FLUXTROL Inc.
Centre for Induction Technology™

Induction Hardening of Gears & Sprockets

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A Joint Class of AGMA and ASM
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GEAR EXPO 2013

Overview

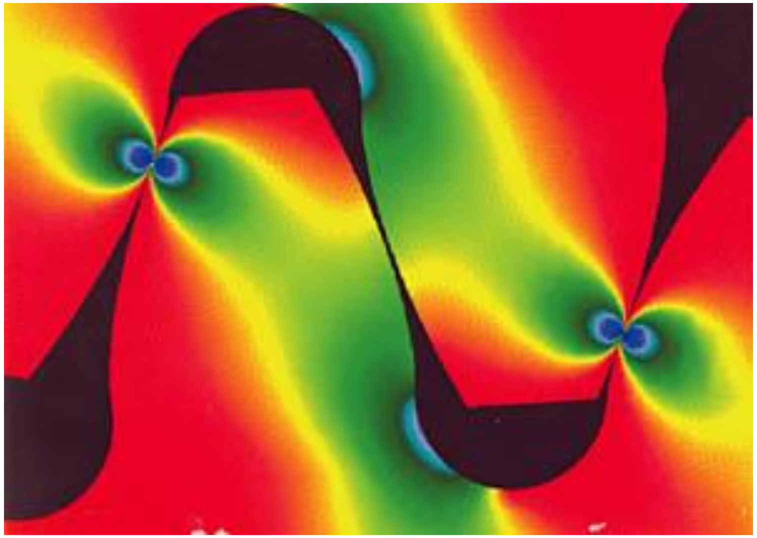
- Specifics and methods of induction gear hardening
- Single-shot aka Spin hardening
  - Single Frequency hardening
  - Dual Frequency hardening
  - Simultaneous Dual Frequency hardening
- Tooth Scan hardening (Delapena process)
- Tooth-by-Tooth simultaneous hardening
- Computer simulation
- Conclusions

SDF Hardened Gear, Eldec Induction

Induction Gear Hardening

Optimal case pattern is a continuously hardened layer on the whole surface:

CONTOUR (PROFILE) HARDENING



Gear tooth loading patterns

Source: Inductoheat

How to Achieve Contour Hardening with Induction Hardening?

1. **Austenization by induction heating and quenching of required surface layer**
2. Hardening after thermochemical surface treatment (carburizing, etc.)
3. Use of steels with limited hardenability

In cases 2,3 the whole gear or tooth area may be heated to austenization temperature and quenched

Methods of Induction Gear Hardening

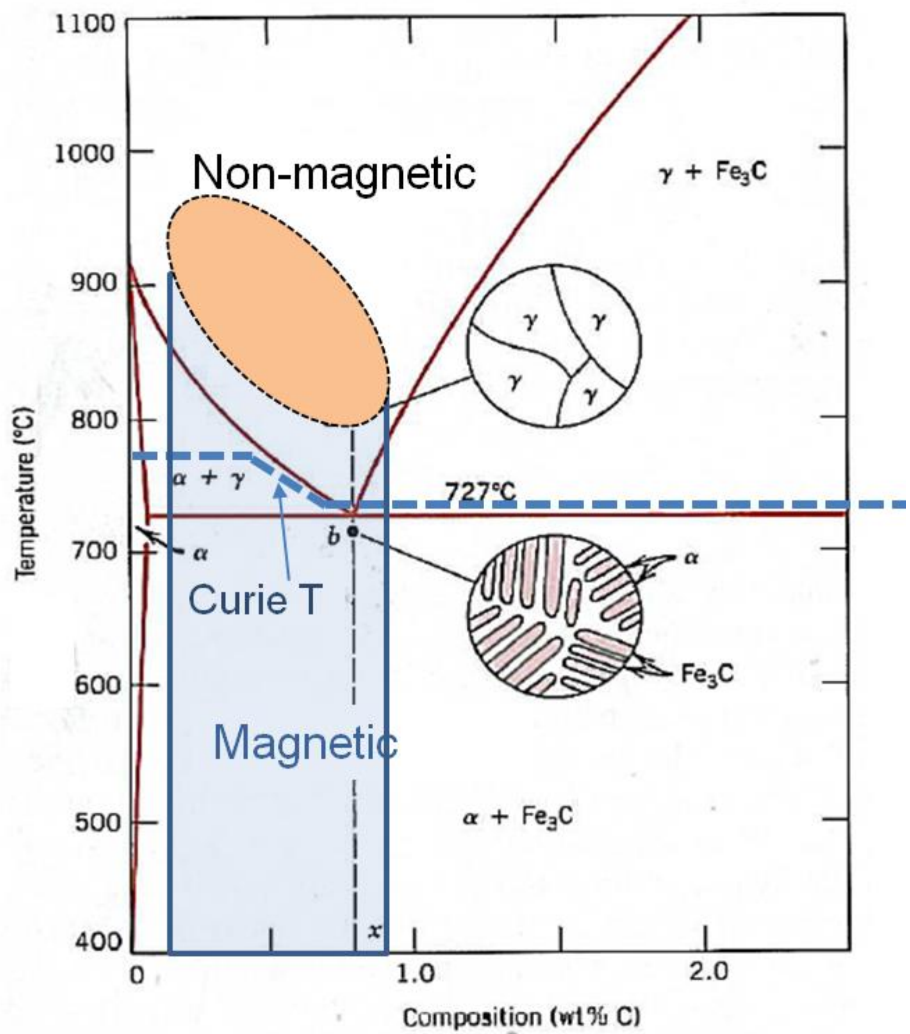
Contour Hardening:

1. Single-shot heating at “optimal” frequency
2. Dual frequency heating
3. Simultaneous Dual Frequency (SDF) heating

Local Hardening:

1. Flank heating
2. Simultaneous tooth-by-tooth hardening
3. Tooth-by-tooth scan hardening (Delapena process)
4. Others

Iron-Carbon Diagram



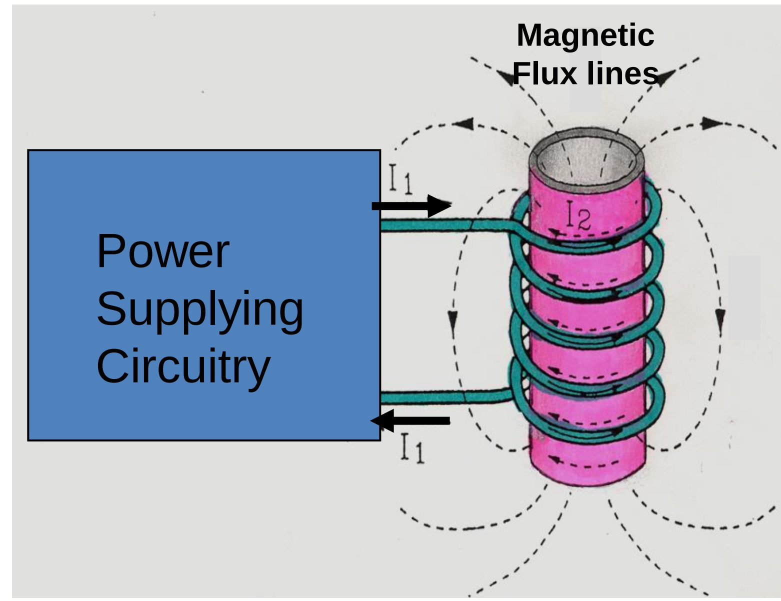
Induction heating intensity and heat distribution depends on properties of heated material.

For a significant part of the heating process (up to 50%) the surface temperature is above Curie temperature, i.e. the surface layer is non-magnetic.

Main Principle of Induction Heating

Chain of phenomena:

1. Power supply delivers current (I1) to induction coil
2. Coil currents (ampere-turns) generate magnetic field. Lines of field always go around the coil turns
3. Alternating magnetic field flowing through the part cross-section (coupled to the part) **induces** voltage in the part
4. Induced voltage creates eddy currents (I2) in the part
5. Eddy currents generate heat in the part
6. In each induction system there are at least 3 closed loops: 1. Induction coil; 2. Eddy current loop in the part; 3. Magnetic flux loop



Skin-Effect in Induction Heating

Induced current tends to take the shortest path under the coil turns but it does not penetrate into the metal to a depth >1.5 δ, where δ is a skin or reference depth. δ depends upon material properties and frequency. For hot steel (non-magnetic state)
$\delta = 500/\sqrt{f}$, mm $= 20/\sqrt{f}$, in.

F, kHz	10	20	50	100	200
δ, mm	5	3.5	2.2	1.6	1.1
δ, mil	200	140	87	63	43

Source of photo:
www.denkikogyo.co.jp

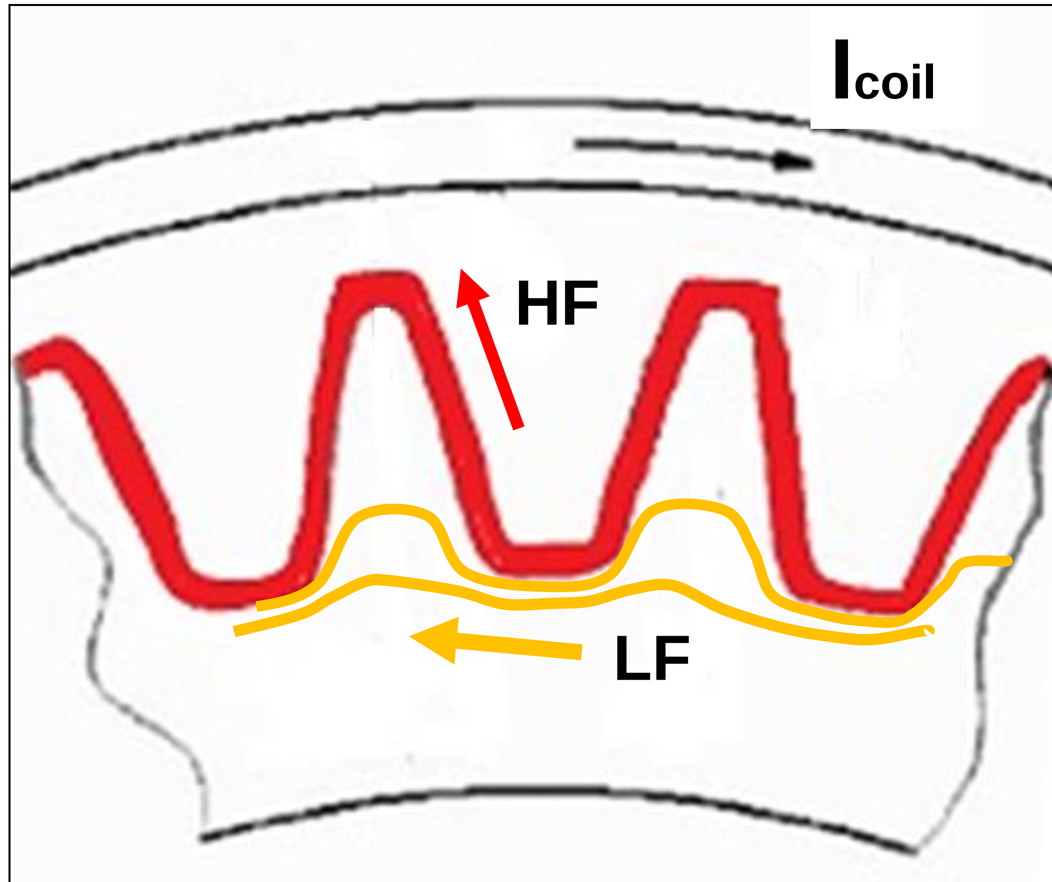
Example: spur gear M = 4 mm, i.e. p = 0.49”
and tooth thickness s = 245 mil
To heat tooth **well**, δ must be less than s/2,
i.e. δ_{max} = 122 mil and min frequency is 27 kHz

