Heat Treatment and Press Quenching of Steel Alloys

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2017 Engineering Symposium in Rochester
April 18, 2017

Total Gear Solutions Gleason

What is Steel?

Steel, in its most basic form, is an alloy of iron (Fe) and carbon (C).

Many other alloying elements such as silicon (Si), manganese (Mn), Chromium (Cr), Nickel (Ni), Tungsten (W), Molybdenum (Mo), Vanadium (V), Cobalt (Co), etc. can be added to steel to impart specific properties.

Steel alloys can be categorized into different groups based upon their chemical composition ranges, the method of production, their microstructures, properties, intended applications, or their heat treatment response.

Stainless Steel

In order to be classified as a stainless steel an alloy must satisfy the following two criteria as a minimum:

1.) It must be an iron based alloy that contains at least 10.5% Cr and 50% Fe.
2.) It must resist corrosive attack from normal atmospheric exposure.

The St. Louis Arch, standing at 630 feet tall (192 m), is the world's tallest arch. More stainless steel was used in its construction than in any other single project in history.

Source: Wikimedia Commons.

Other Steel Categories

Other major categories of industrial steel alloys include:

- Carbon Steels (1018, 1040, 1095, etc.)
- Low Alloy Steels (1140, 4340, 6150, etc.)
- Carburizing Steels (3310, 8620, 9310, 16MnCr5, 20MnCrTiH4, etc.)
- Tool Steels (01, H13, A2, D2, W1, 100Cr6, etc.)
- High Speed Steels (M2, M4, ASP 2030, T15, etc.)
- Powder Metallurgy Steels (Rex 76, ASP 2060, etc.)

Each of these major groups has a large number of subcategories as well. Tool steels can include the following subcategories, among others:

- Cold work tool steels
- Hot work tool steels
- Air hardening tool steels
- Oil hardening tool steels
- Water hardening tool steels

Steel Properties

Why is a particular grade of steel selected for use in a specific application? What needs to be considered?

One of the most important skills for the design engineer to possess is the ability to identify a material that has the right combination of properties. This is critical for success. And all steel alloys are not equal when it comes to these properties.

Steel Properties

Some of the major properties that must often be considered in choosing a material for a specific application are the following:

Attainable Hardness – the capability to reach a specified hardness through heat treatment so the material can resist permanent deformation while under load.
Red Hardness – the capability to retain hardness at elevated temperatures.
Toughness – the ability to resist breakage, chipping, or cracking under impact loading. Toughness may be viewed as the opposite of brittleness.
Wear Resistance – the ability to resist the effects of abrasion and erosion normally encountered by contact and interaction with other materials and outside sources.
Corrosion Resistance – The ability of a material to resist deterioration (usually caused by electrochemical oxidation) in corrosive service environments.

Steel Properties

An example of the application of these principles is in the selection of a steel alloy for producing a simple tool such as a hunting knife or industrial knife.

The steel alloy must:

- Have a high enough modulus of elasticity so that it will possess adequate stiffness for the part geometry and loading conditions experienced during use.
- Possess enough alloy content so that it can be heat treated to reach the proper hardness level for the intended use.
- Exhibit adequate wear resistance so that it will not have to be sharpened too frequently.
- Possess good toughness so that the blade doesn't chip or break.
- Have adequate corrosion resistance so that it does not rust unacceptably.

Photograph courtesy of Wikipedia, attributed to "Hunting Knives" by Mike Searson.

Steel Properties

More complex designs and applications may require additional material properties to be considered. These can include surface finish characteristics, machinability, magnetic properties, etc. Hardness, wear resistance, and toughness are all directly impacted by the heat treatment of the steel.

Assessment of Learning

How are steel alloys categorized?

What are some of the categories?

Identify the properties of steel alloys that often need to be considered in order to select an appropriate grade for a given application.

Heat Treatment of Steel Alloys

Almost all metals and alloys respond to some form of heat treatment in the broadest sense of the definition, but the responses of individual metals and alloys are by no means the same.

- Almost any metal can be softened by annealing after cold working.
- Fewer alloy systems can be strengthened or hardened by heat treatment.
- Practically all steels can be strengthened through heat treatment to some degree.

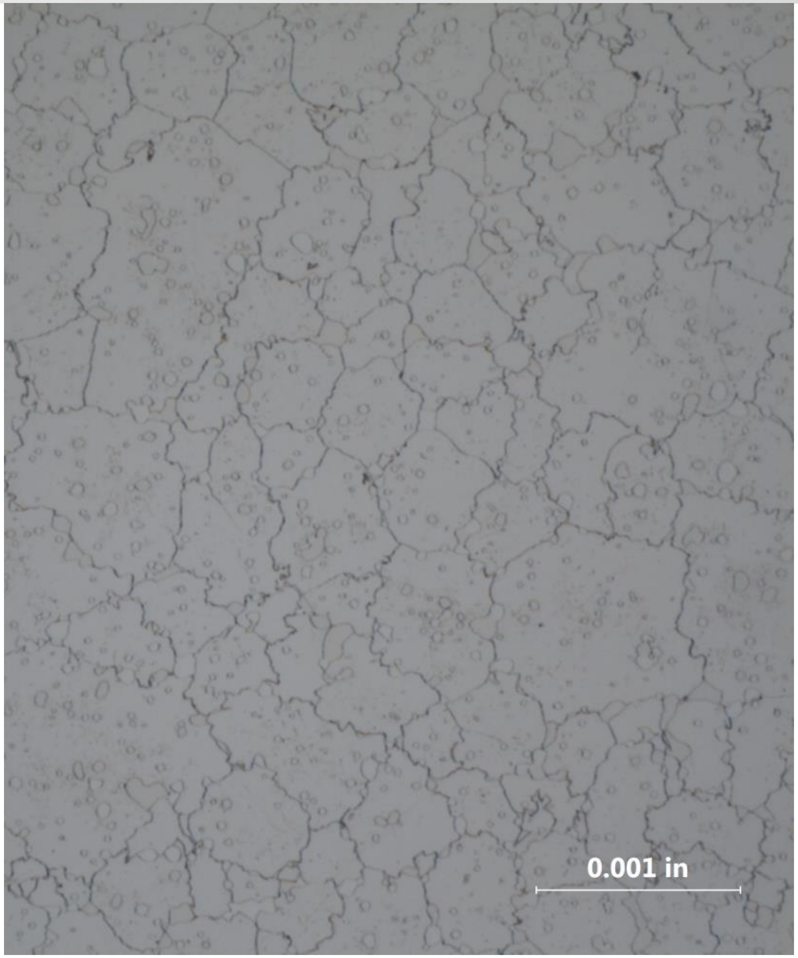
What is Heat Treatment?

Heat treatment is the controlled heating and cooling of a solid metal or alloy by methods designed to change the microstructure in order to obtain specific properties, phases, and/or material characteristics.

The main purpose of heat treatment in steel alloys is to alter the microstructure and properties of the steel so that it will function properly in the intended application.

Crystalline Structure of Metals

Most metallic alloys are crystalline in nature, which means that their atoms are arranged in a long range, orderly, repeatable pattern. These patterns represent the fundamental ways in which atoms can arrange themselves to form three dimensional structures called crystals or *grains*. Grains and grain boundaries make up the microscopic structure—or *microstructure*—of metals and alloys. Grain boundaries, as well as other microstructural features, are often observed by a process of specimen preparation known as *metallography*.

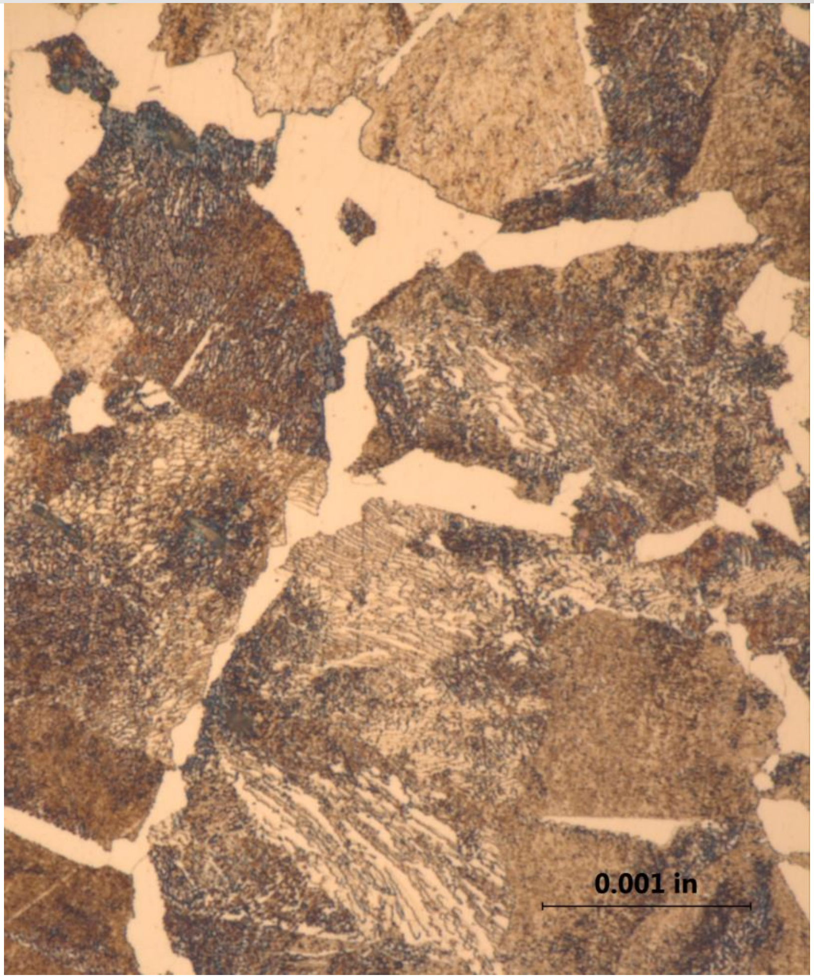


Grain boundaries in an as-quenched M42 high speed steel sample. This sample was etched in a 2% nital solution for 2 minutes. Original magnification 1000X.

