MetAGEAR project activities – work package 3

Surface treatments and coatings for gears

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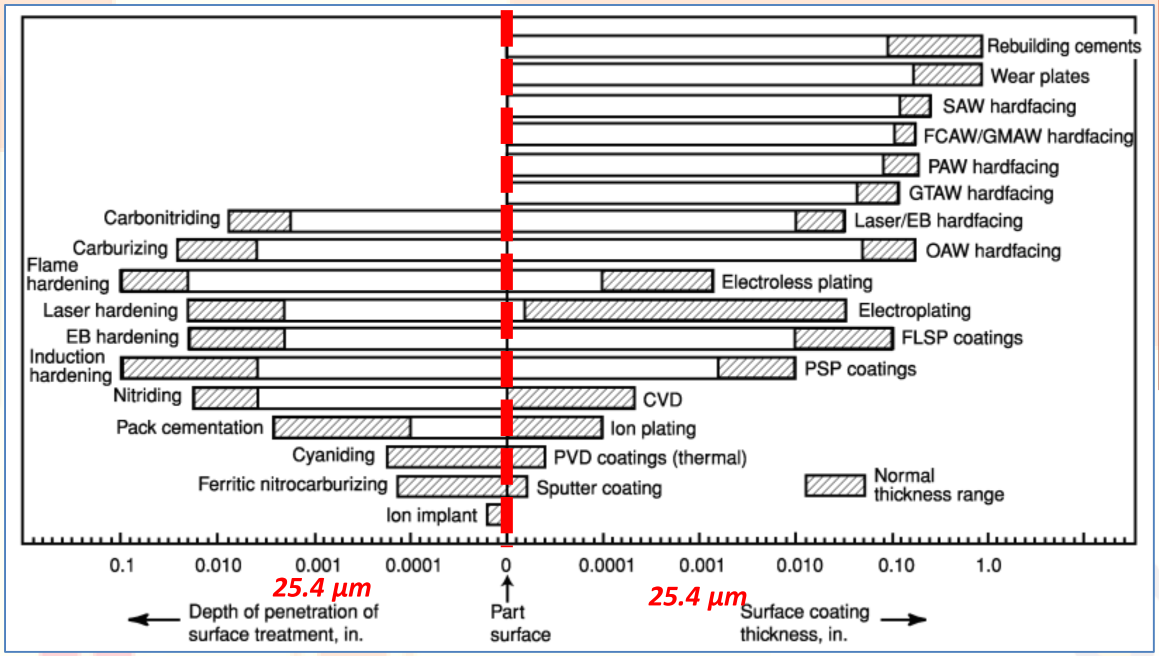
WORK PACKAGE 3 – MAIN ACTIVITIES

1) ***Development and optimization of thermochemical processes*** for the enhancement of the tribological performance

2) ***Development and optimization of vapor deposited films (PVD, PECVD)*** for the enhancement of wear resistance and friction reduction

solid state diffusion ***into*** the material ➔ strengthening by solid solution and precipitation



J. R. Davis, Surface Hardening of Steels, ASM International, 2002

vapor diffusion of the coating material towards the material surface ➔ deposition of a solid film ***onto*** the component

morphological change

3) ***Development of surface patterning techniques*** for the enhancement of the tribological performance

SELECTION OF THE SUBSTRATE MATERIAL

- ***Steel*** gears have the greatest strength per unit volume and the lowest cost per pound
  (from S. P. Radzevich, Dudley's Handbook of Practical Gear Design and Manufacture, 3rd Ed., 2016, CRC Press)

- Some of the ***more important requirements*** for gear steels are their:

1. *Processing characteristics* (for example, hardenability and machinability)
2. **Response to heat treatment** (for example: through-hardening, carburizing, nitriding, carbonitriding, and induction and flame hardening)
3. **Resistance to tooth bending fatigue**—both low-cycle ($\leq 10^5$ cycles to failure) and high-cycle ($>10^5$ cycles to failure) fatigue
4. **Resistance to surface-contact (pitting) fatigue**
5. **Resistance to rolling contact fatigue**
6. **Resistance to wear**
7. Their hot hardness
8. Their bending strength and bend ductility
9. Their toughness, both impact toughness and fracture toughness

(from J. R. Davis, Gear – Materials, Properties, and Manufacture – 2005, ASM International)

The most commonly used ferrous alloys are the wrought surface-hardening and through-hardening carbon and alloy steels.