Eddy Current Flow Path in Gear

HF current flows along the gear contour

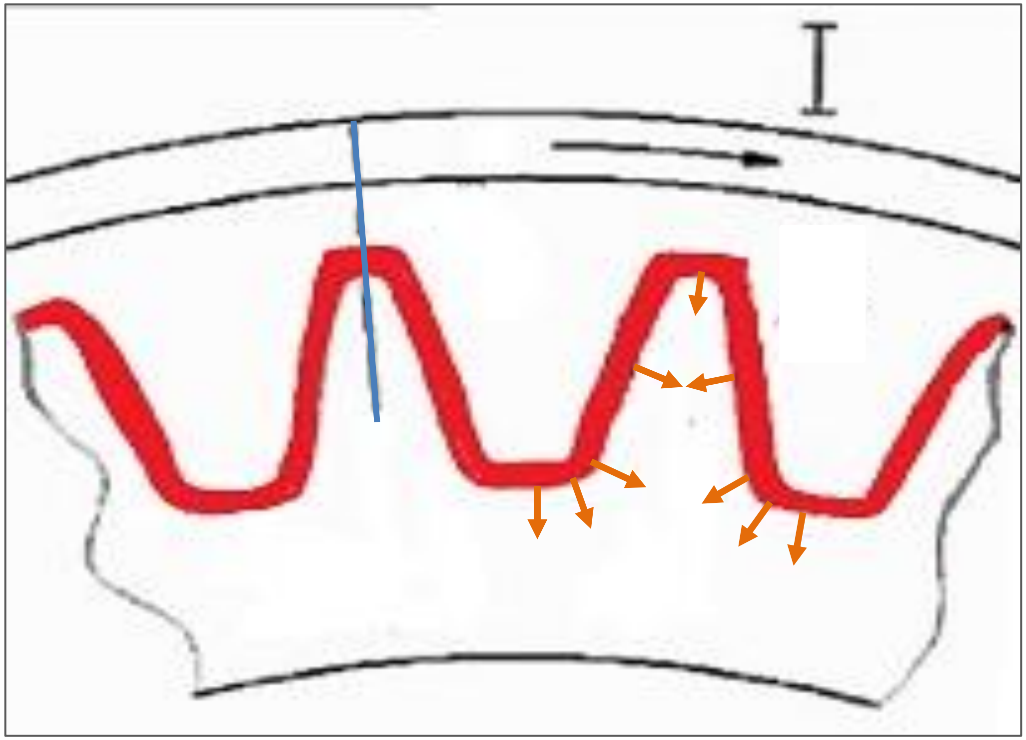
LF current “cuts” the teeth and the gear roots are much more intensively heated

At temperature below Curie point (material is magnetic) skin effect is high even at “low” frequency and current path is similar to HF case



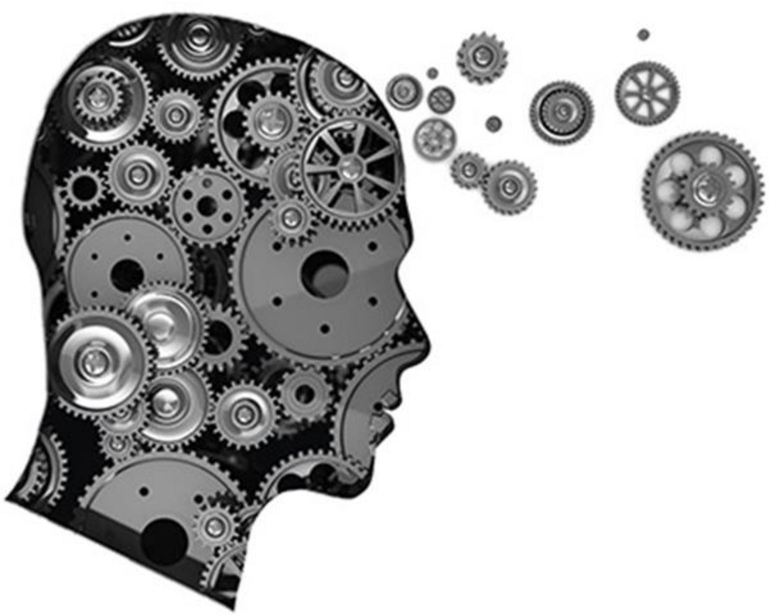
Heat Delivery Requirements

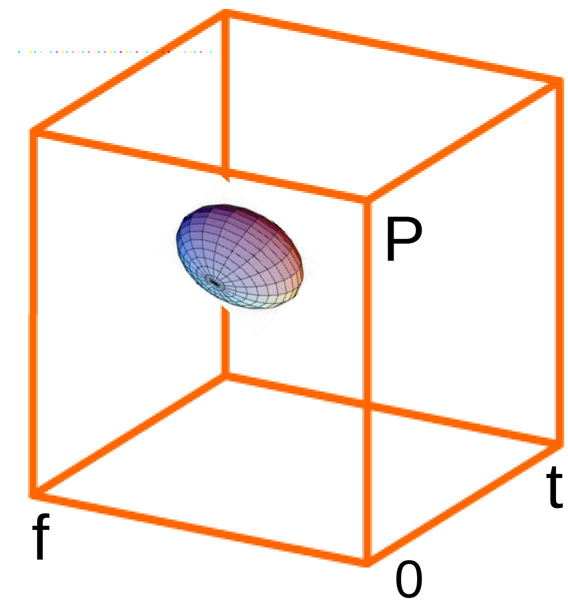
1. Appr. 3 times more heat must be delivered to the root area than to tooth inn order to have the same temperature
2. Power density must be high and heating time “short” to avoid tempera-ture equalization in the tooth and thru hardening
3. Smaller the module (or circular pitch), shorter time and higher specific power required



Heat flow in tooth and root areas

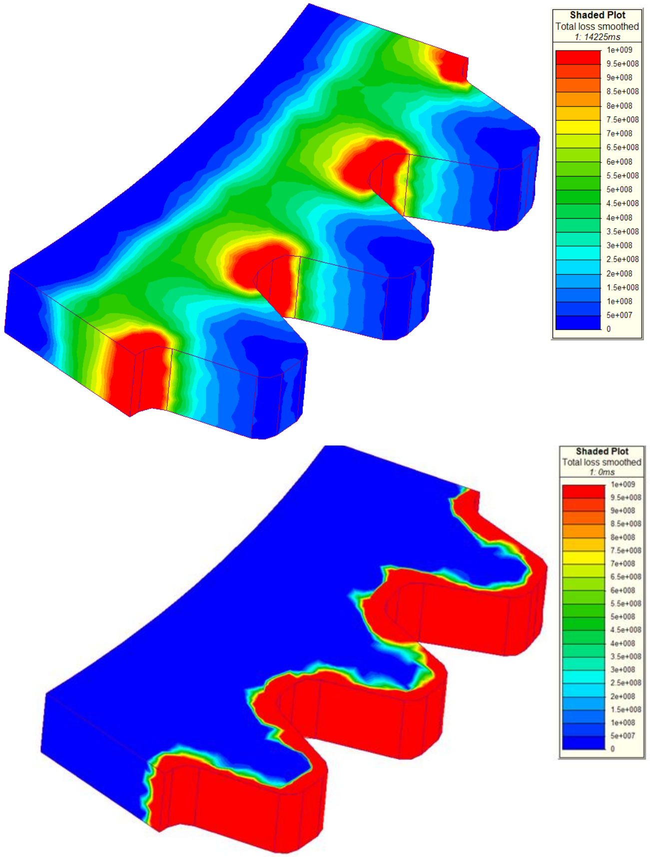
Parameters of Induction Gear Hardening Process





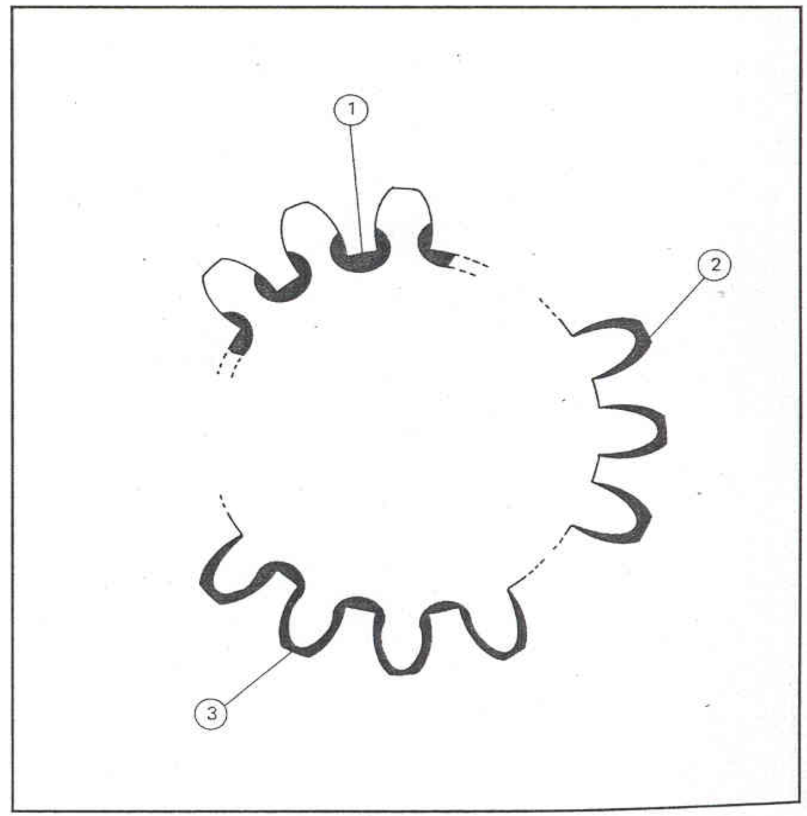
Major parameters of the process: Frequency f, Power P and heating Time t. Process is dynamic and only a combination of these parameters plus optimal induction coil design can give good results