Crystalline Structure of Metals

How these microstructures appear under the microscope is strongly dependent upon a very large number of factors.

These include the type of material under consideration, how it was manufactured and processed, the heat treatment that it received (if any), and how the samples were prepared for examination.

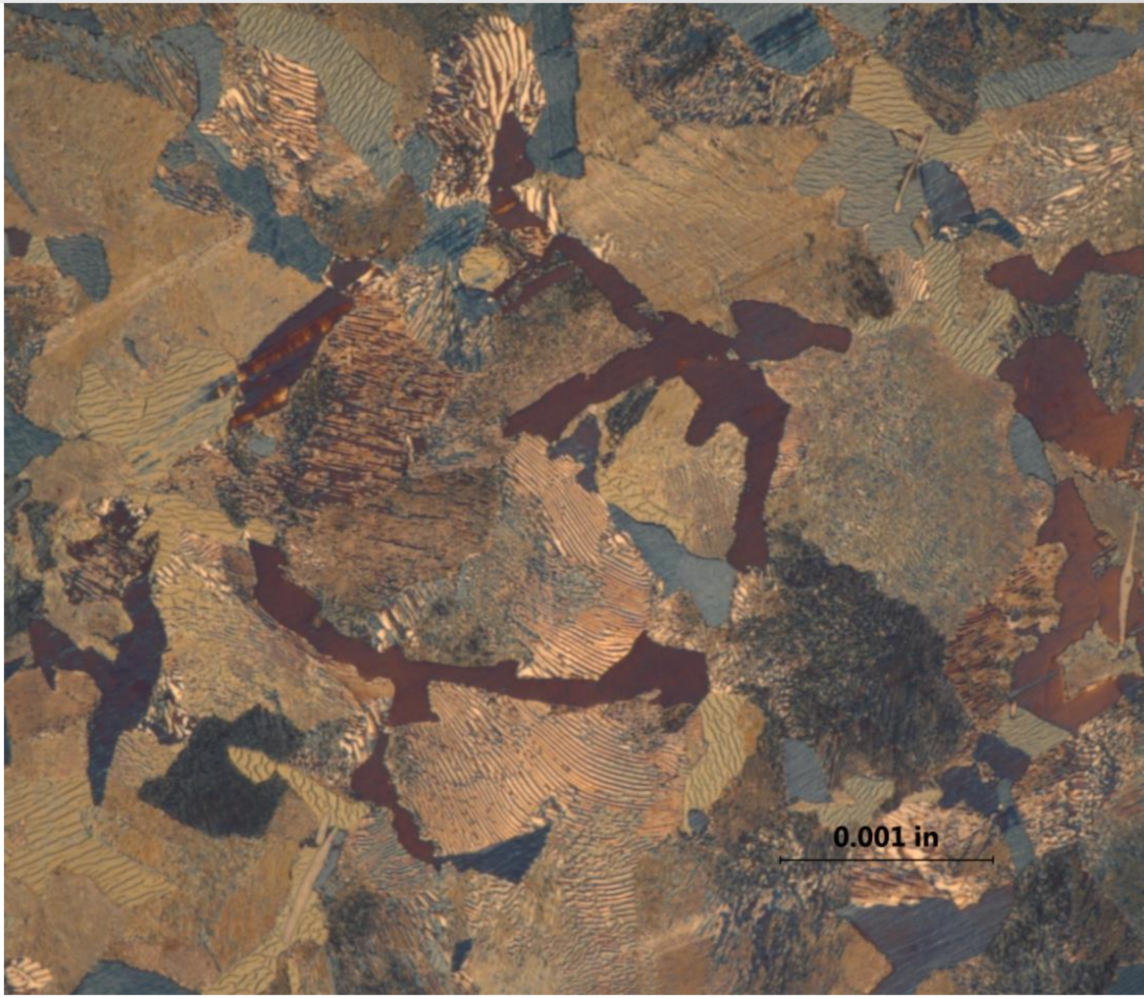


AISI 1050 steel microstructure prepared through nital etching. The ferrite appears white in this image. Original magnification 1000X.

Crystalline Structure of Metals

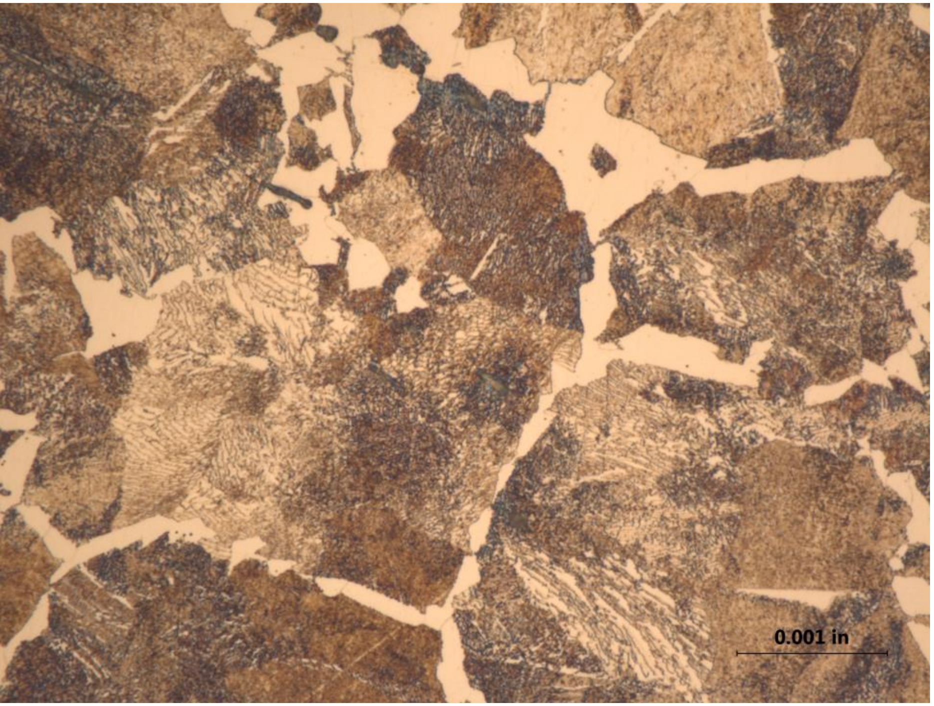
Etching by itself can have a profound impact on the appearance of these microstructures.

The image at right was produced from the same sample that was shown in the previous slide, but after etching with Klemm's reagent. This color tint etching technique preferentially colors the ferrite red and blue, while nital etching leaves the ferrite white in appearance.



AISI 1050 steel microstructure prepared with color tint etching. The ferrite appears red and blue in this image. This sample was etched in Klemm's reagent. Original magnification 1000X.

Crystalline Structure of Metals



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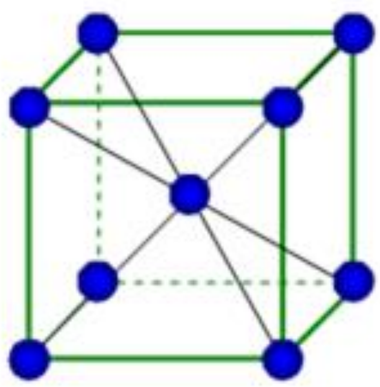
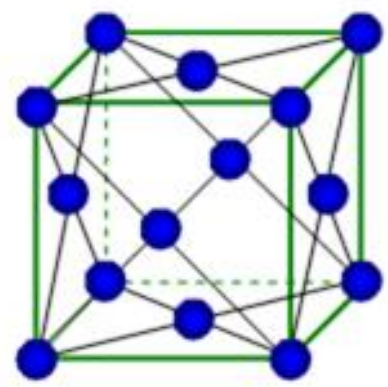
AISI 1050 steel microstructure prepared with color tint etching. The ferrite appears red and blue in this image. This sample was etched in Klemm's reagent. Original magnification 1000X.