(from J. R. Davis, Gear – Materials, Properties, and Manufacture – 2005, ASM International)

\+ Bonfiglioli Forever Forward

According to UNI-EN 10084

17NiCrMo6-4

20MnCr5

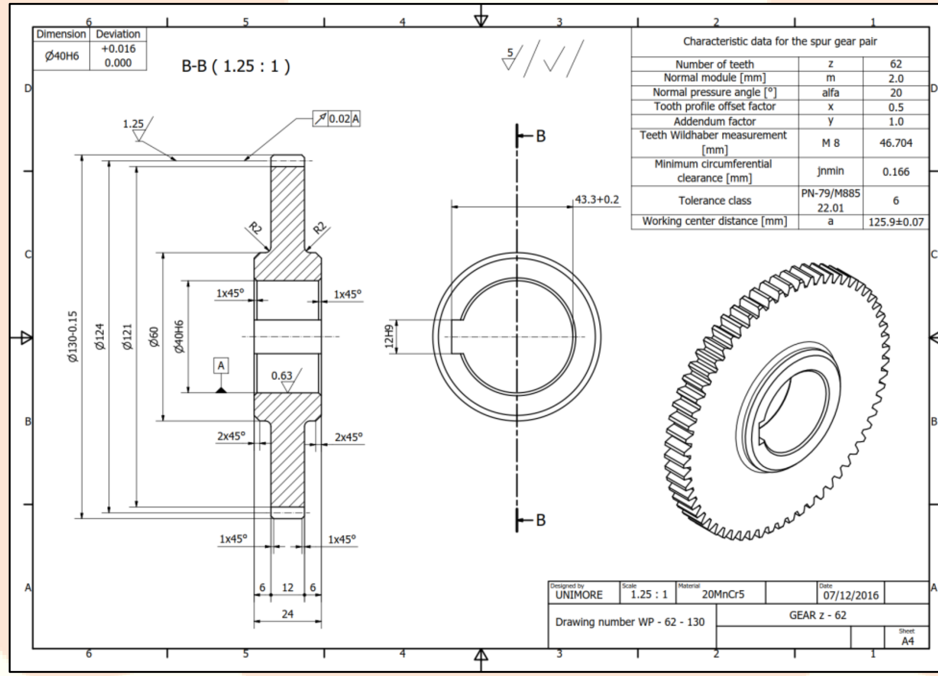
WORK PACKAGE 3 – WORKING FLOW - 1

Gear test rig developed in *work package 1*

*Technical requirements for the **gear design*** to be manufactured in 20MnCr5 steel

Surface treatments and coatings studied in *work package 3*

*Technical requirements for the **gear microstructure and surface roughness*** to be manufactured in 20MnCr5 steel



The microstructure of the gears must be suitable for the following hardening treatments

Hardening & tempering («bonifica»)