Frequency Selection



Power distribution pattern:
Top – Low Frequency
Bottom – High Frequency

Source: Ajax Tocco Magnethermic



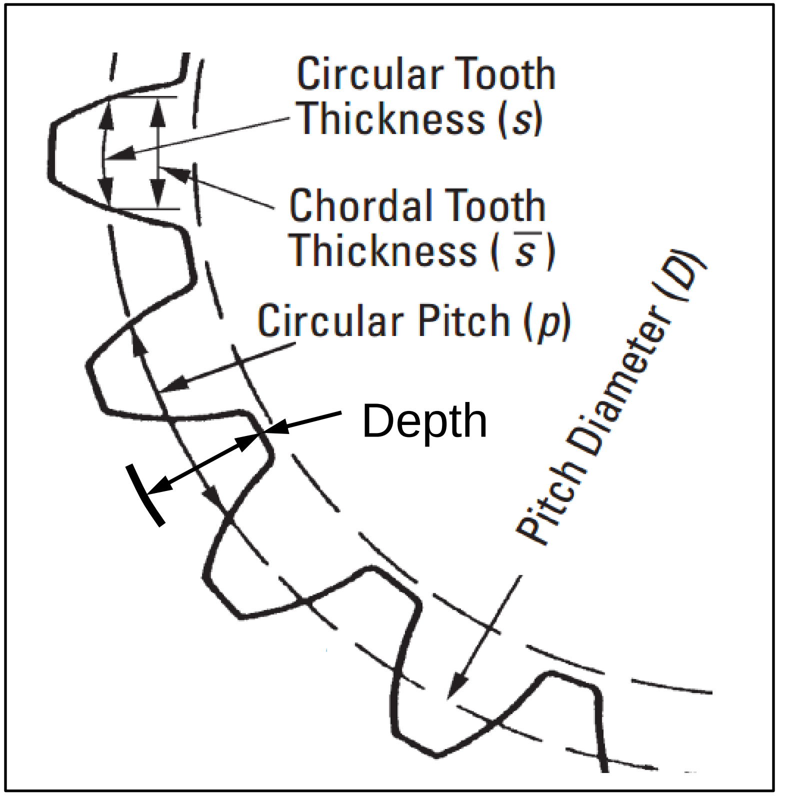
Hardened layer pattern:
1 – Low Frequency
2 – High Frequency
3 – Optimal Frequency, Power and Time

Single-Shot Hardening
aka
Spin Hardening

Optimal Frequency for Single-shot Contour Hardening

<u>Metric system:</u>
$F_{opt} = K/M^2$, kHz
with M – gear module in mm
K = 350-600 depending on gear tooth geometry, case depth and material

<u>British system:</u>
$F_{opt} = (6\text{-}10)/p^2$, kHz
with p – circular pitch in inches



<u>Relation:</u> $M = 25.4\, p/\pi = 8.085p$
with p in inches and M in mm

Process Parameters

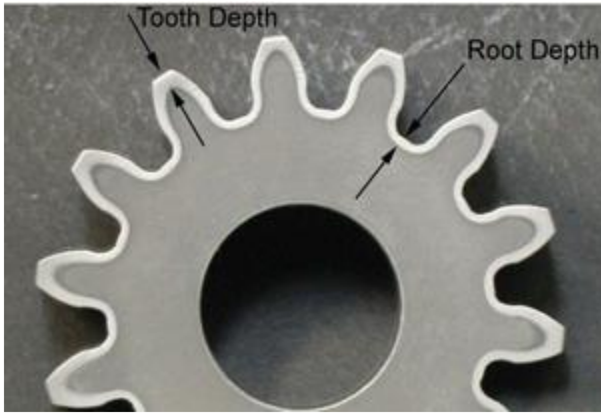
Process is characterized by combination of frequency F, specific power P_0 and heating time t. P_0 and F can vary during the process.

Total power Pp = Sp*P_0 with Sp - heated surface.

Module, mm	3	4	5	6
Circ. Pitch, in	0.37	0.49	0.62	0.75
Fopt, kHz	40-65	20-30	10-17	7-12
Time, sec	0.2-0.25	0.6-0.7	0.9-1.1	1.2-1.4
Specific power, kW/sq.in	20-24	14-16	12-14	7.5-8.5

This table gives you only estimate values; they must be corrected for a particular gear

Induction Hardening Pattern



Good contour harde-
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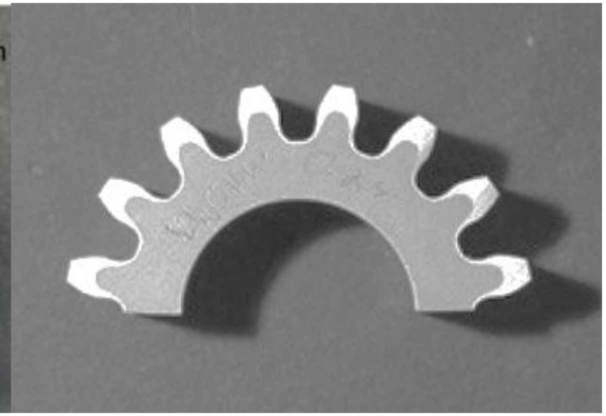
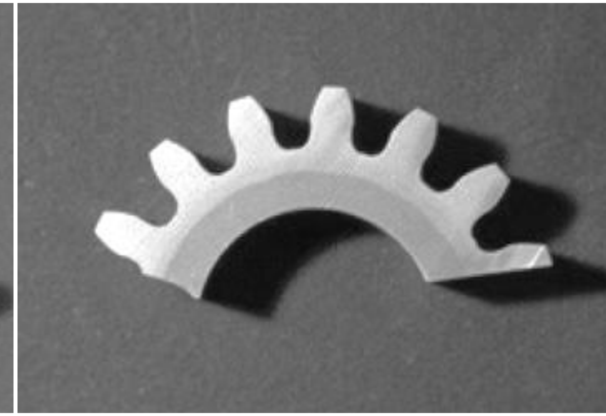


Non-uniform contour hardening due to longer than optimal heating at relatively high frequency



Through hardening of the whole teeth area due to too long heating

Source: www.gearsolutions.com

Example of Gear Optimally Hardened by Single-shot Process

Optimal induction hardening provides:

- High surface hardness and contact strength
- High wear resistance
- Favorable distribution of compressive stresses
- High bending strength
- Slow progression rate of pitting

A 6150 spur gear profile hardened using single-frequency single-shot technique

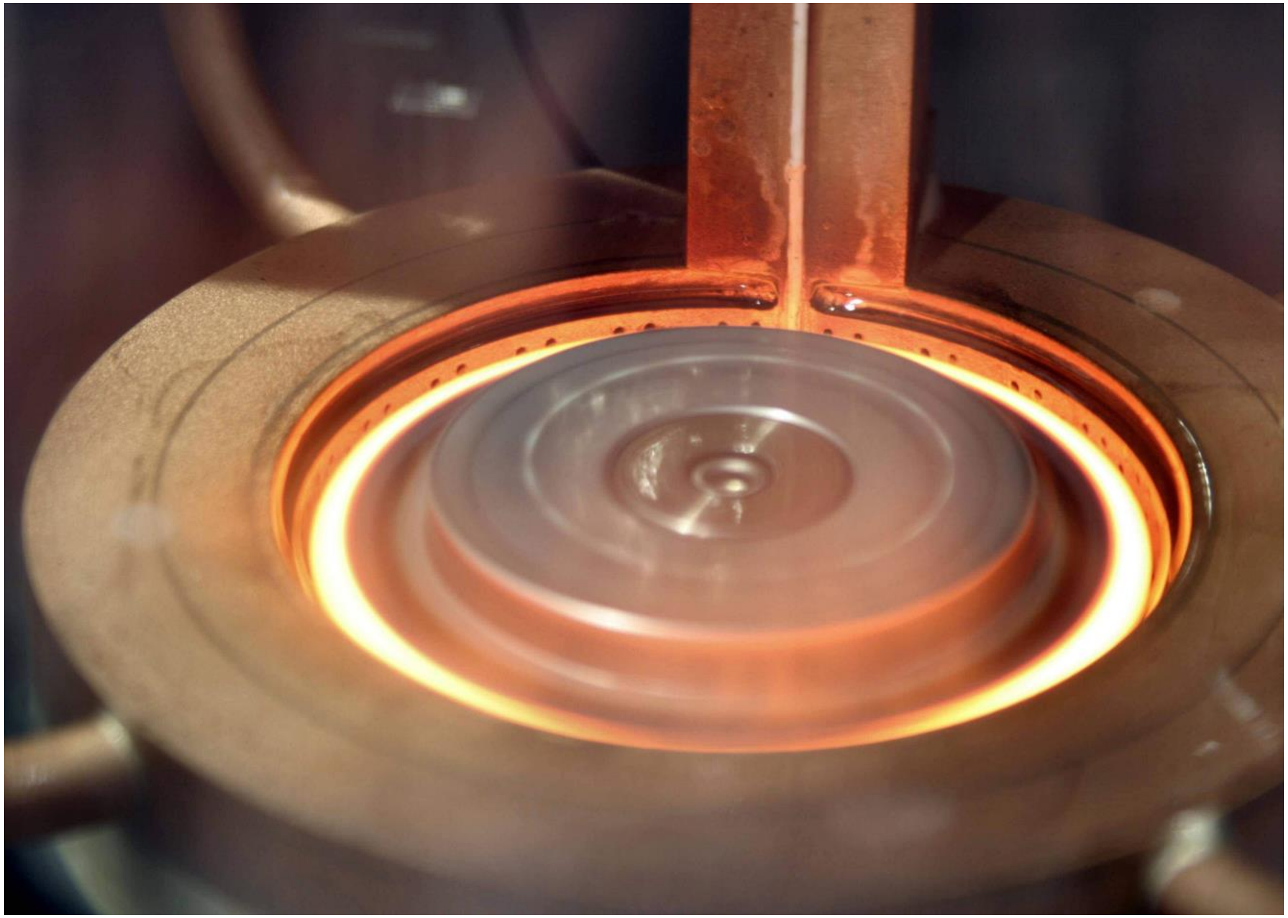
Source: Inductoheat

Gear Contour Hardening

Gear heating: optimal combination of frequency, power and time
Slight overheating of root end areas (may be attributed to the coil design)