Crystalline Structure of Metals

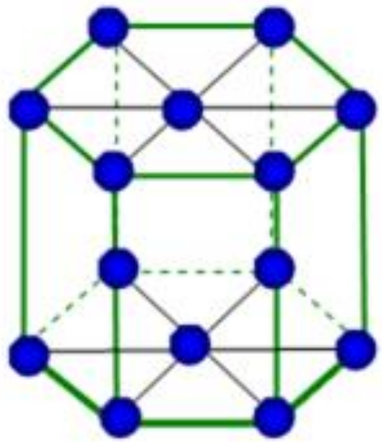
The three primary crystal structures for metals



Body Centered Cubic



Face Centered Cubic



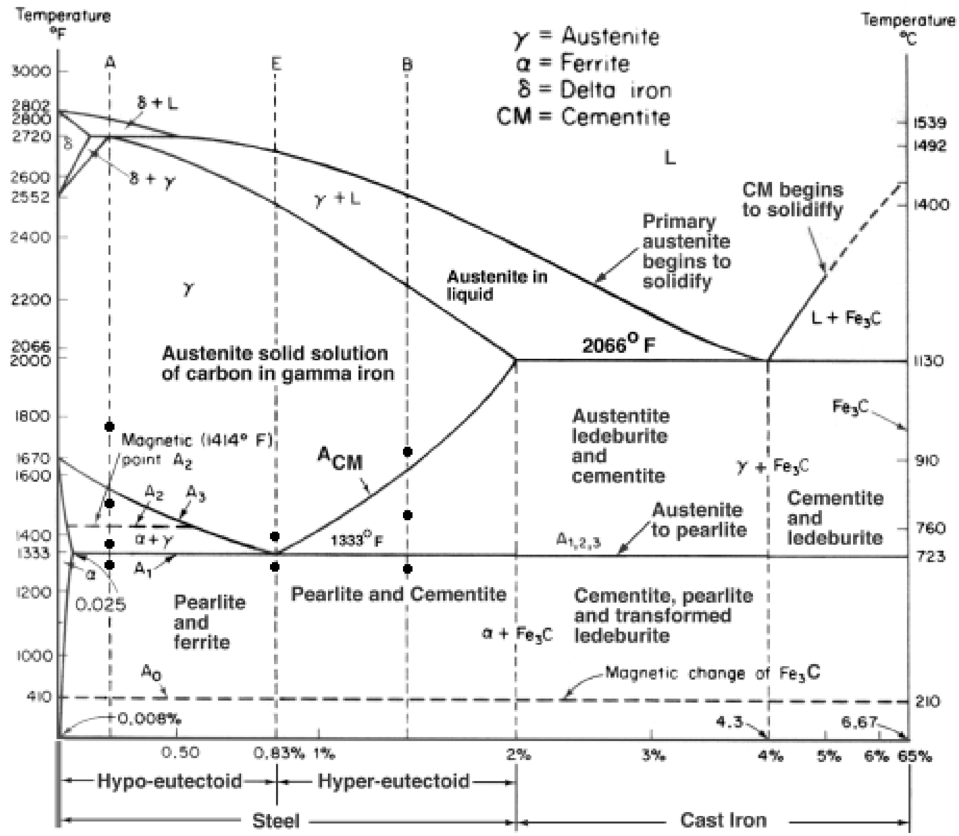
Hexagonal Closed Packed

The crystal structures of some metals can be altered or transformed into a different crystal structure by changing the temperature or by suitable choice of alloy additions (or both).

Iron is an allotropic element, which means that iron atoms change their crystal structure at specific temperatures known as *transformation temperatures*. One crystal structure of iron is a body-centered cubic (bcc) lattice that is stable from below room temperature to 912ºC (1675ºF). This phase of bcc iron is known as α-ferrite. Another phase of iron is a face-centered cubic (fcc) lattice known as austenite or γ-iron, and occurs between 912 and 1394ºC (1675 and 2540ºF). Finally, another solid bcc phase known as δ-ferrite occurs from 1394ºC (2540ºF) to the melting point of iron.

Crystalline Structure of Metals

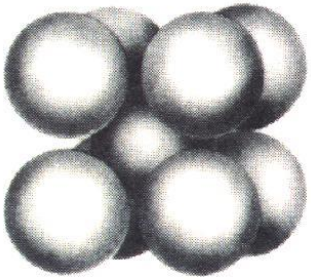
Carbon plays an important role in the heat treatment of steel, because it expands the temperature range of austenite stability. Higher carbon content (up to about 0.8%C) lowers the temperature needed to austentize steel—such that iron atoms rearrange themselves to form an fcc lattice structure. Under normal conditions austenite cannot exist at room temperature in plain carbon steels, but only at elevated temperatures within the austenitic γ region of the Fe-C phase diagram.



What is heat treatment?

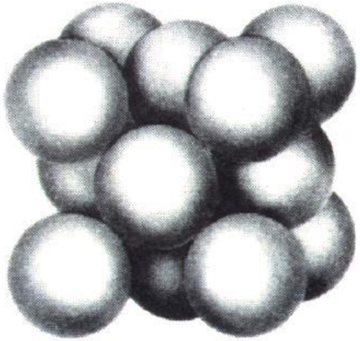
What role does carbon play
in the heat treatment of steel alloys?

Crystalline Structure of Metals



Body-centered cubic

Ferrite



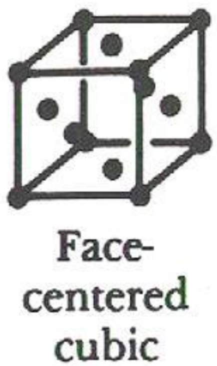
Face-centered cubic

Austenite

Carbon is almost insoluble in ferrite, because the interstitial positions available in the bcc lattice are not large enough to accommodate it. However, carbon is more soluble in austenite, because the interstices in the fcc lattice are considerably larger. The solubility limit of carbon in α ferrite varies from 0.008 wt% at -18°C (0°F) to a maximum solubility limit of 0.022 wt% carbon at 727°C (1340°F). In contrast, the maximum solubility of carbon in austenite is about 2%, which is approximately 100 to 250 times higher.

Ferrite

Austenite



Heat Treatment of Steel Alloys

Quench Hardening - The quench hardening of steel alloys is a very common method used to achieve high levels of hardness. It involves heating the steel to a high enough temperature where austenite is formed in the steel microstructure. The steel is then cooled or quenched rapidly back to room temperature in order to transform the austenite in the steel microstructure into martensite, a very hard and brittle phase.

Martensite needles (darker, acicular phase) and retained austenite (white background phase) in a quenched and tempered 92523 case carburizing steel.

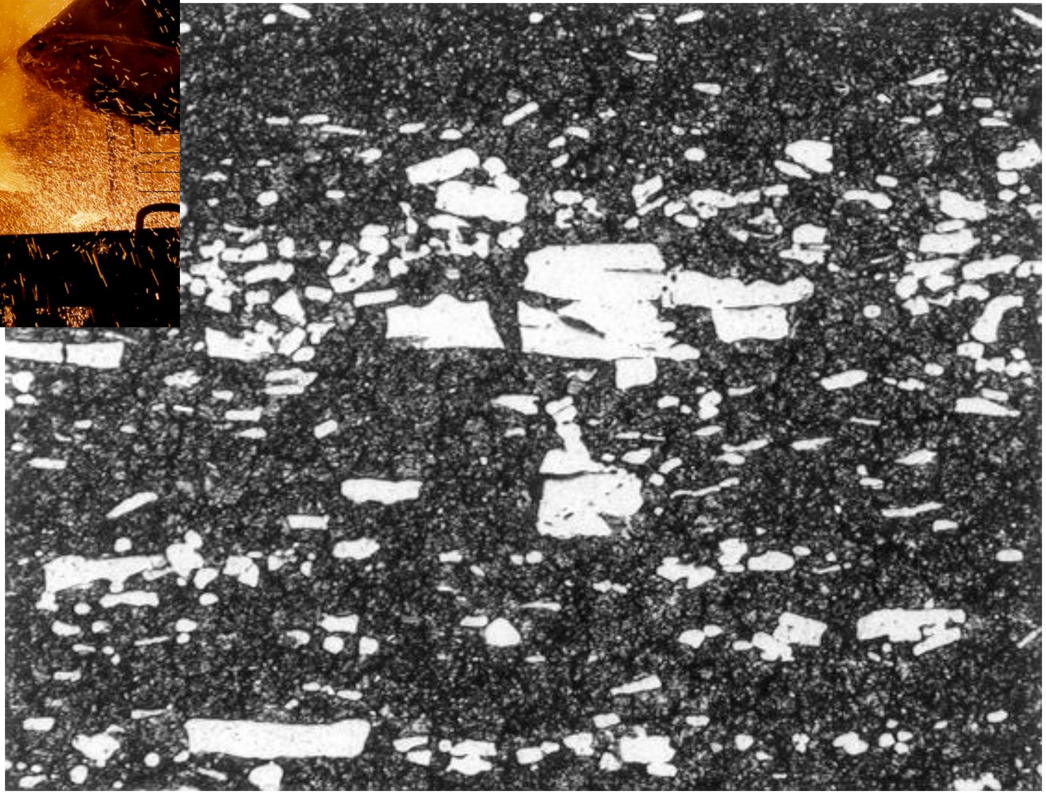
Martensite possesses a body centered tetragonal (bct) crystal structure. It does not appear as a phase on the iron-carbon equilibrium phase diagram, because it is a *metastable* (nonequilibrium) structure that occurs from rapid cooling. Martensite only forms because it is possible to cool carbon rich austenite faster than it can reject the carbon by diffusion to form ferrite and cementite. Martensite is extremely hard, and forms the basis of most steel hardening processes.