The surface roughness will change anyway after the hardening treatments

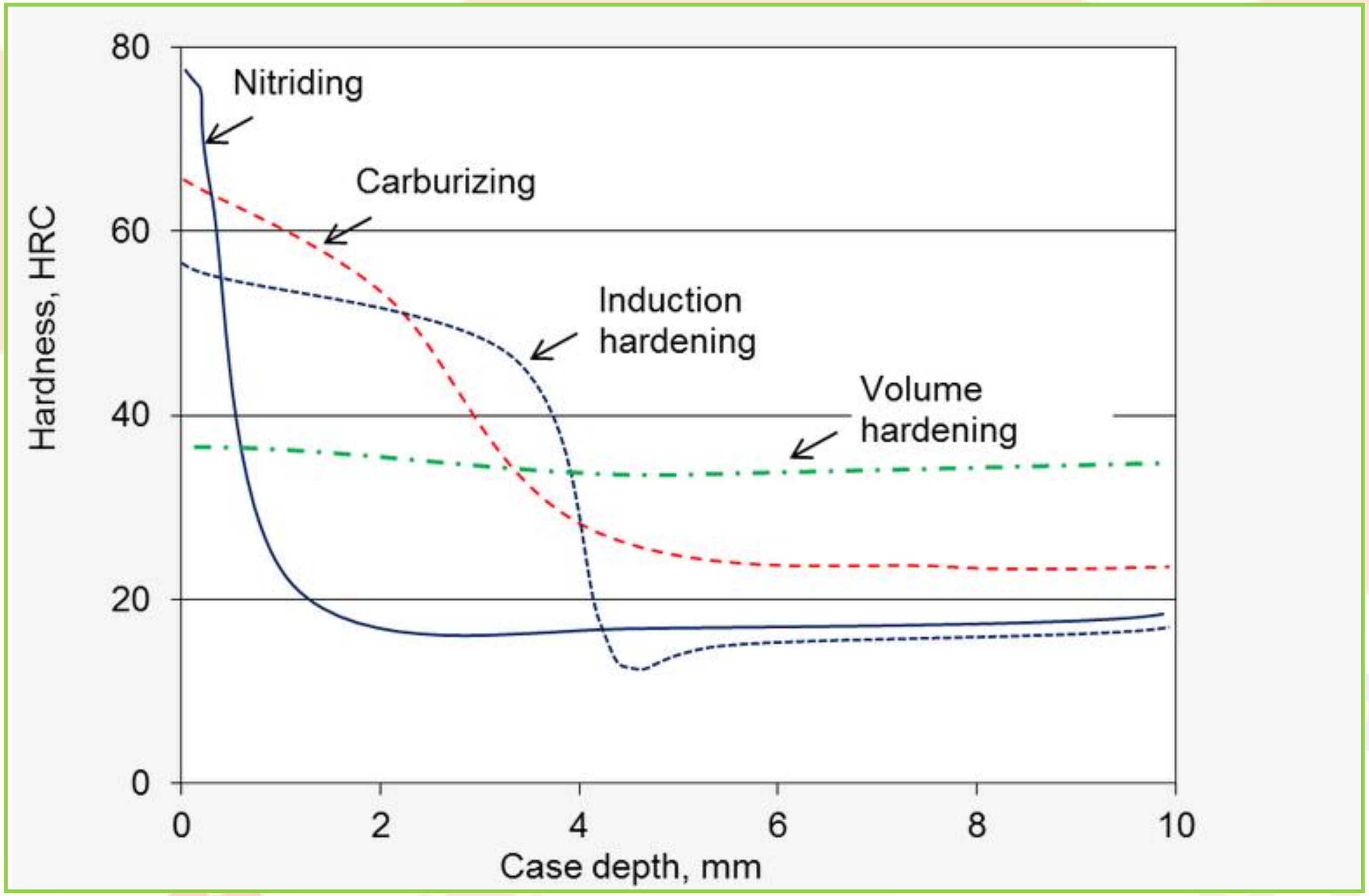
Grinding suitable for coatings or patterning will be carried out *after* surface hardening

MetAGEAR · InterMech Mo.Re. · SIR · Bonfiglioli Forever Forward · DEMOCENTER · MechLav Laboratorio per la Meccanica Avanzata

WORK PACKAGE 3 – THERMOCHEMICAL TREATMENTS

SOLUTION 1

Case-hardening treatments (carburizing and nitriding) were selected *in order to increase the surface hardness and wear resistance, preserving high toughness*



Heat Treatment – Conventional and Novel Application,
Frank Czerwinski, September 2012 INTECH