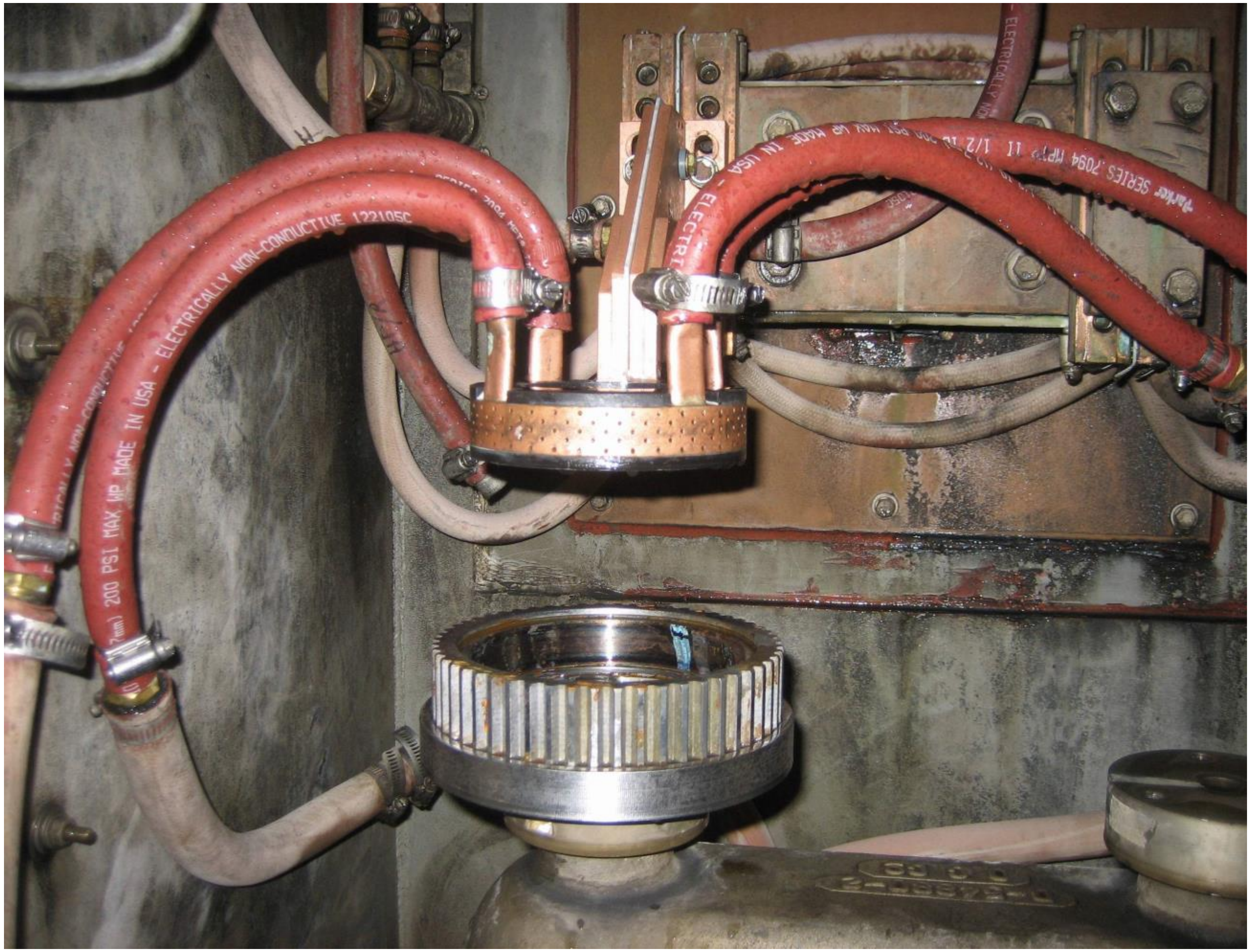
Source: www.denkikogyo.co.jp

Heating for Less Than 2 Seconds



Source: Ajax Tocco Magnethermic

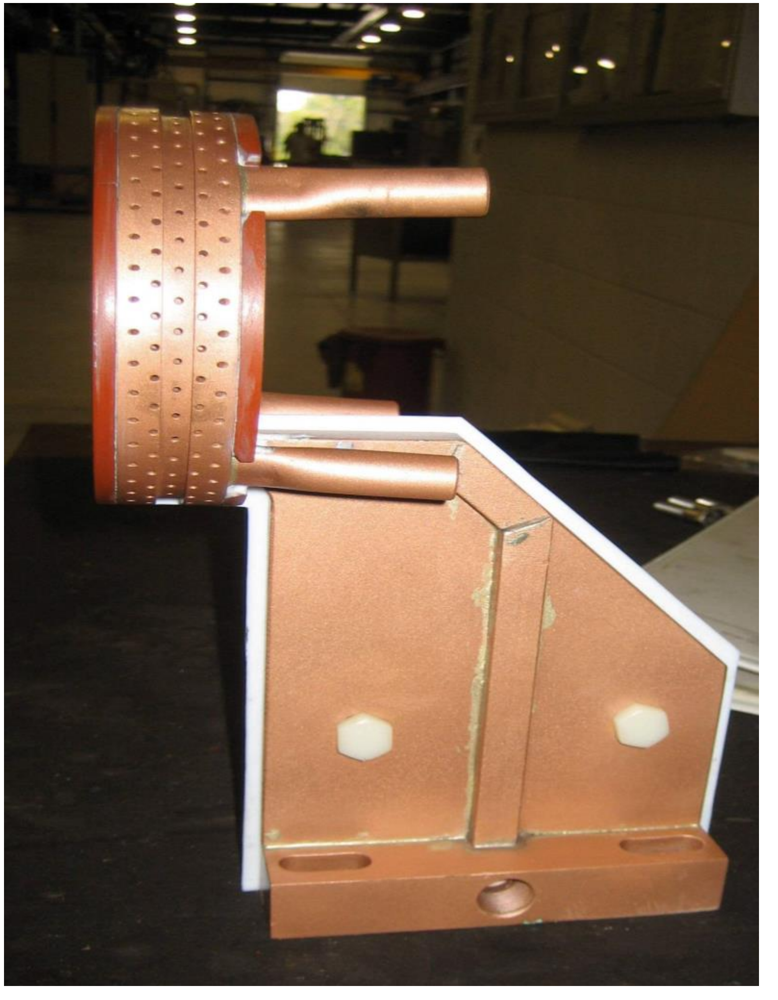
Case Hardening of ID Gear Surface



Source: Ajax Tocco Magnethermic

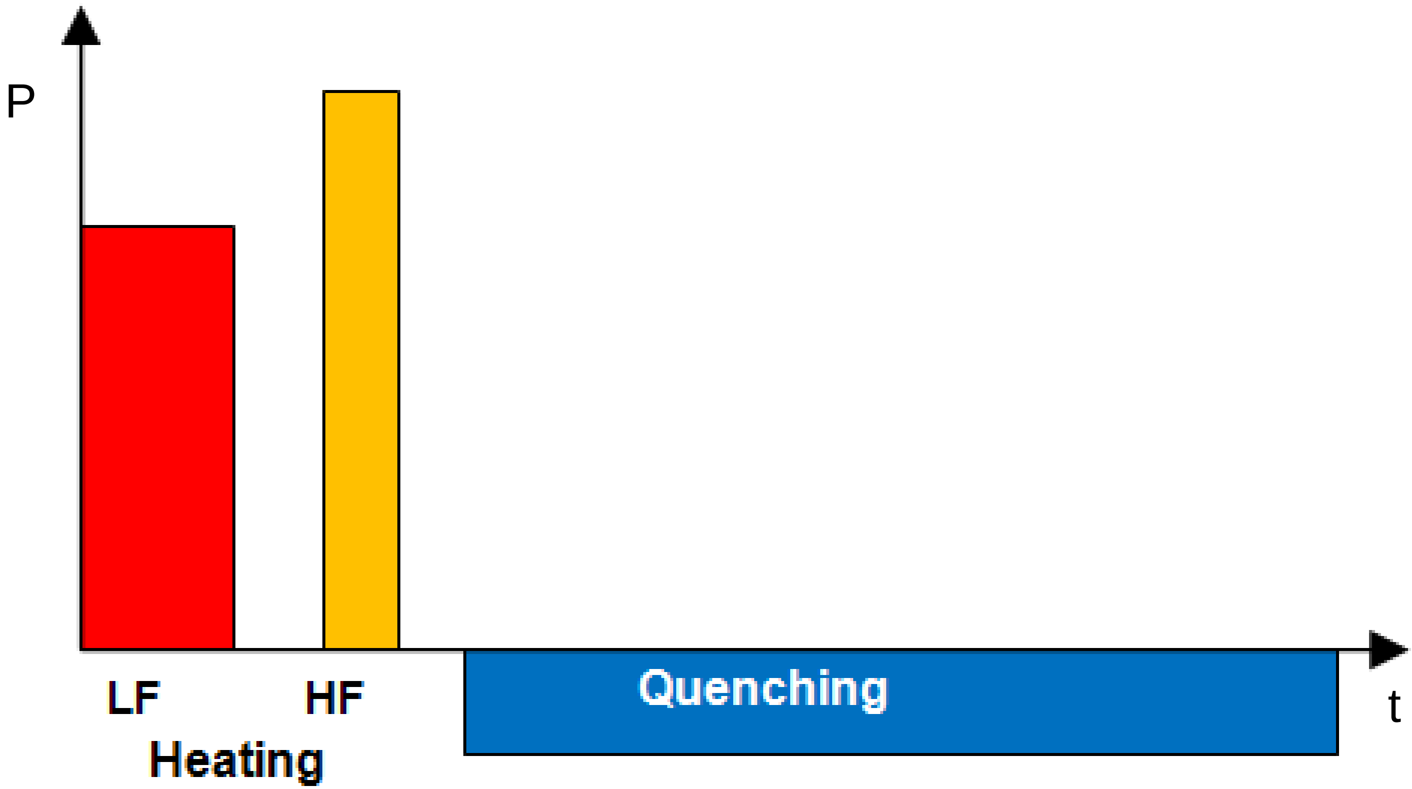
Machined Coil with Integral Quench

Magnetic flux concentrators are highly recommended for ID coils
They dramatically reduce coil current demand, improve process efficiency and part quality