Body-centered tetragonal

Coventionally Cast Tool Steel Microstructure

(Conventional ingot metallurgy)

↑ AOD melting

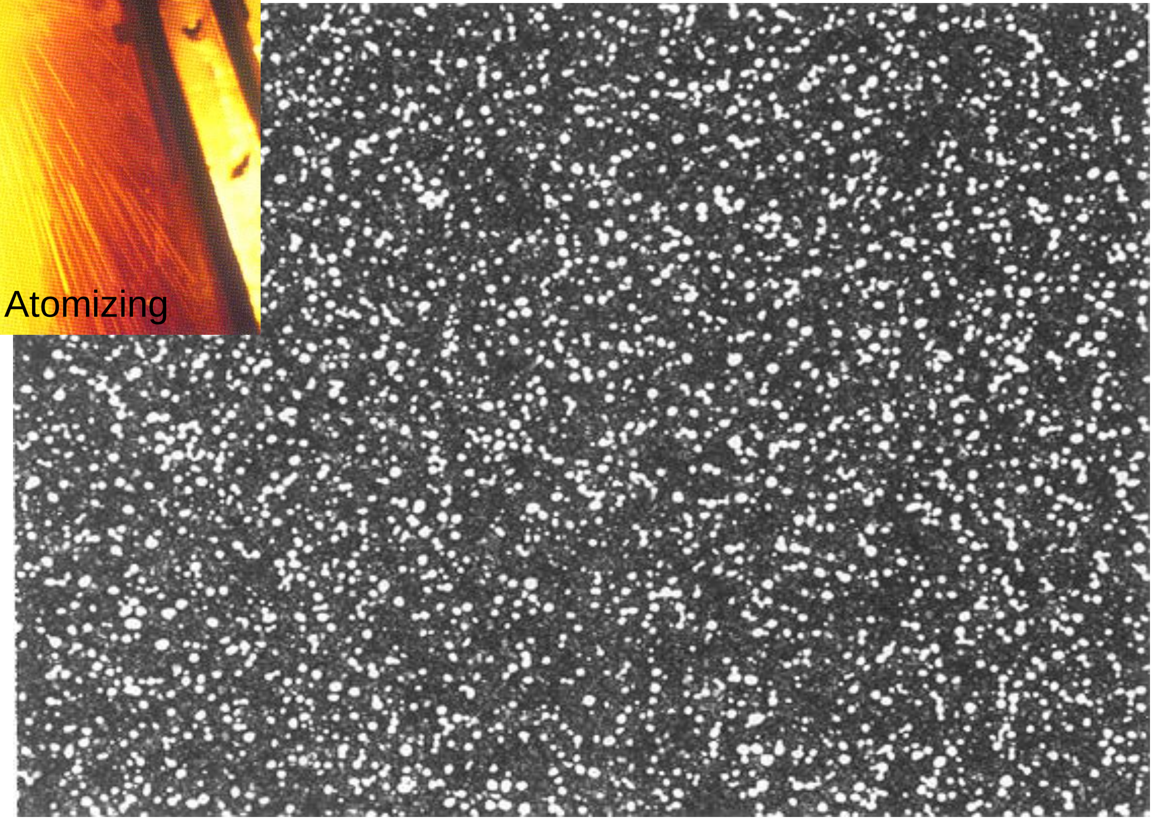


ingot-cast and forged bar →

Primary Carbide Distribution ~ 500x

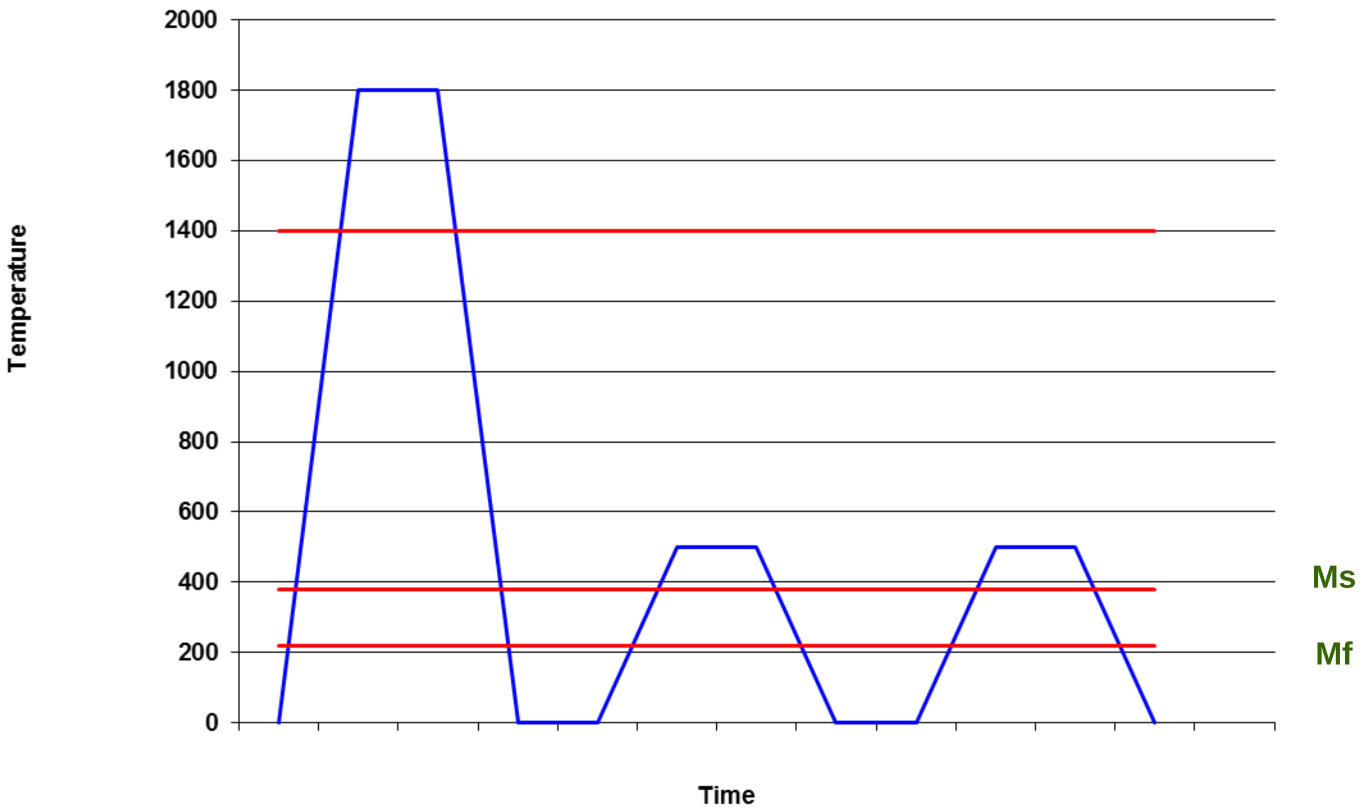
PM High Speed Steel Microstructure

as-HIP or
forged bar
→



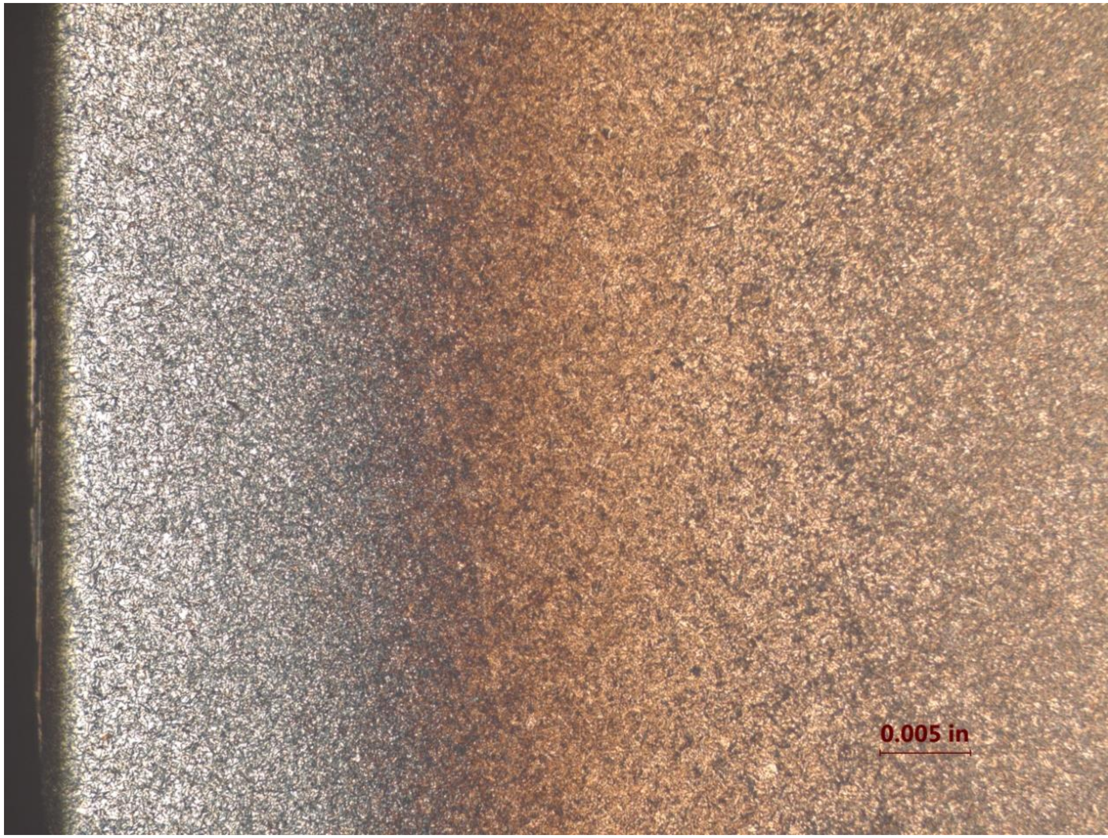
Primary Carbide Distribution ~ 500x

Heat Treatment of Steel Alloys



Heat Treatment of Steel Alloys

As carbon levels increase and as the amount of other alloying elements increase, the M_s and M_f temperatures decrease. If they fall too low, the result is retained austenite; i.e. austenite which did not transform during heat treatment. This can be corrected through further cooling (cold treatment or cryogenic processing), or through high temperature tempering.



