam follower

Here, the cam follower is mounted to the follower by a screw. So, the screw part also should be hard. The head of this screw is the contact surface of the cam follower. And the cam dollower can be replaced from the follower, then the cam follower is damaged.

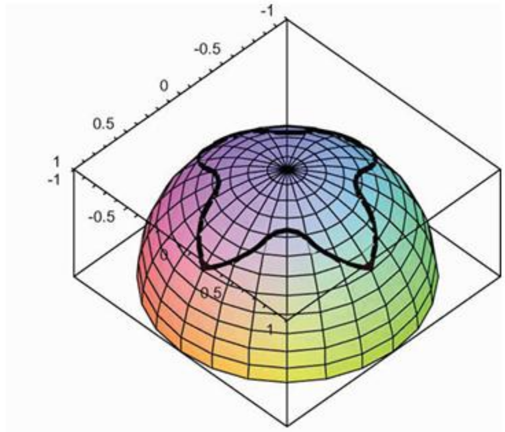


Figure 4: Contact geometry of spherical cam follower

This figure shows the area of the cam follower which is to be in contact with the follower. So, this part should be relatively more abrasive resistant

03.MANUFACTURING ROUTE SELECTION FOR THE SPHERICAL CAM FOLLOWER

The spherical cam follower in this design is manufactured using 20MnCr5 (AISI 8620), a low-alloy case-hardening steel widely used in components subjected to tribological loading. This follower experiences high Hertzian contact stresses, rolling–sliding motion and cyclic impact loading during operation.
Therefore, the selected manufacturing route must ensure:

- a tough, defect-free core,
- a high-hardness, wear-resistant carburized case,
- minimal distortion during heat treatment, and
- excellent contact fatigue resistance.

Several manufacturing processes were evaluated—casting, machining from bar stock, powder metallurgy, additive manufacturing, and closed-die forging. The comparison focuses on microstructure, defect formation, dimensional control, and the ability to meet the mechanical requirements of a fatigue-critical ferrous alloy component. Based on this evaluation, closed-die forging is identified as the most appropriate manufacturing method.

3.1 PROCESS COMPARISON

Process	Microstructure Produced	Defects / Porosity	Mechanical Properties	Dimensional Accuracy	Suitability for Cam Follower
Closed-Die Forging	Directional grain flow; refined ferrite–pearlite then martensitic case after HT	Very low; fully dense	Highest toughness, very high fatigue strength, excellent wear after carburizing	Good near-net shape; minimal distortion after HT	Excellent — best choice
Casting (Sand/Investment)	Random coarse grains; segregation; dendritic microstructure	High risk: shrinkage, gas porosity	Lower toughness, reduced fatigue strength, poor wear resistance	Moderate; high distortion during HT	Poor — unsafe for Hertzian contact
Machining from Bar Stock	Bar stock grains elongated along the	No porosity, but no grain flow	Good strength but inferior fatigue vs forging	High accuracy but high	Moderate — acceptable

	rolling direction only	matching the final shape		material waste	but inferior to forging
Powder Metallurgy (P/M)	Sintered grains with necks; residual porosity	Always some porosity	Moderate strength, low toughness, poor fatigue	High precision	Weak — porosity unacceptable in contact stresses

Forging vs Casting

- Forging produces a *fully dense*, porosity-free structure with directional deformation and refined grains.
- Casting forms a dendritic microstructure, with common defects such as micro-shrinkage, blowholes, segregation, and hot tears.
- These inclusions and pores act as fatigue crack initiation sites under Hertzian stresses — making casting unsuitable for cam followers.

Forging vs Machining from Bar Stock

- Machined components inherit the rolled bar grain direction, which is straight, not following the geometry.
- Forging forces the material to flow into the shape of the sphere and stem, improving resistance to contact fatigue and impact.
- Machined components have higher waste, no grain contouring, and lower resistance to impact loading.

Forging vs Powder Metallurgy

- P/M always contains residual porosity even after high-pressure compaction and sintering.
- In ferrous alloys, these pores drastically reduce contact fatigue life, making P/M only suitable for low-load followers.
- Forging eliminates porosity and provides strong interfaces for high cyclic loading.