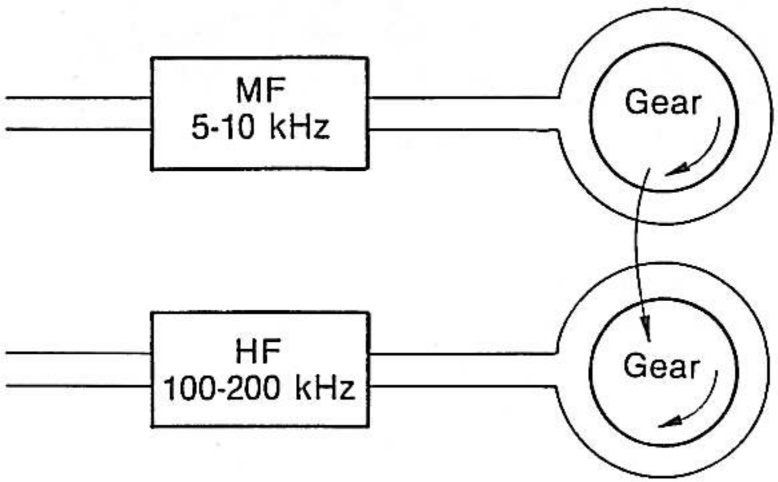
ID coil with Fluxtrol Soft Magnetic Composite core (concentrator)

Dual Frequency Hardening

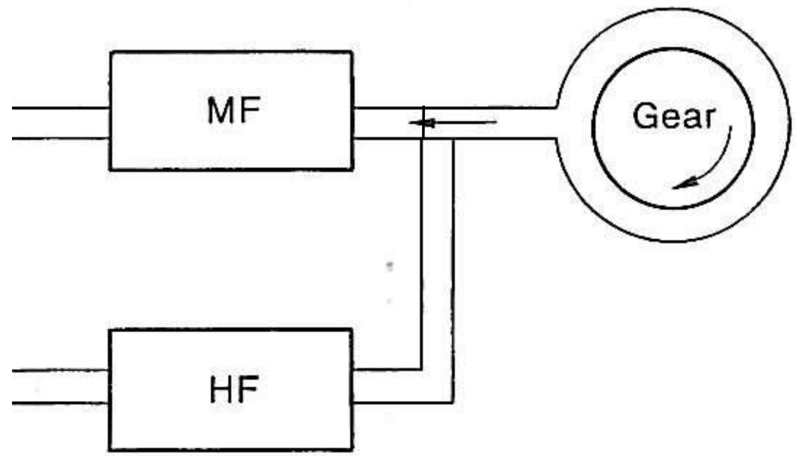


Dual frequency hardening is more flexible and reliable process than single-frequency one

Two Types of Dual Frequency Heating



Dual frequency heating with part transportation



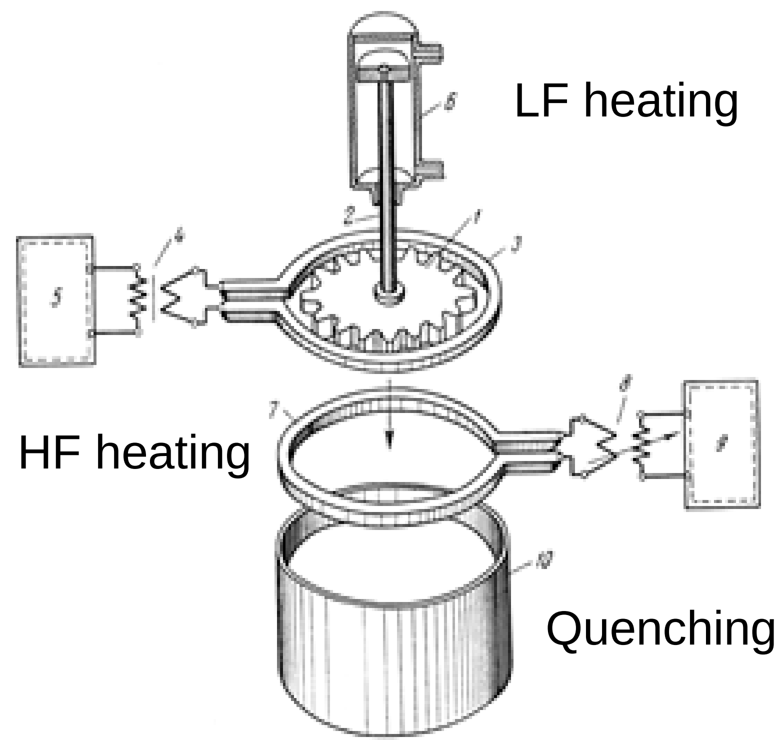
Simultaneous Dual Frequency (SDF) heating. Typical frequencies: 10 kHz and 100 - 200 kHz

Dual Frequency Hardening

Dual frequency hardening may be made by sequential heating at Low and High frequency in two inductors or in the same inductor.

LF heating brings teeth to a temperature slightly higher than Curie point and the roots - to temperature close to a final value.

HF heating must be short. It forms a required austenitized layer on the whole gear circumference



Simultaneous Dual Frequency Hardening

SDF hardened bevel gear:
Heating time 0.2 sec
Frequencies 10 kHz and 230 kHz
Total power 580 kW

1000 kW SDF machine,
Eldec Induction

Source: Book of A. Muehlbauer "History of Induction…"

New Generation of SDF Induction Machines

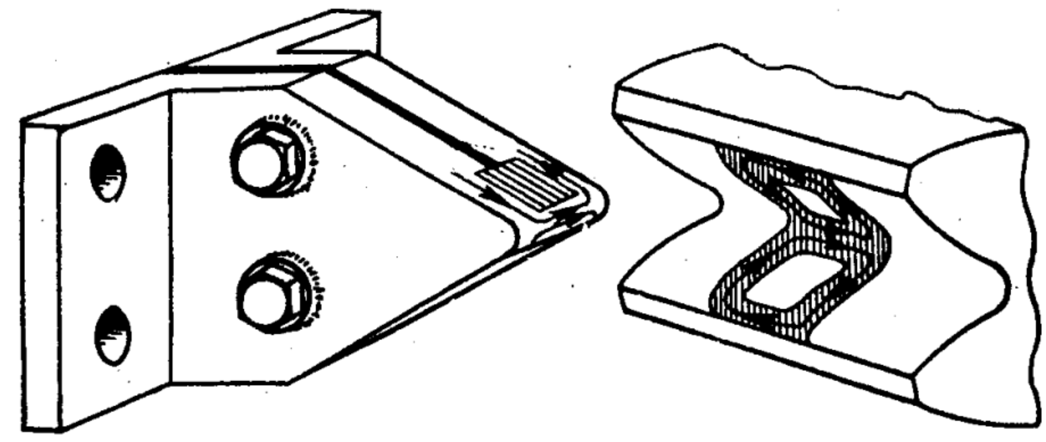
Total power of SDF machines is up to 3000 kW

The MIND—Modular INDuction—machine.

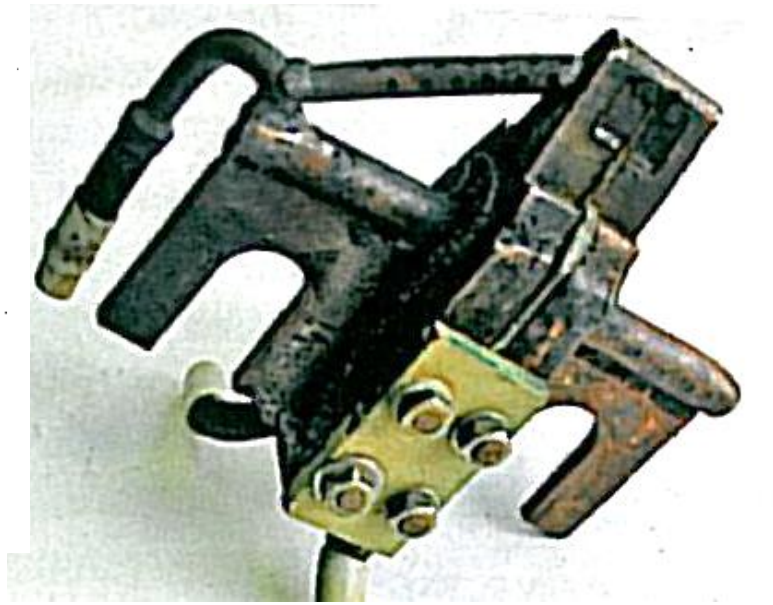
Source: Eldec Induction

Scanning: Delapena Process

Delapena Style Coil



Inductor and Current Flow Print

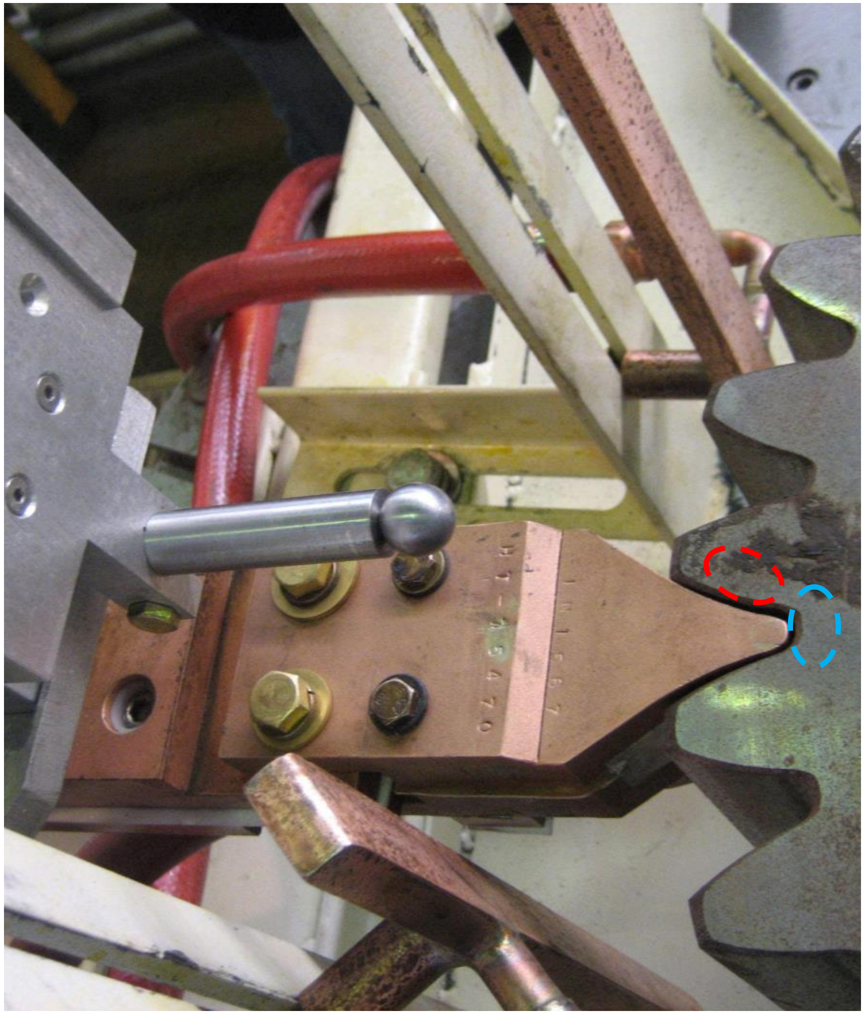


Used inductor for large gear hardening

Source: Book of A. Muehlbauer "History of Induction Heating and Melting, Vulkan, 2008"