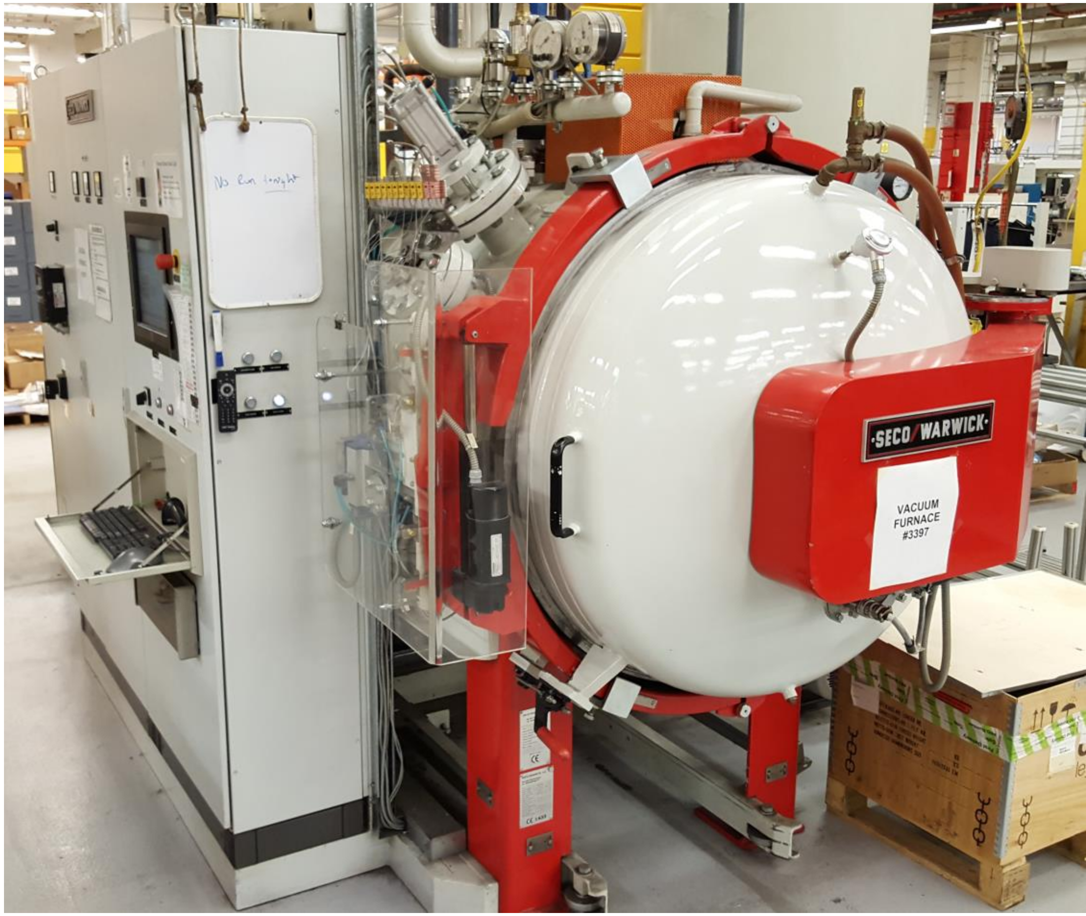
Retained austenite in an 8620 case carburized, heat treated and tempered pinion. This sample was etched in a 2% nital solution for 20 seconds. Original magnification 100X.

What is martensite?

How is martensite formed during heat treatment?

What Commercial Hat Treating Methods are Available?

- Vacuum heat treatment
- Salt bath heat treatment
- Fluidized bed heat treatment
- Flame hardening
- Induction hardening
- Atmosphere controlled batch furnace
- Atmosphere controlled continuous furnace
- Cryogenic treatment



Seco-Warwick vacuum furnace at The Gleason Works in Rochester, NY.

What is Press Quenching?

Press quenching is a specialized technique that can be used during heat treatment to minimize the distortion of complex geometrical components.

It is performed in a quenching machine. Specialized tooling is used to generate concentrated forces at key locations on the part surface to carefully control the movement of the component during the quenching operation.

How does a Quenching Machine Work?

Temperature controlled quenching oil is circulated through a well defined pathway and at a specified flow rate around the part being quenched. The quench oil absorbs heat from the hot part and is then circulated to a chiller for heat extraction.

What does the Quenching Machine Control?

The quenching machine can only control roundess, flatness, and taper in the parts that are being oil quenched.

The quenching machine does *not* control the physical size of the parts.

Modern Quenching Machines

Modern quenching machines are equipped with more advanced capabilities than their predecessors that allow very specific quenching recipes to be developed and stored.

Computer control, digital interfaces, and an increased number of quenching parameters are available for tailoring the recipes to optimize the processing of each individual component.

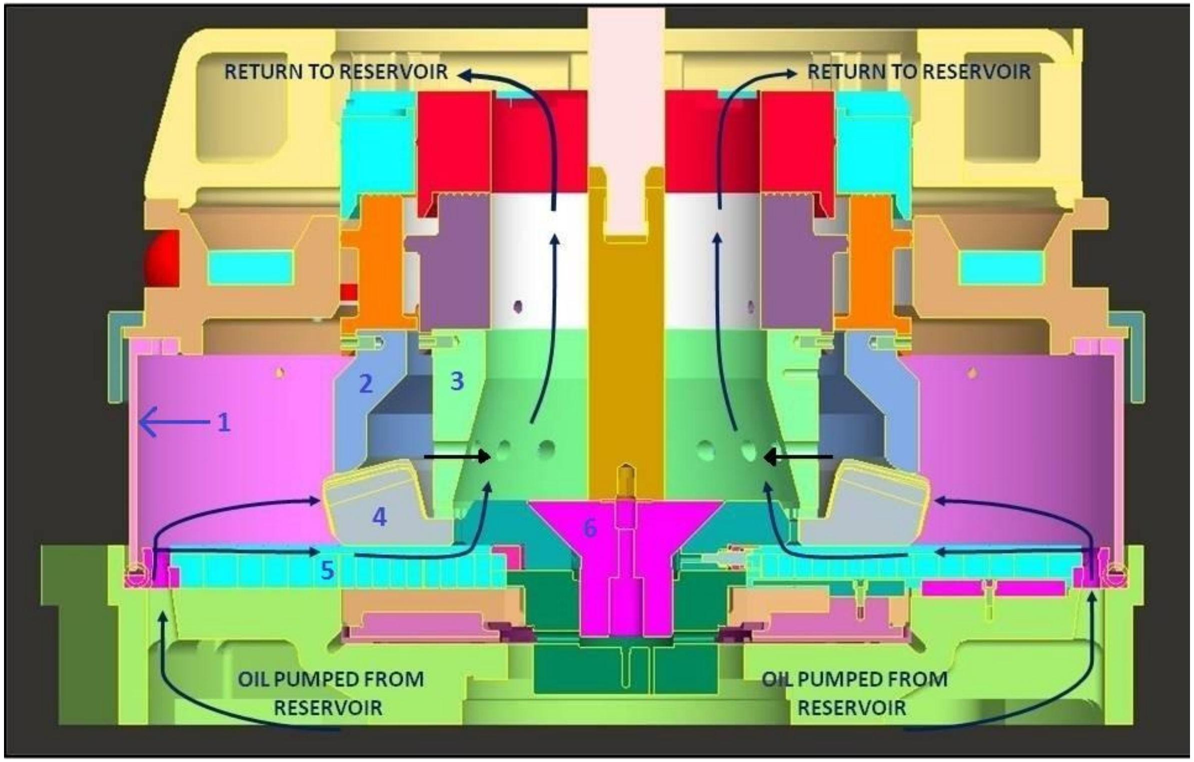
Total Gear Solutions Gleason

Lower Die Assembly

During the press quenching operation, the component to be quenched is removed from a separate furnace and is placed onto the tooling of the lower die assembly. A close-up view of this die assembly is shown here.