Forging vs Additive Manufacturing

- AM parts contain lack-of-fusion defects, micro-porosity, and require extensive post-processing.
- Resulting fatigue strength is inconsistent and unacceptable for follower–cam contact.
- Forging remains far superior, especially for steels requiring carburizing and heavy cyclic loads.

3.2 JUSTIFICATION FOR CHOOSING FORGING

Microstructural Advantages

During closed-die forging, plastic deformation causes grains to flow along the contour of the part. In the cam follower:

- the spherical head develops a curved grain flow pattern,
- the stem develops an axial grain structure.

This directional grain alignment improves fatigue resistance, impact toughness and resistance to crack propagation. Such microstructural refinement cannot be achieved by casting, machining or additive manufacturing.

Defect Elimination and Density

Forging compresses and consolidates the material, closing any micro-voids and minimizing segregation. In comparison:

- casting may contain shrinkage cavities, blowholes and inclusions,
- P/M parts always retain porosity,
- AM may contain lack-of-fusion defects.

These defects significantly reduce fatigue life under Hertzian loading. Forged components exhibit excellent structural reliability and high density, which are mandatory for contact-loaded steel parts.

Dimensional Stability After Heat Treatment

Forged parts exhibit uniform density and refined grain size, resulting in:

- reduced distortion during carburizing and quenching,
- predictable dimensional changes,
- improved accuracy during final grinding of the spherical surface.

Alternative processes such as casting and AM demonstrate unpredictable distortion during heat treatment due to non-uniform microstructures or internal defects.

Industrial and Economic Considerations

Closed-die forging offers high consistency, repeatability and low unit cost for medium- to high-volume production. Machining alone is costlier and inefficient due to material waste. Forging requires limited finishing operations, making it the most economically viable method for components of this nature.

3.3 POSSIBLE DEFECTS IN FORGING AND THEIR REMEDIES

Although forging is the most suitable manufacturing route for the 20MnCr5 spherical cam follower, a few defects may still occur if process parameters are not properly controlled. The following summarizes the most relevant defects and their key remedies.

a) Laps / Folds

Description: Surface discontinuities formed when metal folds over itself without bonding.
Causes: Poor die design, low forging temperature, or improper metal flow.
Remedies: Adequate die radii/draft, proper flash design, correct forging temperature (1050–1150 °C), good lubrication.

b) Cracking

Description: Surface or internal cracks formed during deformation.
Causes: Low temperature, excessive single-pass deformation, pre-existing billet defects.
Remedies: Maintain correct temperature, use multi-step forging, inspect billets, control strain rate.

c) Die-Shift

Description: Misalignment between upper and lower dies causing uneven geometry.
Causes: Die misalignment, worn guide pins, poor setup.
Remedies: Proper die alignment, regular maintenance, use dowels/keying systems.

d) Scale / Oxide

Description: Oxide layers form on the surface at high temperatures.
Causes: Exposure to air during heating and forging.
Remedies: Protective coatings, controlled-atmosphere heating, shot blasting after forging.

e) Internal Voids / Pipe

Description: Central porosity present in the billet.
Causes: Unsound billets or insufficient reduction.
Remedies: Use sound billets, apply adequate forging reduction (50–60%), perform upset forging.

f) Underfilling

Description: Die cavity not completely filled.
Causes: Low billet volume, low pressure, poor die design, low temperature.
Remedies: Correct billet size, increase press force, improve die flow paths, maintain temperature.

g) Surface Roughness / Cold Shut

Description: Wrinkled surfaces due to premature cooling.
Causes: Low temperature, inadequate lubrication, slow operation.
Remedies: Maintain temperature, improve lubrication, reduce transfer time.

3.4 Post-Forging Finishing Steps

Following forging, several operations are performed to ensure quality:

- Flash trimming to remove excess material.
- Shot-blasting or pickling to remove scale.
- Normalizing (if required) to refine grain structure and relieve stresses prior to carburizing.
- Carburizing, quenching and tempering to develop a hard martensitic case and tough core.
- Final machining and spherical grinding to achieve dimensional precision.
- NDT (MPI or UT) to ensure defect-free parts before assembly.

These steps ensure a high-integrity, wear-resistant, and dimensionally accurate cam follower.