Source: VNIITVCh, Russia

Coil Positioning with Contact Guide



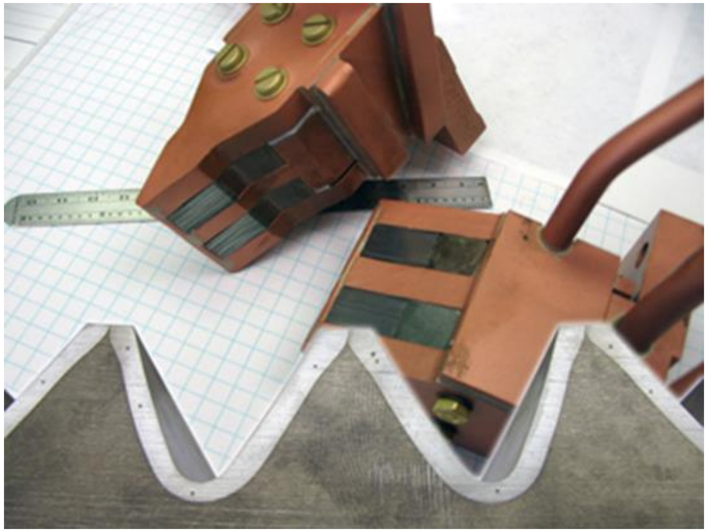
Source: Ajax Tocco Magnethermic

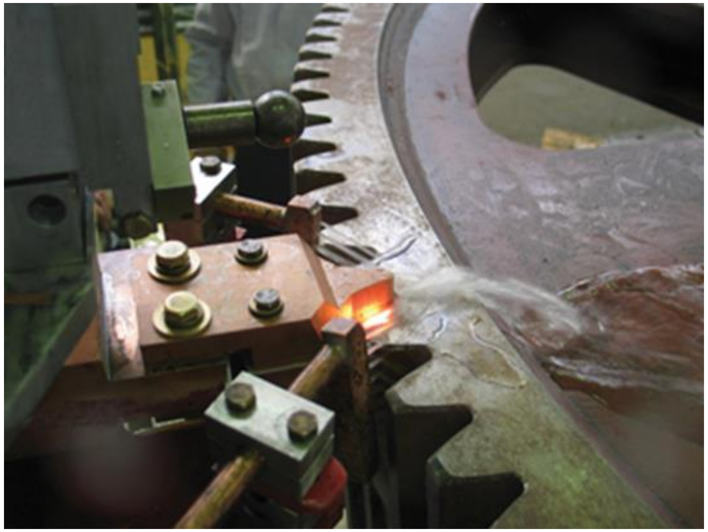
Difficulties:

- Small gaps “coil-gear” and accurate positioning are required
- Overheating of flanks and underheating of root bottom near the end of gear may occur
- Water sprays required for correction of heat pattern on the tooth tips and at the end of gear.

Flank Sprays Prevent Temper Back on Adjacent Tooth

Double Coil of Delapena Style





This coil allows better temperature control at the beginning and the end of scanning path

Source: www.thermalprocessing.com

Installation for Tooth by Tooth Scan Hardening

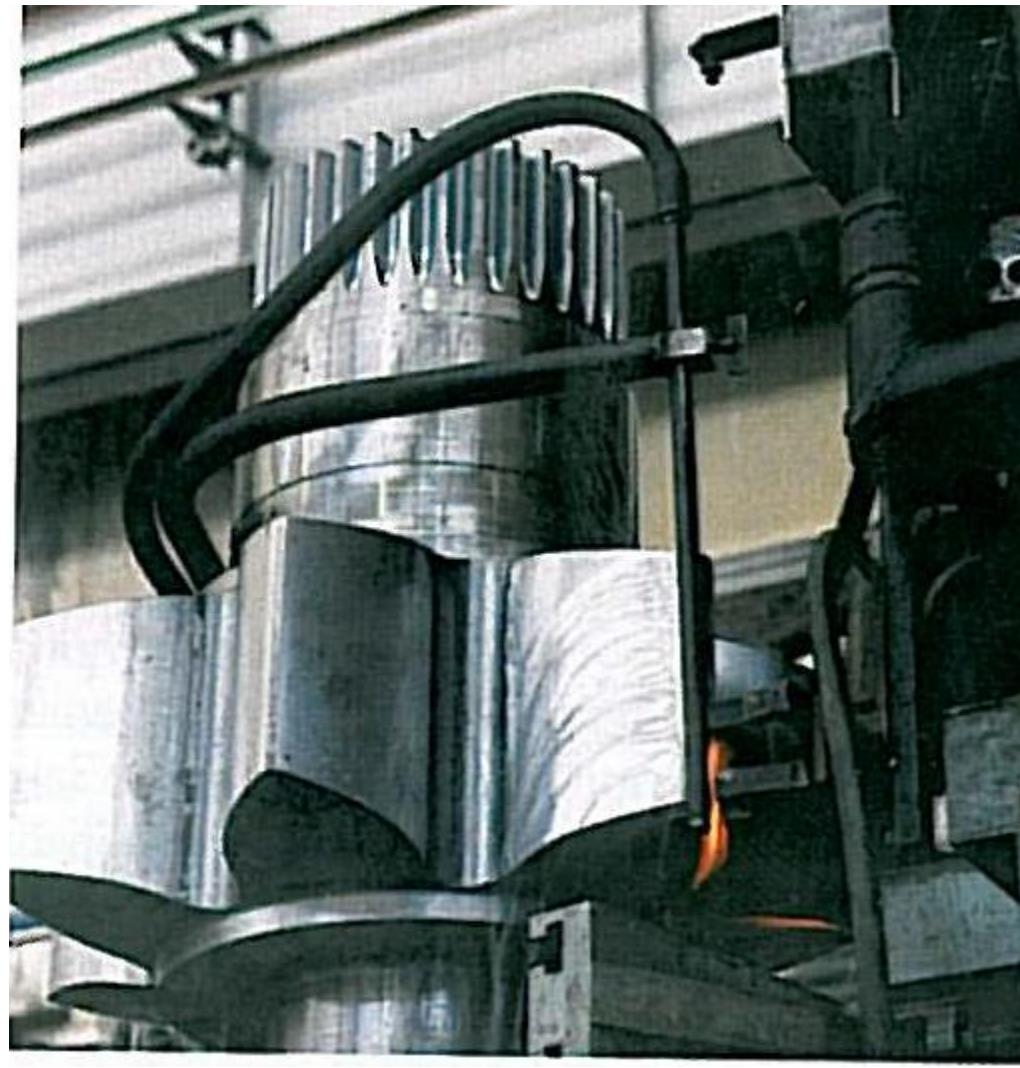
Source: Ajax Tocco Magnethermic

Scan Hardening of Large Gear

Gear OD = 750 mm (29.5")