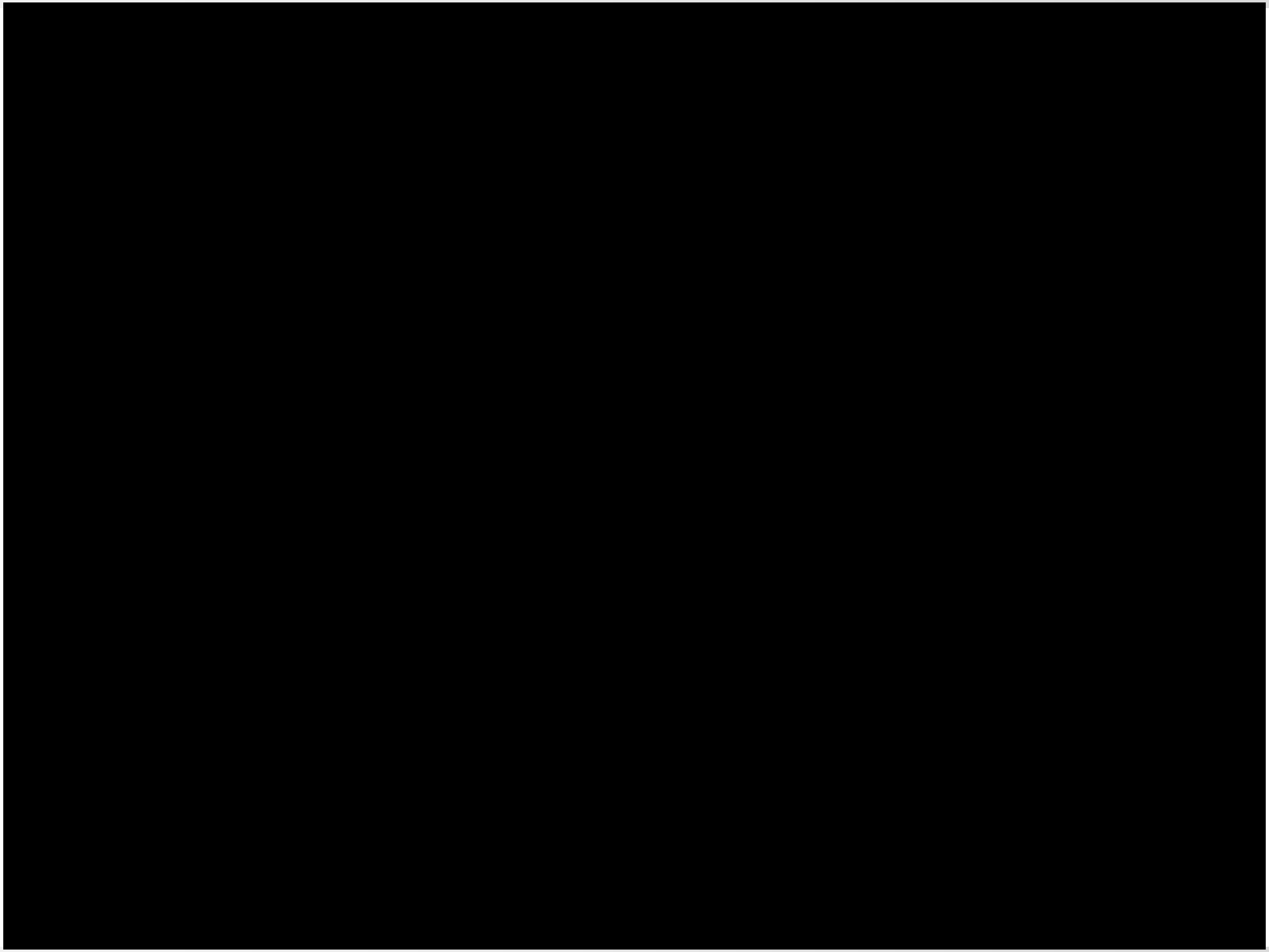
A red hot bearing ring is positioned on the lower die assembly just before it is retracted into the machine for oil quenching.

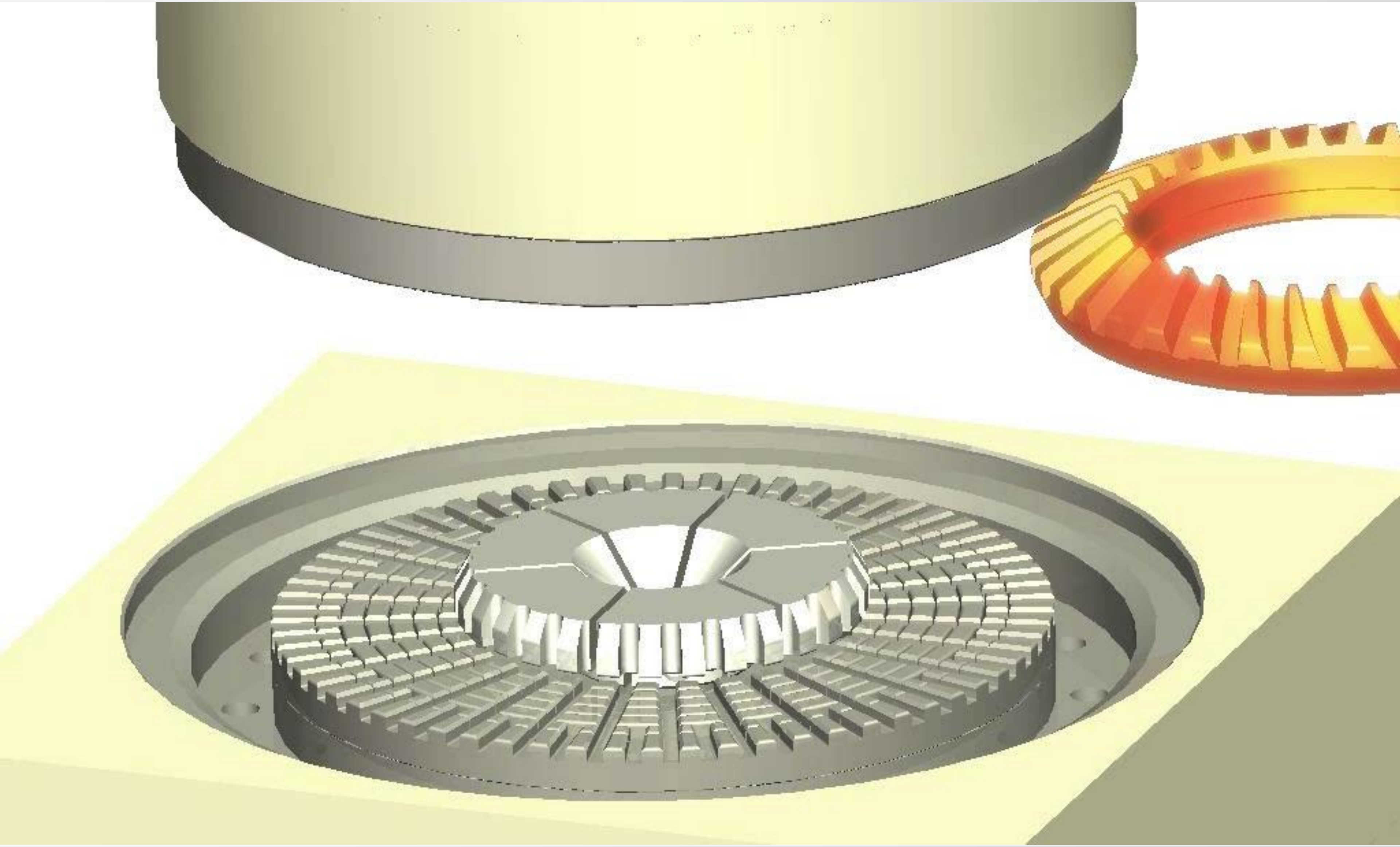
Dies Functioning



Schematic cross-sectional diagram illustrating the contact of the center expander and the inner and outer dies with the part during quenching. The components labeled in the diagram are (1) the machine guard (2) outer upper die; (3) inner upper die; (4) component undergoing quench; (5) lower die assembly; and (6) center expander cone. The oil flow path through the quench chamber is depicted by the flow line arrows.

Video





Press Quenching

The quenchant flow rate profile that is established for the part in question must be carefully selected so that the hardness and geometry requirements are satisfactorily met.

- Too slow of a quench rate will result in a slack quench. This can produce a mixed microstructure coupled with low hardness.

- Too rapid of a quench rate could result in cracking and/or distortion.