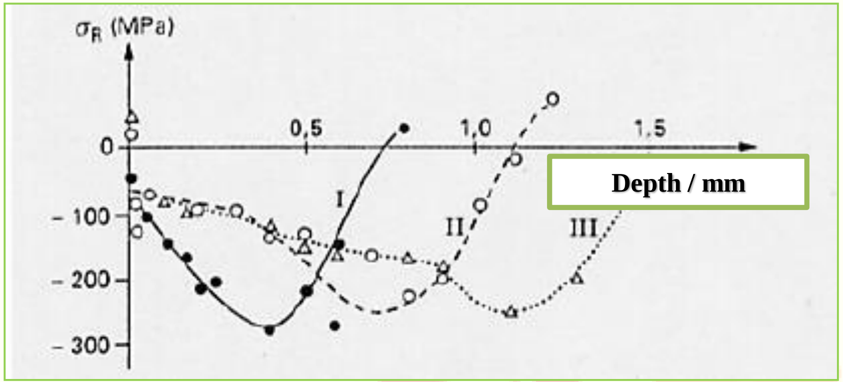
THERMOCHEMICAL TREATMENTS

SOLUTION 1

CARBURIZING

1) Heating at T > A_{c3} in carburizing atmosphere (usually 4-8 h)
2) First quenching
3) Heating at T > A_{c1}
4) Second quenching

The surface region affected by *carbon diffusion* undergoes martensitic trasformation → ***high hardness and compressive residual stresses***



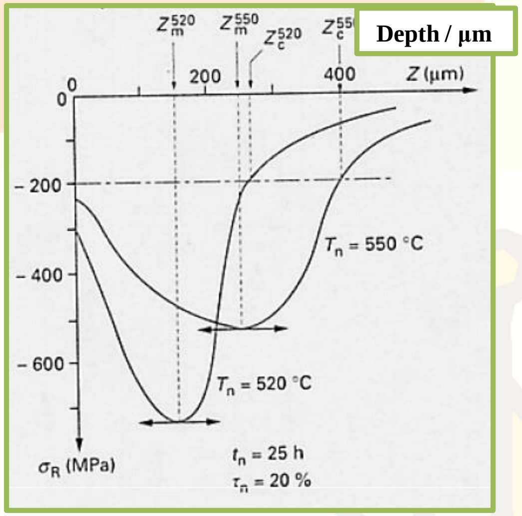
Compressive residual stresses obtained after carburizing (at different time of treatments)

NITRIDING

1) Heating at T < A_{c1} (usually 500-550°C) in nitriding atmosphere for long time (usually > 20h)
2) Cooling

Formation of iron nitrides (and nitrides of alloying elements, like Al, Cr, Mo) in the surface region affected by *nitrogen diffusion* → ***high hardness and compressive residual stresses***