04.DIE DESIGN

4.1 MATERIAL SELECTION

Criteria	AISI H13 (DIN 1.2344)	AISI D2 (DIN 1.2379)	AISI H21	AISI 4140
Wear resistance	High retains ~50 HRC at 500–600 °C (VC, Cr, Mo carbides). Suitable for hot forging abrasion.	Very high at RT, but loses hardness above ~300 °C → poor for hot forging.	High hot strength but lower toughness than H13; more costly.	Low red-hardness; will wear rapidly in hot forging.
Thermal fatigue	Good alloyed for thermal cycling resistance; high toughness helps arrest cracks.	Poor brittle, high risk of catastrophic cracking under cyclic thermal shock.	Moderate better than D2 on heat resistance but lower toughness → risk of chipping.	Moderate toughness but lacks hardness to resist wear; heat-check not main failure mode.
Toughness /	Good balanced ductility/toughness; handles tight radii better.	Poor Brittle not recommended for sharp features.	Fair–Poor can chip at tight radii.	Good toughness but insufficient hardness to hold geometry.
adhesion	Good responds well to nitriding and coatings to reduce adhesion.	Fair surface treatments are possible but thermal instability limits effectiveness.	Fair can be treated but coatings cost higher.	Poor limited surface-treatment benefit.
Heat treatability	Industry standard for hot-work dies; predictable HT	Hard to use for hot dies designed as	Usable for hot applications	Common alloy steel; requires heavy hard

	and tempering window.	cold-work tool steel.	with caution; costlier HT.	facing or surface treatment for hot forging.
Typical use-case	high-volume hot forging die.	Not recommended for hot forging dies.	Alternate if H13 unavailable and cost is secondary; watch toughness.	Not recommended unless only for low-volume, short-run or hardened overlays.

Table 6 Comparison of materials to produce Die

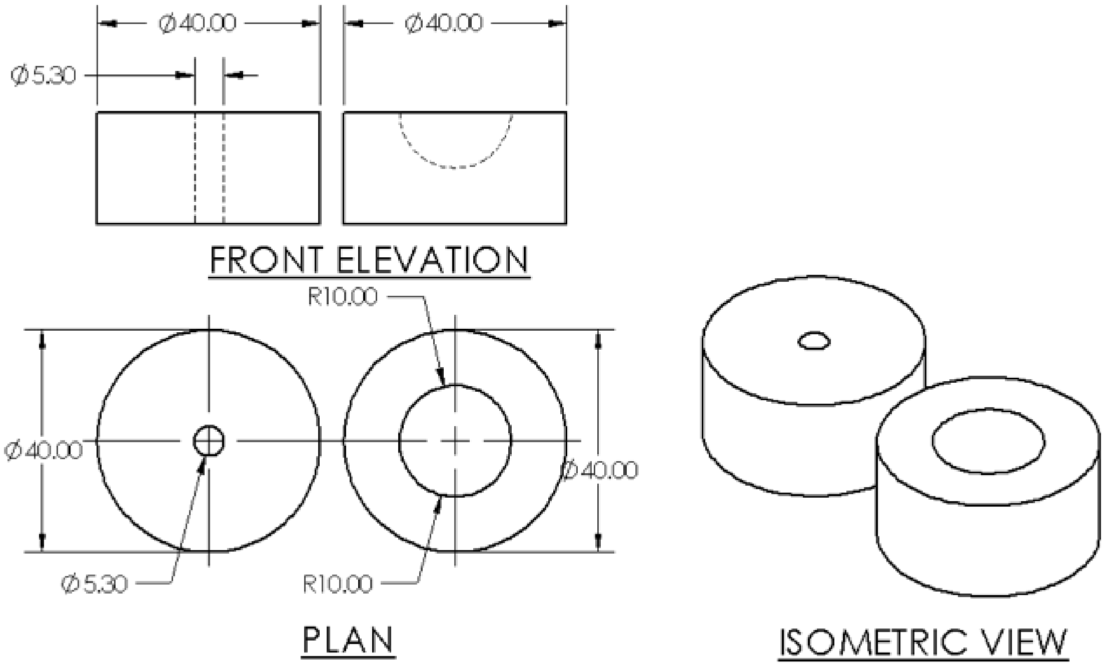
4.1.1 MATERIAL JUSTIFICATION AND COMPARATIVE ANALYSIS