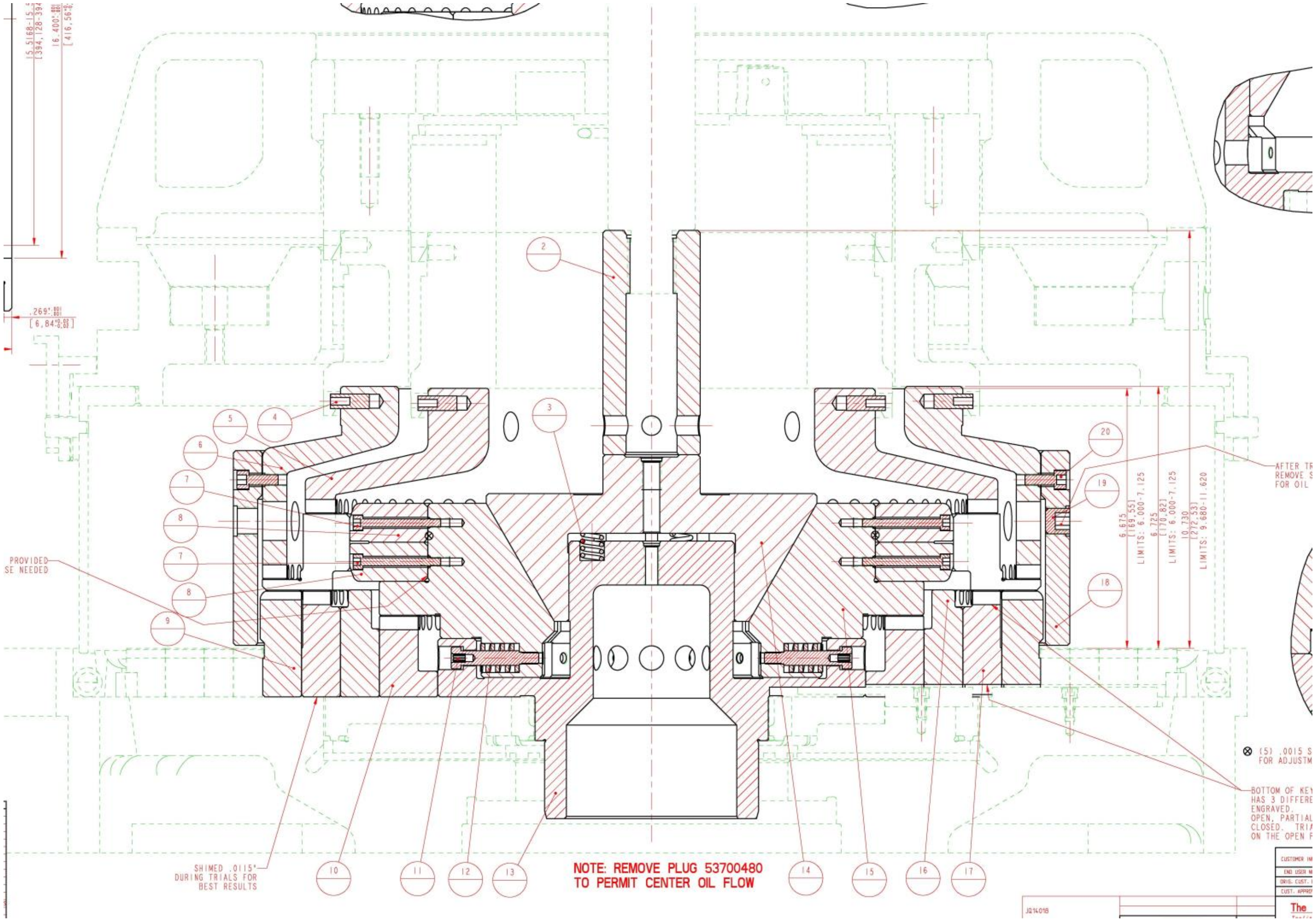
What is press quenching?

Can press quenching completely eliminate all forms of distortion during heat treatment?

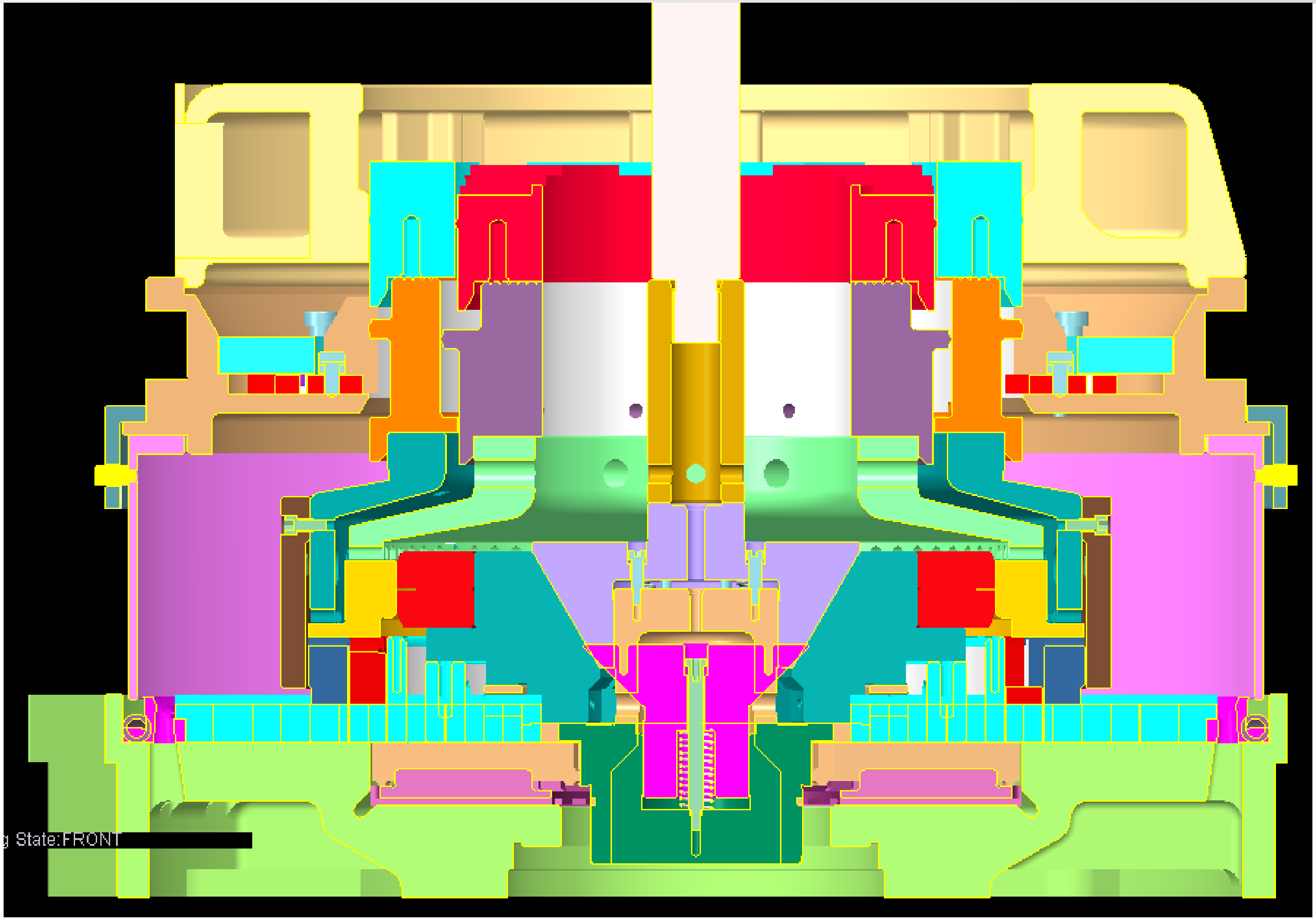
Die Tooling

Each component that is press quenched requires a specific die tooling design configuration and machine set-up. The use of expanding segmental dies are often employed to maintain bore roundness in bearing rings and gears.