HIGH FATIGUE RESISTANCE

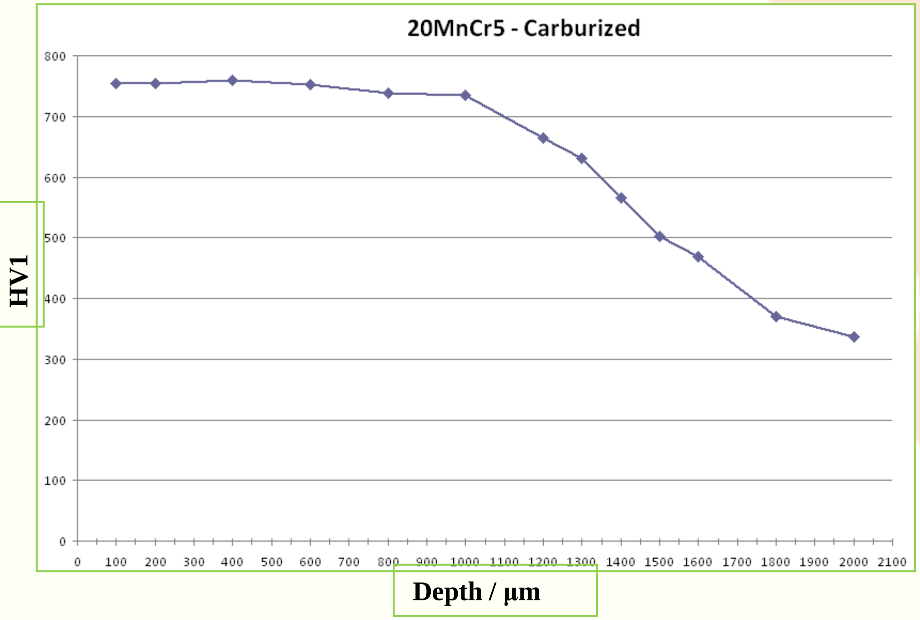


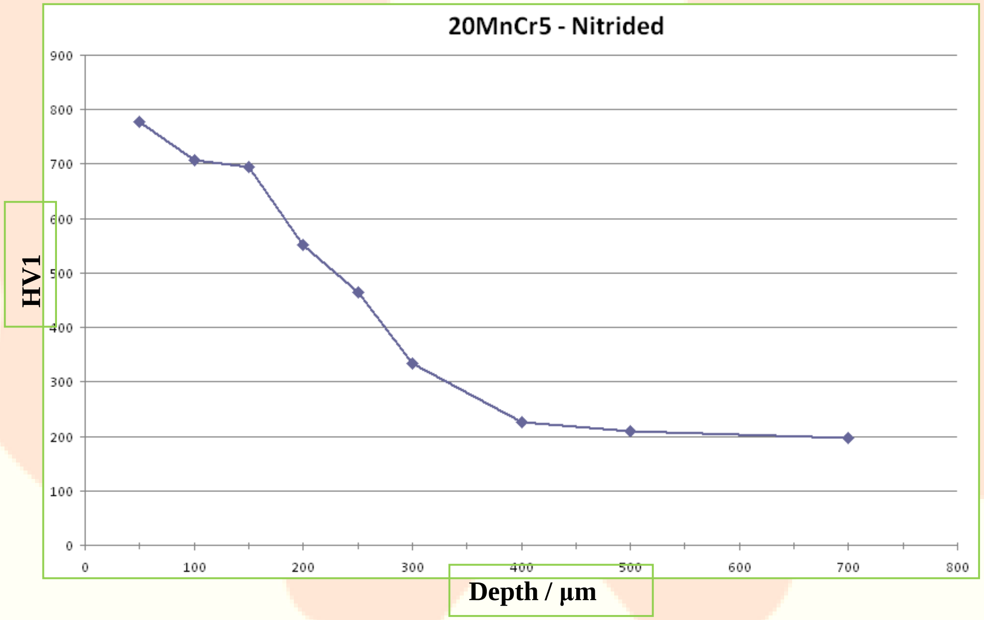
Compressive residual stresses obtained after nitriding (at different temperature)

THERMOCHEMICAL TREATMENTS: preliminary results

SOLUTION 1

HV_1 depth profiles obtained with optimized condition of carburizing and nitriding on the selected steel





Both the treatments preserve the toughness of the steel

The depth profile obtained with carburizing is smoother

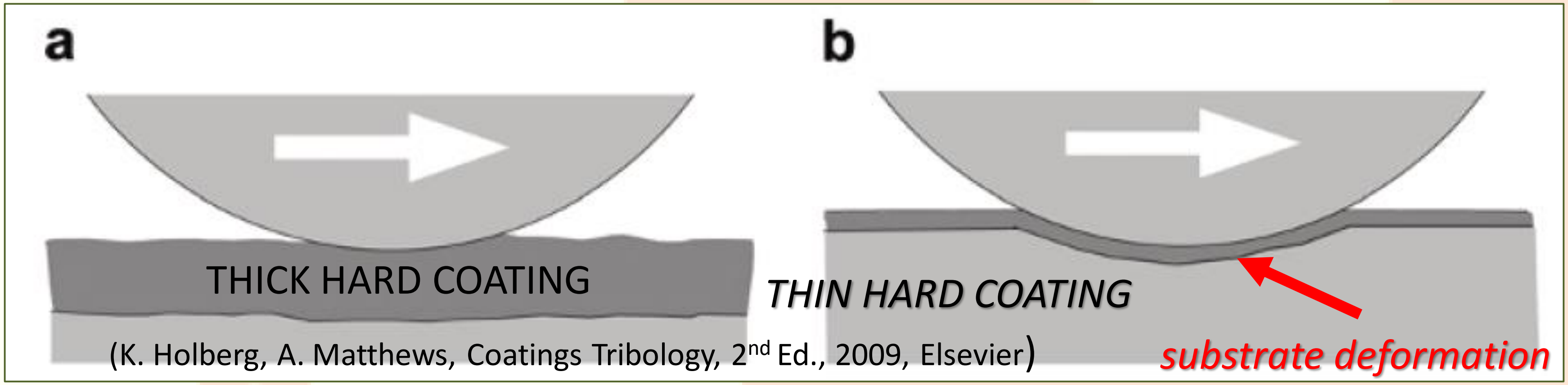
Nitriding preserve the original bulk-hardness of the material