The selection of AISI H13 Hot-Work Tool Steel for the cam follower forging die is based on its proven capability to counter the dominant failure modes in hot forging: abrasive wear, thermal-fatigue cracking, and material sticking. H13 provides an optimal balance of properties required for dies operating at elevated temperatures. Its red hardness, retaining approximately 50 HRC at 500–600 °C, ensures dimensional stability and wear resistance under repeated high-temperature contact. Its high toughness helps arrest micro-crack initiation and propagation caused by thermal cycling. Additionally, H13's compatibility with surface nitriding allows for forming a hard, ceramic-like surface layer that significantly reduces sticking and improves service life.

Alternative materials were evaluated but rejected due to critical shortcomings. AISI D2, a cold-work steel, suffers rapid hardness loss above ~300 °C and exhibits high brittleness, making it unable to withstand thermal shock or impact loads in forging. AISI H21, although offering superior hot-strength, lacks adequate toughness and is prone to chipping—especially at sharp die features—and shows reduced reliability under quench-cooling conditions. AISI 4140, while tough and economical, does not provide the required hot-hardness; under forging temperatures it would experience rapid wear and early geometric distortion, making it unsuitable for high-volume die applications.

Given the thermal and mechanical demands of forging cam followers and the associated failure mechanisms, the required material must come from the Hot-Work Tool Steel (Group H) category, which is designed specifically for forming operations involving heated workpieces—such as hot forging, hot extrusion, and die casting. Based on this classification and performance criteria, AISI H13 (DIN 1.2344 / X40CrMoV5-1) is the recommended and justified choice for the cam follower forging die.

4.2 DESIGN



DIMENSIONS IN MILLIMETERS

Figure 5: Dimensions and Drawing of Die

This die is made by AISI H13 Hot-Work Tool Steel. This is resistant to high temperature. This die has 2 parts. The hemispherical part is forged in the right-side die, while the stem is forged in the left-side die. The excess steel is removed through the free end of the hole in right-hand side die. After air cooling flash is removed and threads are cut in the stem.

05.FUNDAMENTAL PRINCIPLES OF HEAT TREATMENTS

1. Normalizing

Forged steel samples have internal residual stresses. When an austenitic microstructure is formed, these internal stresses are relieved. This process makes the samples dimensionally stable before the hardening process. Also recrystallizes the steel and produces a fine, even grain size. This makes the steel to be harden uniformly.

Here, low Carbon (~0.2% C), low alloy steel is taken. So, it is reasonable to analyze the Fe-diagram. The result of this step is hyper eutectoid steel with pearlitic and proeutectoid ferritic microstructure. It may contain some bainite and austenite too.

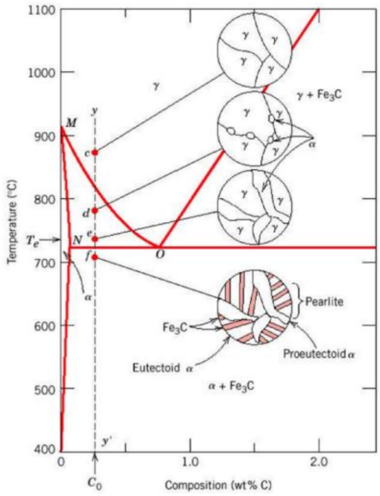


Figure 6 Fe-C Diagram

2. Gas carburizing

By introducing C containing gases to the high temperature steel sample, the C atoms are diffused into the surface. Normally, Carbon content of the carburized surface layer or case normally is increased to about 0.8 to 1.0 wt%. This makes to form more martensite only at the surface. Steel samples should be kept above the austenitizing temperature to ensure all Fe atoms exist in austenite form. Then C defuses into the steel uniformly.

3. Quenching

Just because the steel is carburized, it is not hardened. It should be rapidly cooled to be harden by forming martensitic surface. This gives an extremely hard, wear-resistant case to the cam follower. This makes the contact surface of the follower last longer.