Weight M = 0.75 t

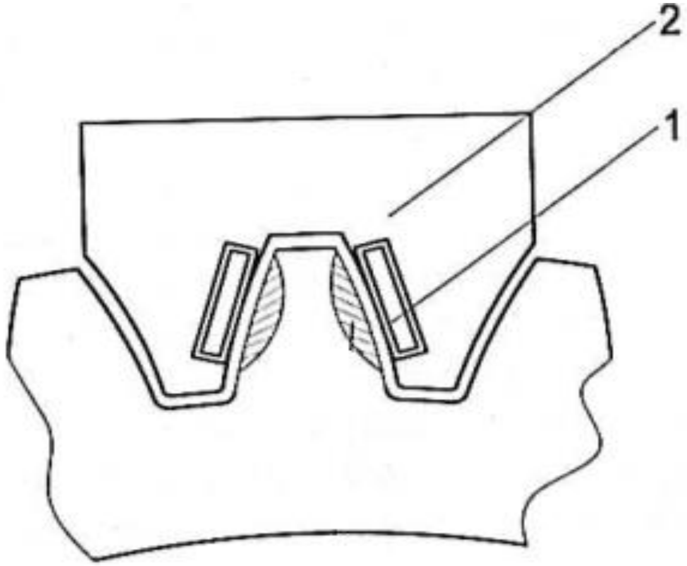
Teeth number N = 7



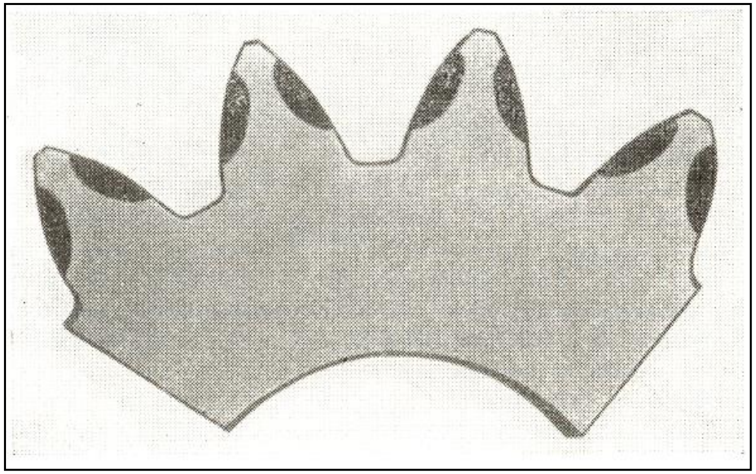
Source: VNIITVCh, Russia

Other Methods

Flank Hardening

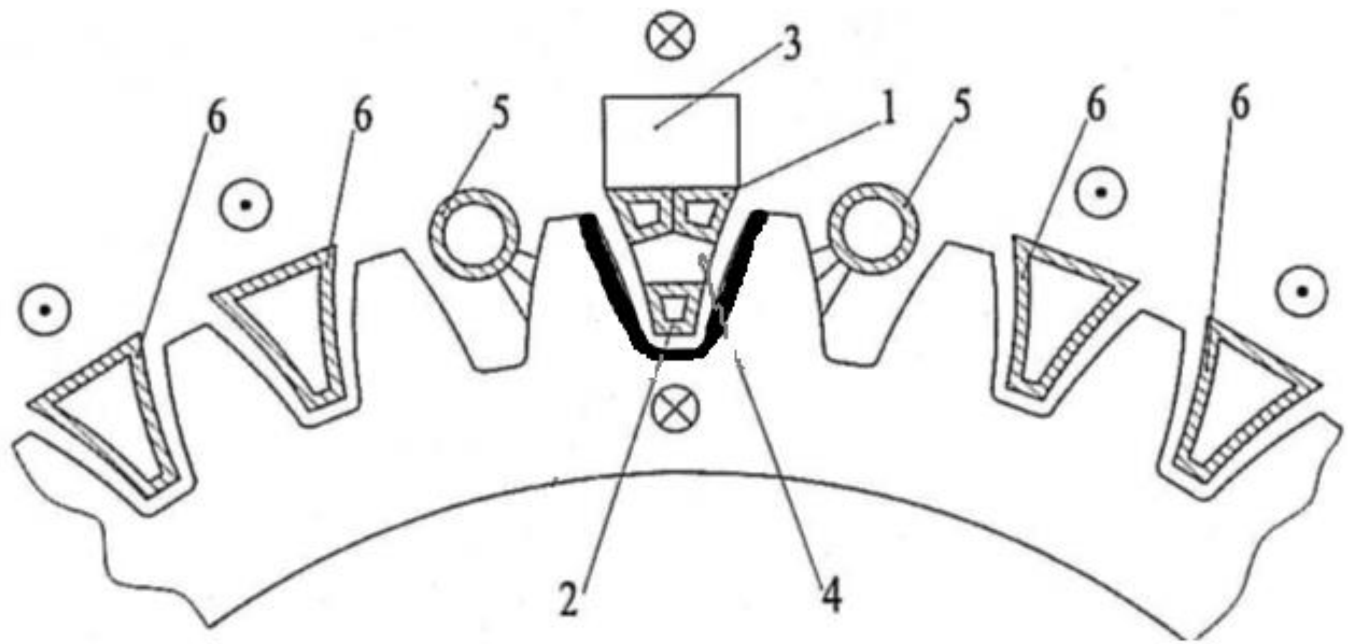


1 – coil turn; 2 – magnetic controller



Hardness pattern

Root by Root Hardening



1,2 – active coil turns; 3,4 – magnetic controllers;
5 – cooling shower; 6 – return coil legs

Example: hardening of tractor satellite gear M = 6.5 mm;
process is sensitive to design and setup

Design: VNIITVCh, Russia, 1966

Large Sprocket Hardening

Coil with magnetic controller

Source: VNIITVCh, Russia

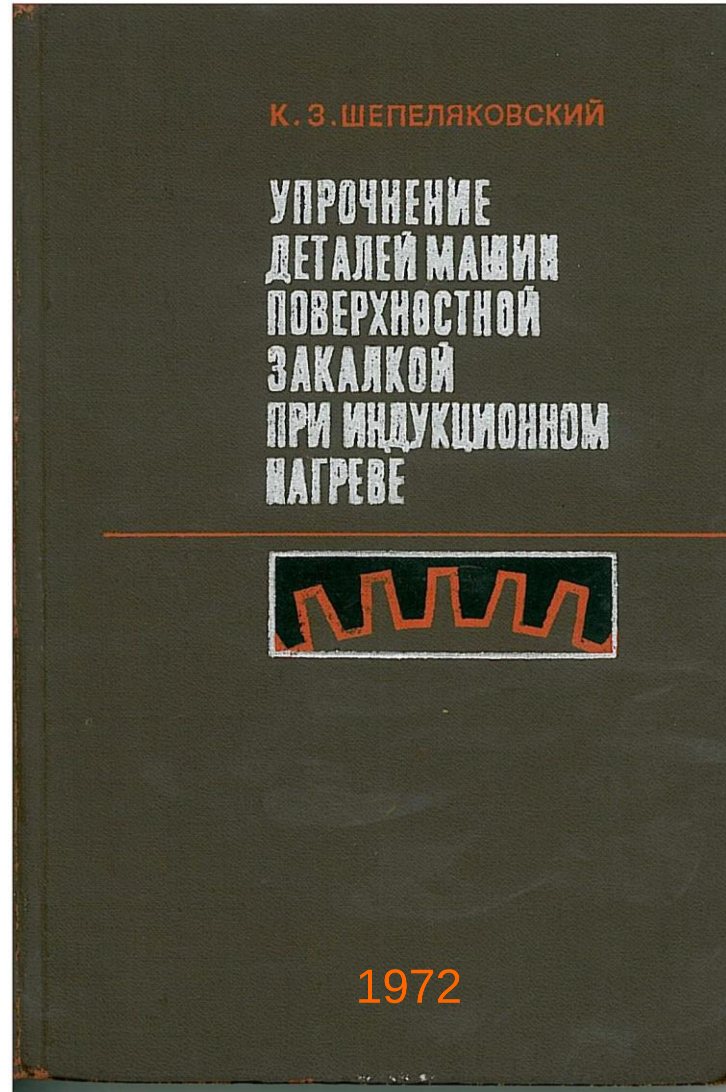
Large Gear and Slewing Rings Hardening

GH Induction machine for large wind generator gear hardening using “tooth-by-tooth” technology

Using Steels with Controlled Hardenability

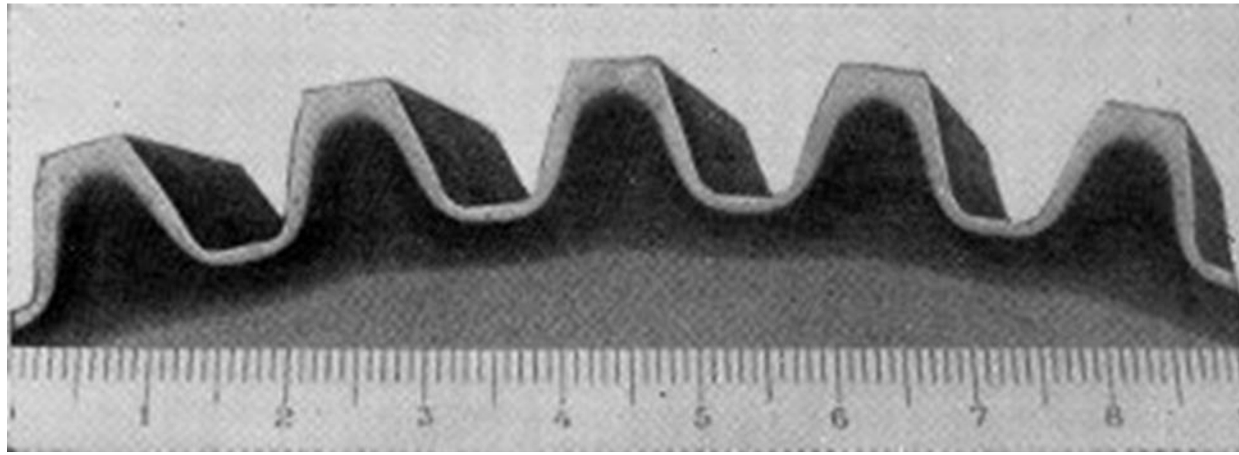
Gears from Steels with Controlled Hardenability

Technology was developed by Prof. Konstantin Shepelyakovskiy in 1960s, Moscow Automotive plant “ZIL”.
It is used in automotive and rail road industries for gears and other compo-nents in Russia and Belorussia



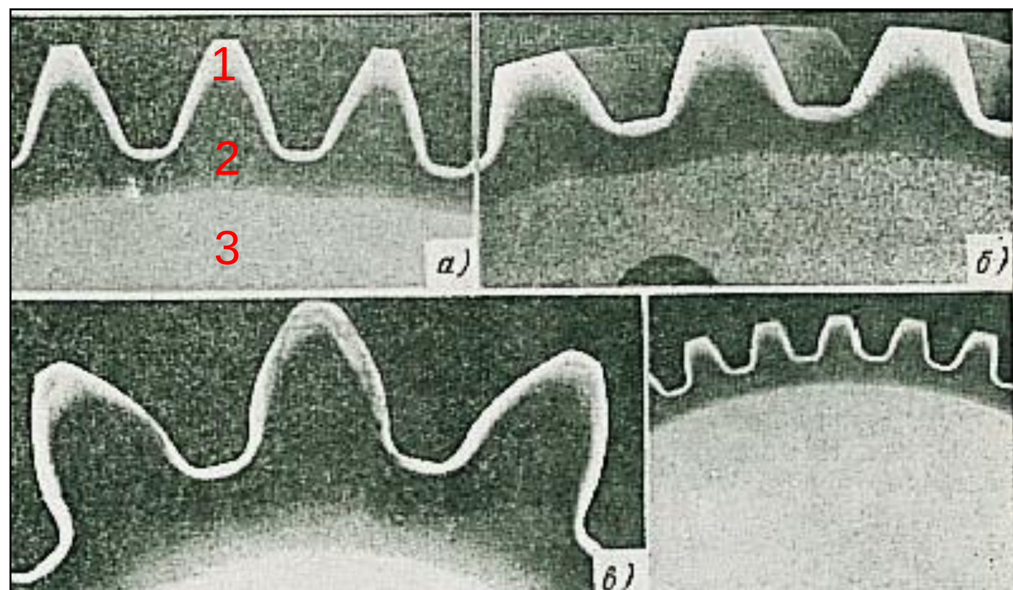
Microstructure of Hardened Gears

Truck gear:
M = 6 mm or
p = 0.74”
DP = 4.2



Miscellaneous Gears:

1 – martensite
2 – sorbite
3 - initial structure



Sorbite X 500

Special Features of the Method

- Low alloyed steels made according to a special technology
- Deep induction or even furnace heating may be used
- Very intensive water quenching is required to achieve optimal results
- Sorbite layer formation under the martensite layer improves gear performance
- Method is low sensitive to heating process

Source: Prof. K. Shepelyakovskiy

Computer Simulation

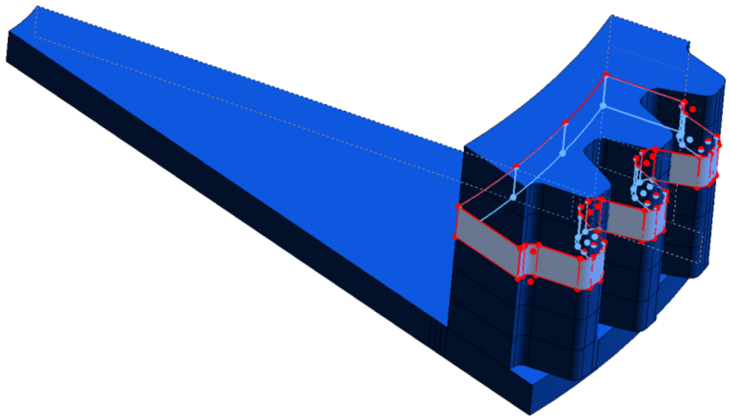
Simulation of Gear Hardening

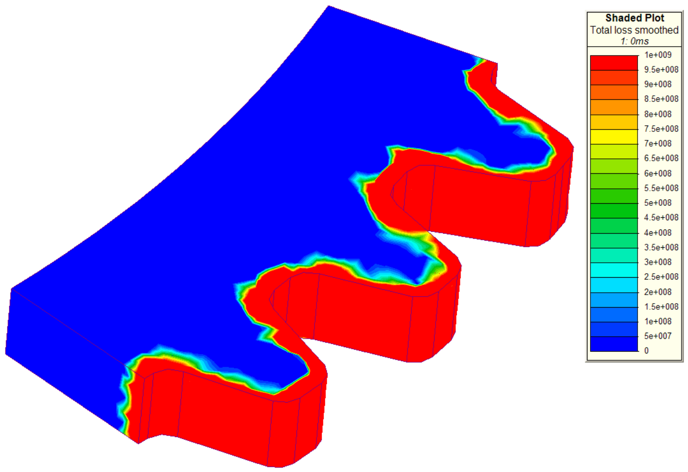
Computer simulation of induction gear hardening is one of the most difficult tasks of induction heating due to:

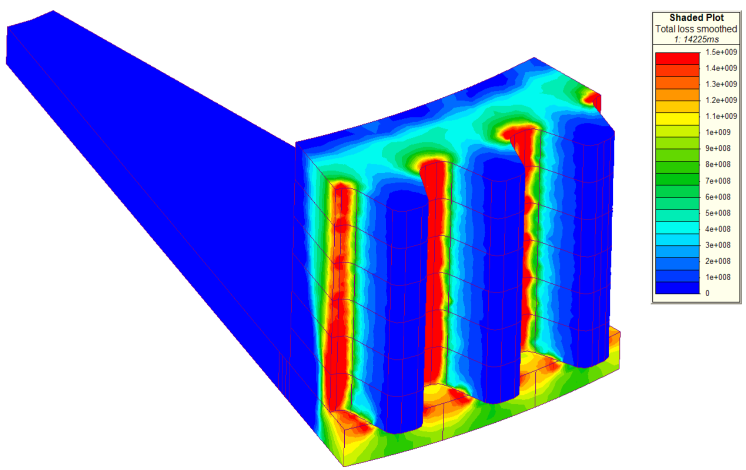
- 3D nature geometry of the system
- Strong coupling of Electromagnetic and Thermal phenomena
- High frequency and large gradients of magnetic and thermal fields require fine meshing
- Frequency variation or application of two different frequencies (in the case of SDF heating)
- System geometry variation in the case of scan hardening (at the extremities of the gear)

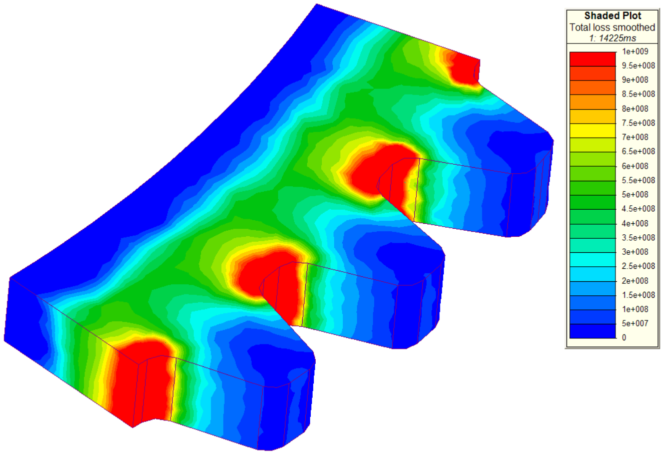
In spite of these difficulties at present time we have successful examples of computer simulation of Electromagnetic, Thermal and Structural phenomena and even Stress and Distortion distributions.

3D Simulation of Power Density Distribution in Gear



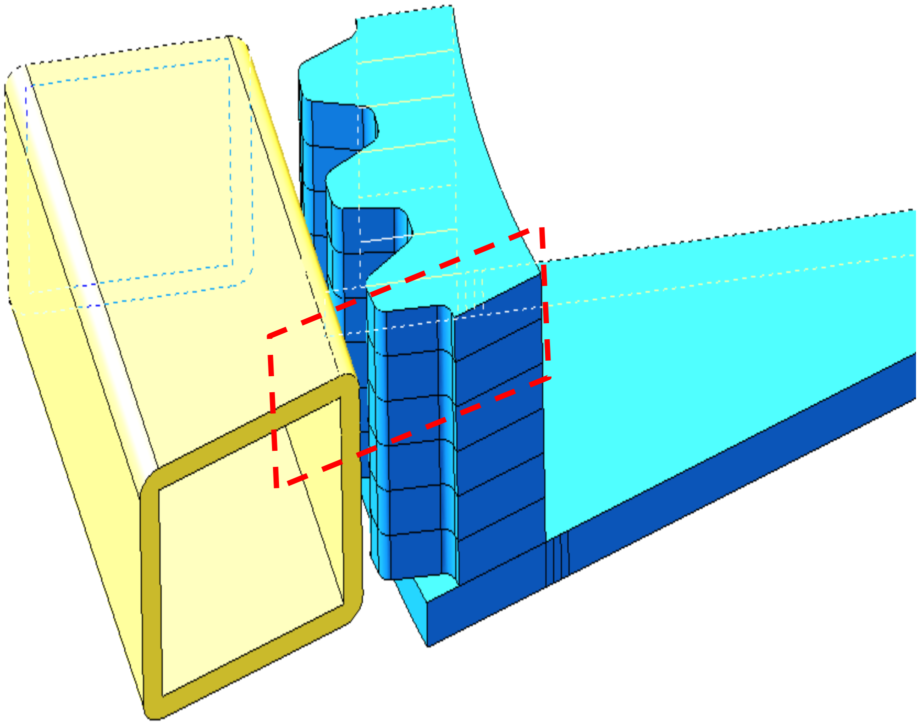






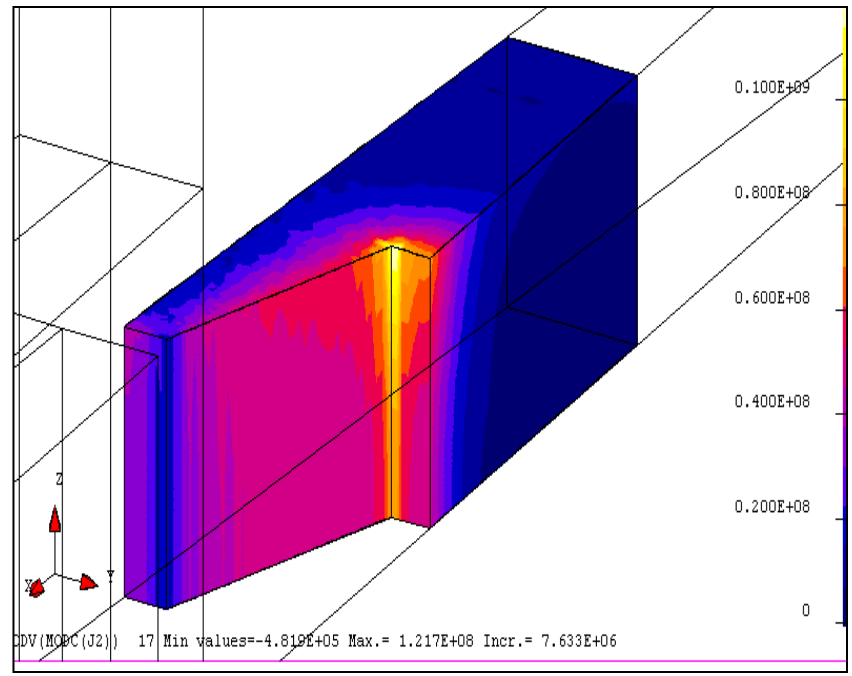
Source: Ajax Tocco Magnethermic

Current Density Distribution in Gear Tooth



Sketch of gear heating in a single-turn inductor

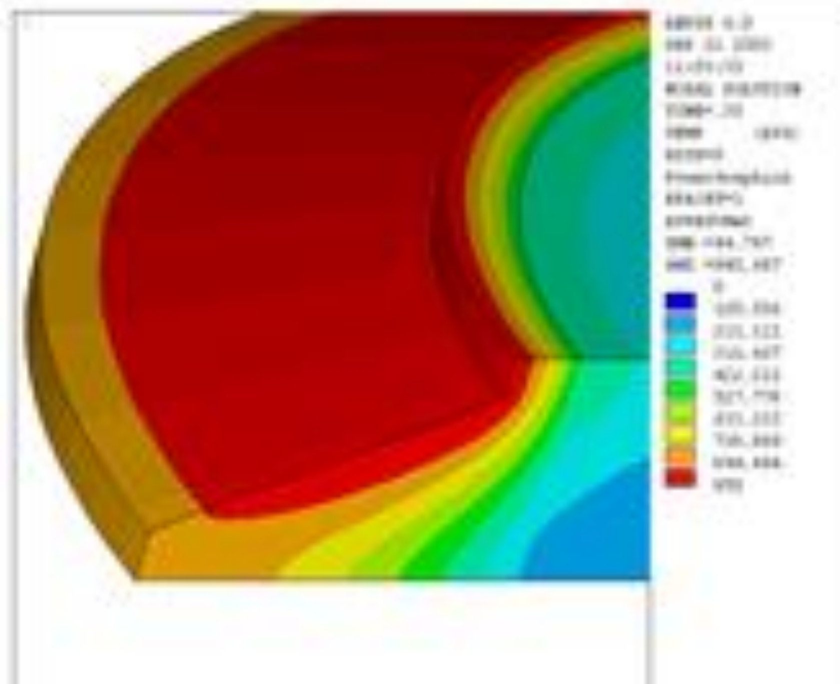
Source: Ajax Tocco Magnethermic



3D simulation of ¼ of gear tooth; program Flux3D

Source: Fluxtrol. Inc.

Simulation of Dual Frequency Hardening of Worm Gear



Right – simulated temperature distribution (ETP, Hanover)
Left – experimental sample (Eldec Induction)

Conclusions

Advantages:

- Fast processing with individual control
- Carbon and low alloyed steels may be used
- Favorable stress distribution may be created
- Low distortion due to local heating
- Big energy savings
- Environment friendly process
- Possibility of in-line processing
- Very large parts may be treated

Disadvantages:

- Process must be individually developed for each type
- Difficult to harden complicated gear types

Quote

"I have been amazed at the testing results of the components that have broken many of the established rules of structure, carbon level, hardness, etc., of the component attributes" – Dick Collins, Borg Warner Automotive, talking about induction hardened parts

FLUXTROL® Inc.
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