Nitriding allow higher surface hardness (subsurface hardness is not plotted)

THE IMPORTANCE OF SUBSTRATE HARDENING FOR COATINGS

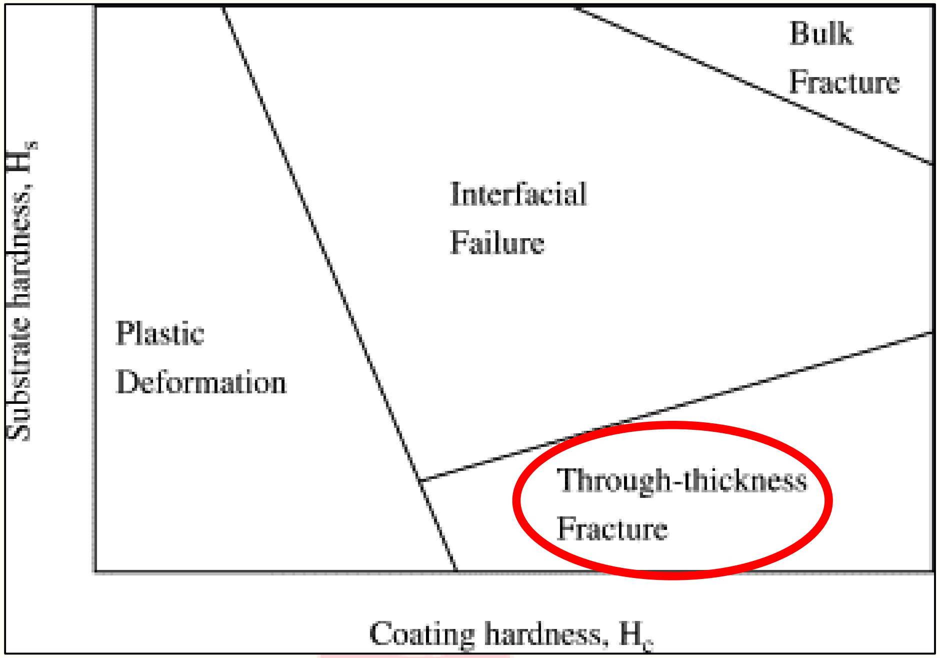
SOLUTION 2

*The coating must be **thin** to respect tolerances*, then, ***the technical requirement, when a hard film is applied, is a hard substrate to carry the load.***



(K. Holberg, A. Matthews, Coatings Tribology, 2nd Ed., 2009, Elsevier)

A thin hard coating on a untreated steel would easily fracture under the applied load



- In the various combinations of treatments/coatings, *coated untreated gears* will ***not be*** studied
- ***The aim is to understand if an added layer can improve the performance of hardened gears***