Here, Carbon percentage of the outer surface is close to eutectoid composition, so it is reasonable to analyze the TTT diagram of eutectoid plain Carbon steel. If the cooling rate curve of the surface exists left to the N point (Very high cooling rate), 100% martensite is formed at the surface. If the cooling rate curve of the surface exists right to the N point (Low cooling rate), martensite percentage formed at the surface is reduced.

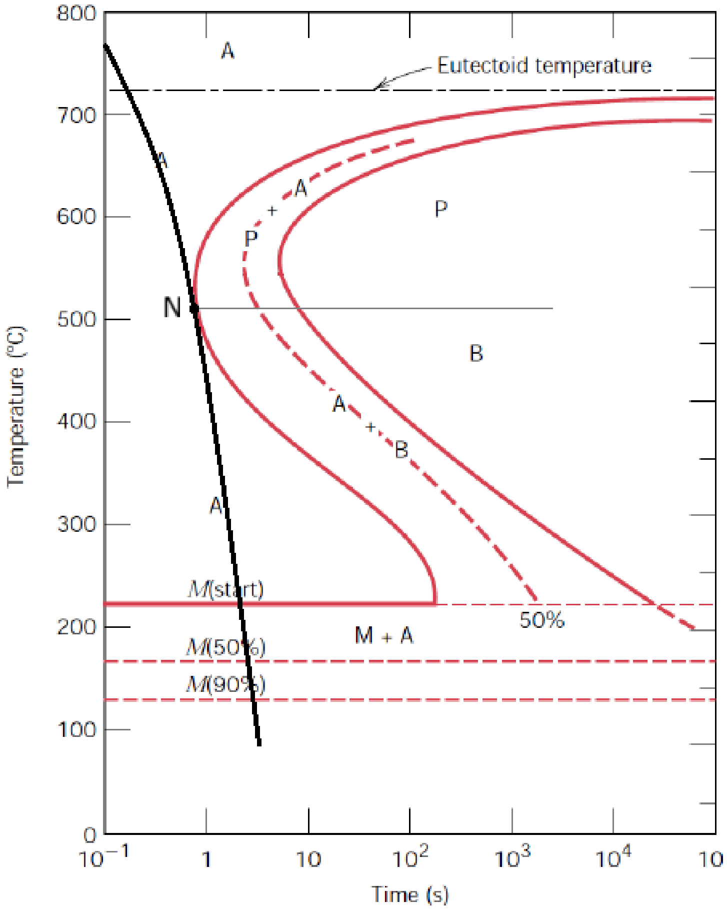


Figure 7 TTT Diagram

4. Tempering

The martensite formed in above step is very brittle. To reduce the brittleness, the steel should be heated to 150 - 200°C and let it cool in air. Then the brittleness is reduced without reducing much hardness. This process reduces the internal stresses in the core, resulting a tough and ductile core.

Finally, a tough, ductile product with a hard, wear resistant surface can be gained.

06.PROCESS OF MAKING CAM FOLLOWER

6.1 PROCESS STEPS

01.Raw material preparation

- Material: 20MnCr5 (case-hardening steel with good forgeability and grain refinement potential).
- Cut the billet to the required length considering upset ratio, material flow allowance, and flash requirements.
- Deburr and clean the cut surface to prevent oxide entrapment and surface laps during forging.

02. Heating

- Heat the billet in a controlled-atmosphere furnace (reduces scale formation and decarburization).
- Maintain 950–1150 °C, the optimum forging range for 20MnCr5 to ensure ductility and avoid cracking.
- Avoid overheating, as it causes grain coarsening, reduced toughness, and non-uniform flow.
- Soak for 10–20 min per 25 mm cross-section to achieve uniform temperature through the core.
- Use pyrometer or infrared sensors to verify temperature accuracy before forging.

03.Die preparation

- Apply high-temperature lubricant (graphite-based or synthetic) to reduce friction, prevent sticking, and improve metal flow.
- Pre-heat dies to 150–250 °C (typical range) to reduce thermal shock and prevent die cracking.
- Check and align upper and lower dies to prevent geometrical defects, off-centering, and folding.
- Confirm die cavity cleanliness and remove scale or debris before forging.