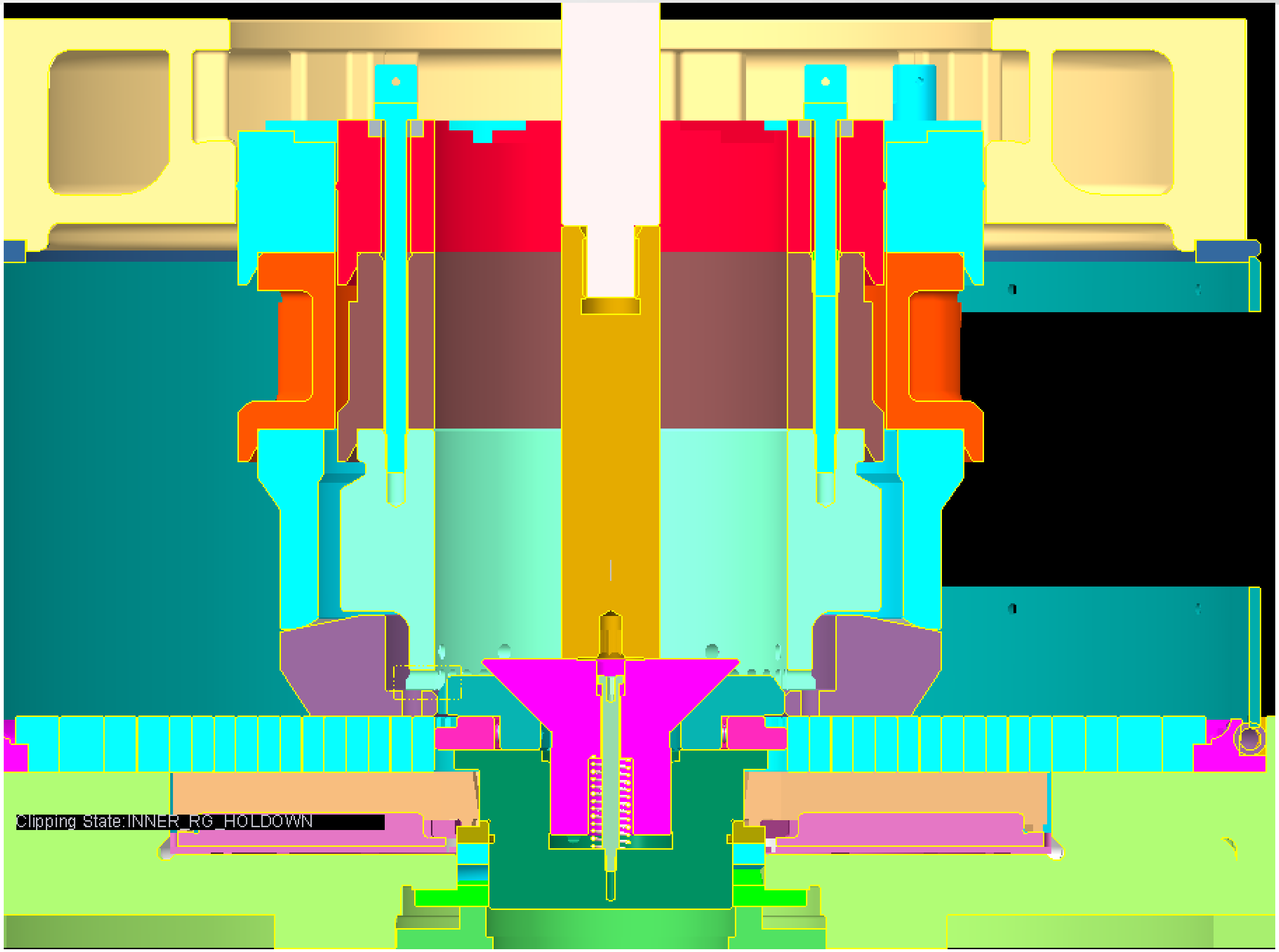
Lower expanding segmental die tooling for an industrial bearing ring.



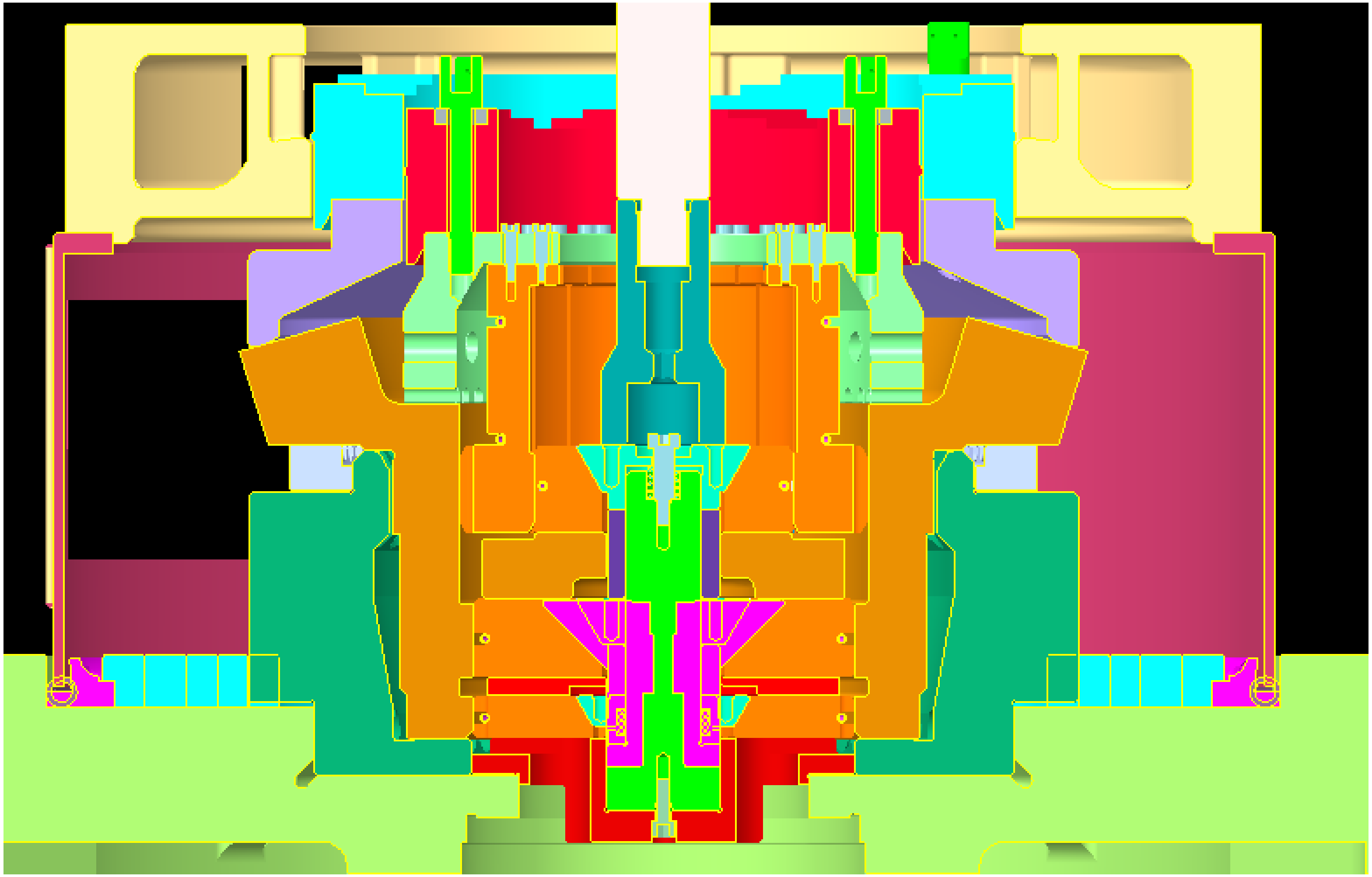
Expanding segmental die tooling design including inner and outer upper dies.



Expanding segmental die tooling design. The part being quenched is colored in gold.



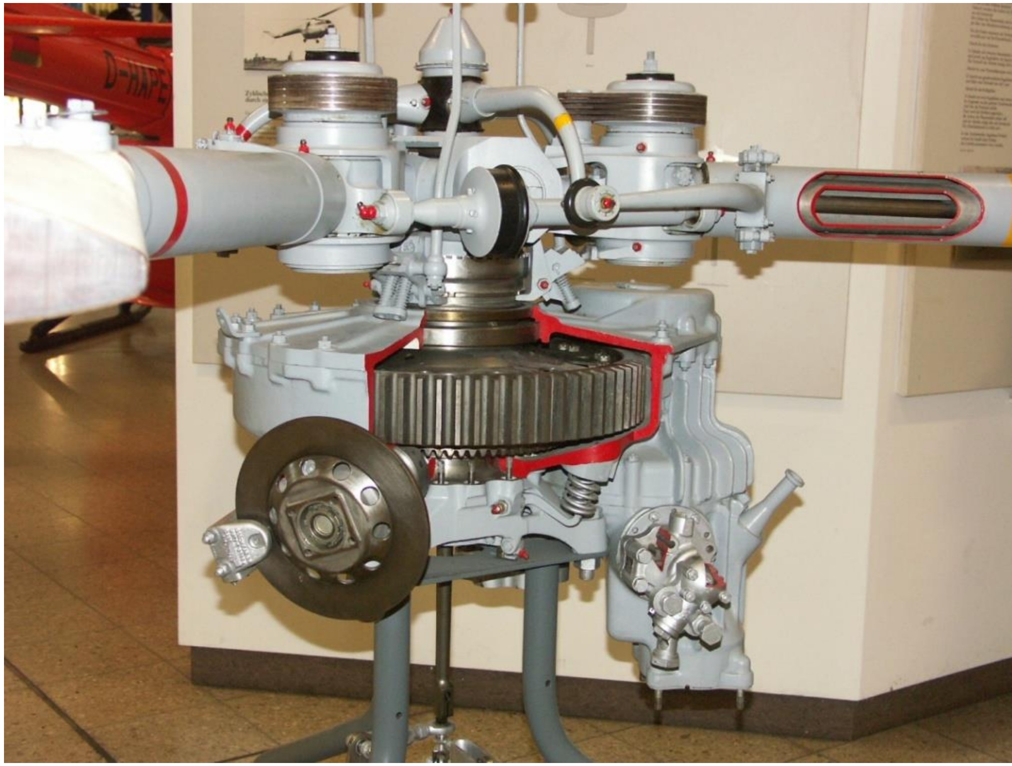
Simple expanding die set-up. The quenched part is in purple.



Stacked expanding die tooling set-up.
The quenched part is colored orange.

Die Tooling

In addition to expanding dies, contracting dies are also available to maintain the geometrical tolerances for the outside diameter where this is a critical factor. A good example of this are gears which incorporate thin web sections in conjunction with relatively heavy sections for gear teeth, bosses, and bearing diameters.



Bristol 171 Sycamore helicopter main gear box and rotor head. Source: Wikimedia Commons.

Thank you!

Any Questions?

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