S. J. Bull, E. G. Berasetegui, Volume 39, Issue 2, February 2006, Pages 99–114, Tribology International

COATED GEARS

SOLUTION 2

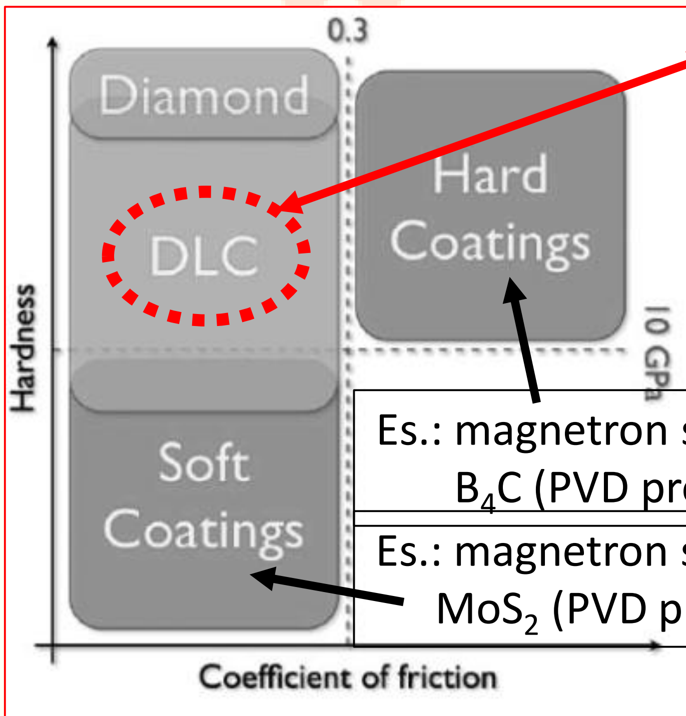
The potential advantages of using surface coatings on gears are:

(K. Holberg, A. Matthews, Coatings Tribology, 2[nd] Ed., 2009, Elsevier)

- control of the running-in process,
- prevention of scuffing or scoring with wear-resistant ***low-friction coatings***,
- *increasing rolling contact fatigue life by surface stress level reduction* or surface strengthening
- decreasing the noise level using a soft coating.

Technical requirement: *the coating must be hard and provide a low friction coefficient*

Technical requirement: *the coating process temperature must prevent microstructural changes and distortion in the hardened gears*



Diamond-Like Carbon

Es.: magnetron sputtered B_4C (PVD process)

Es.: magnetron sputtered MoS_2 (PVD process)

Pure or metal-doped DLC films are usually deposited < 250°C, both by PECVD (Plasma Enhanced Chemical Vapor Deposition) or PVD (Physical Vapor Deposition)

The thin coatings studied in this project are all carbon-based, vapor deposited films, i.e. **Diamond-like Carbon**

(C. Donnet et al., Tribology of Diamond-Like Carbon Films, 2008, Elsevier)

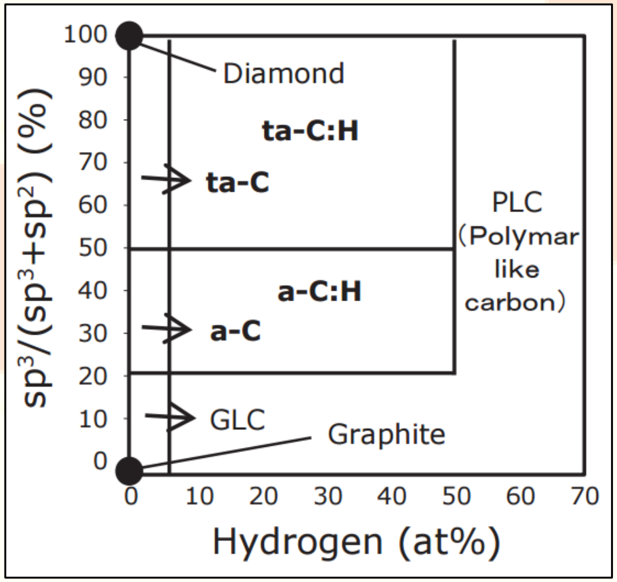
DIAMOND-LIKE CARBON FILMS

SOLUTION 2

"…Despite the ***DLC films*** good results, PVD/PECVD coating technology has not been established in gear transmission technology yet. The use of a PVD/PECVD coating leads to higher component costs and longer manufacturing time…."