04. Placing the Workpiece in the Die Cavity

- Position the hot billet accurately at the center of the cavity to ensure symmetric flow.
- Control transfer time from furnace to press to avoid excessive heat loss and temperature gradients.
- Avoid misalignment, which leads to laps, fold-over defects, underfill, or sidewise flash formation.

05. Applying Force Using a Press

- Use mechanical, hydraulic, or servo press depending on required strain rate and accuracy:
  Mechanical: high speed, fixed stroke
  Hydraulic: controlled force/stroke for larger parts
  Servo: precise, programmable control

- Apply controlled compressive force—metal undergoes plastic deformation and flows according to die geometry.
- Monitor ram speed, tonnage, dwell time, and stroke to ensure complete die filling.
- Excess material flows into the flash land, increasing resistance and forcing metal deeper into the cavity (critical for closed-die forging).
- Ensure proper strain distribution to avoid internal defects like burst or central cracking.

06. Ejection and trimming

- Open dies carefully; allow the forged part to cool in still air or controlled cooling setup to avoid thermal shock.
- Remove flash using hot trimming (preferred) or shearing to obtain a near-net shape.
- Inspect for surface defects, underfill, laps, or misruns before further processing.
- Prepare the component for final heat treatment

07. Heat treatment

- The samples are subjected to several heat treatments such as normalizing, carburizing, austenitizing, quenching and tempering. These processes are done to enhance the required properties of the cam follower.

08. Final machining & finish grinding

- Final machining is required because carburizing & quench cause dimensional change. Final matching is done after tempering and any stabilizing operations.
- Centering / cylindricity corrections of stem and mounting features.

09. Surface enhancements

- Shot peening imparts compressive residual stress near surface. It improves fatigue life.
- If coatings are expected to be applied, it should be applied after final finishing. (DLC, TiN)
- Final cleaning and reservation
- The parts of residues should be cleaned, better if corrosion inhibitors are applied. The items should be packed carefully avoiding contact damage.

6.2 HEAT TREATMENT PROCESSES

Here it's explained about the step 7 in process step

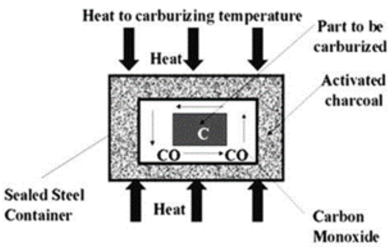
1. Normalizing

The forged samples are subjected to machining and trimming in Process step so the internal stress are build there. To those relieve residual internal stresses and to avoid distortions during carburizing and quenching the normalizing is done . And by relieving internal stresses, uneven carbon diffusions can be avoided [16]. Also, forging makes grains large and irregular. Normalizing makes the grains uniform. Here, the steel samples are heated to 850 - 880 °C, and they are air cooled to room temperature.

2. Gas carburizing

Samples should be reheated to 860–920 °C with a carbon-rich gas atmosphere (CO, CH_4). At high temperatures, carbon from the gas atmosphere diffuses into the surface of the steel. Typical diffusion time depends on the required effective case depth [17]. In this case, nearly 0.8 mm effective case depth can be gained by carburizing for 2-4 hours.

By this process, the C percentage becomes high in the surfaces which is needed to harden the samples later, while keeping the core tough and ductile. Normally, 20MnCr5 steel is tough and ductile due to the low C percentage.



3. Quenching

In quenching, the samples are rapidly cooled in oil or suitable liquid. Here, austenite is transformed into martensite. Martensite is the hardest microstructure that steel can form. Its surface hardness is around 58–62 HRC. This makes the cam follower extremely hard and wear resistant. Previously, carburization should be done to harden more by forming more martensite on surfaces. Nevertheless, the core is tough and ductile, it helps the cam follower to maintain strength without breaking.

4. Tempering

In the carburized case, martensite is very hard but brittle. Also, very high residual stresses are formed in the case and core, by quenching. To overcome these conditions, samples should be reheated to a low temperature (150–200 °C) and held for about 1–2 hours. This process reduces brittleness without losing much hardness. Also, tempering relieves internal stresses in the case and core. This avoids distortions and cracks in the samples, improving dimensional stability.

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