C. Brecher et al., Influence of surface finishing on the load capacity of coated and uncoated gears, AGMA FTM 2015

« diamond»



« graphite»

Moriguchi et al., SEI TECHNICAL REVIEW · NUMBER 82 · APRIL 2016

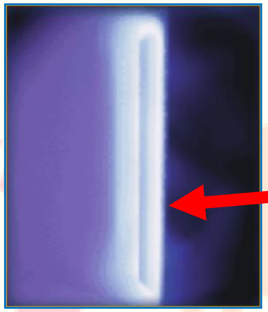
Diamond-like Carbon films are amorphous carbon layers which cannot be «diamond», because they are deposited at low temperatures and pressure.

- They are made of «3D» bonds (sp^3, like in diamonds) and «2D» bonds (sp^2, like in graphite)
- *The coating properties can be tuned* by modifying <u>the deposition parameters</u> and/or <u>doping the film with metals</u>

<u>PECVD (Plasma Enhanced Chemical Vapor Deposition)</u>

Hydrocarbons are introduced as gas precursor in the deposition chamber, where a vacuum << mbar is present. *A plasma gas is formed and the hydrocarbon molecule partially broken => **C & C-H => a-C:H***

DLC films typical manufacturing ***batch*** processes



<u>Sputtering PVD (Physical Vapor Deposition)</u>

Argon is introduced as sputtering gas in the deposition chamber, where a vacuum << mbar is present and a **graphite solid target is charged negatively**. *A plasma gas is formed and the Ar gas erodes carbon form the target=> **C => a-C or ta-C***

METAL DOPED DIAMOND-LIKE CARBON FILMS

SOLUTION 2

«*Although the gear industry has been slow to implement gear coatings*, there have been a fairly wide variety of coating methods/materials that have been used to coat gears…”…”…***WC/C coatings*** are applied by the reactive sputtering PVD process. Application areas, both present and potential, for these coatings include motorcycle gears, concrete mixer gears, bevel gear actuators…

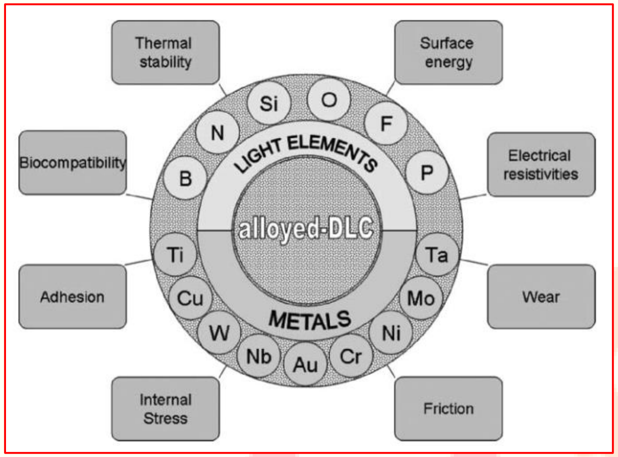
(from J. R. Davis, Gear – Materials, Properties, and Manufacture – 2005, ASM International)

“*Coatings are typically viewed as a failure mode waiting to happen.*” … “…most manufacturers are unwilling to talk about the coatings they use, because they don’t want their competitors to know how they don’t want their competitors to know how they achieve their performance level…one good example are auto racing teams who started employing ***WC/C films***…”

(from W.R. Scott, Myths and Miracles of Gear Coatings, Gear Technology, July/Aug 1999, p 35–44)

By alloying elements to DLC, different film properties such as thermal stability, hardness, internal stress, tribological properties, electrical conductivity, surface energy and biocompatibility *can be continuously adapted to a desired value for specific applications.*

WHICH DLC DOPING ELEMENTS CAN BE USEFUL TO GEAR APPLICATIONS ?



Alloying with **transition metals** helps in reducing *excessive compressive stresses*

Alloying with **carbide formers transition metals** *increases DLC toughness* thanks to the formation of nanosized cabride inclusions

W ➔ W-C:H

NOTE: equivalent to WC/C films

(C. Donnet et al., Tribology of Diamond-Like Carbon Films, 2008, Elsevier)

WC/C FILMS COATED GEARS

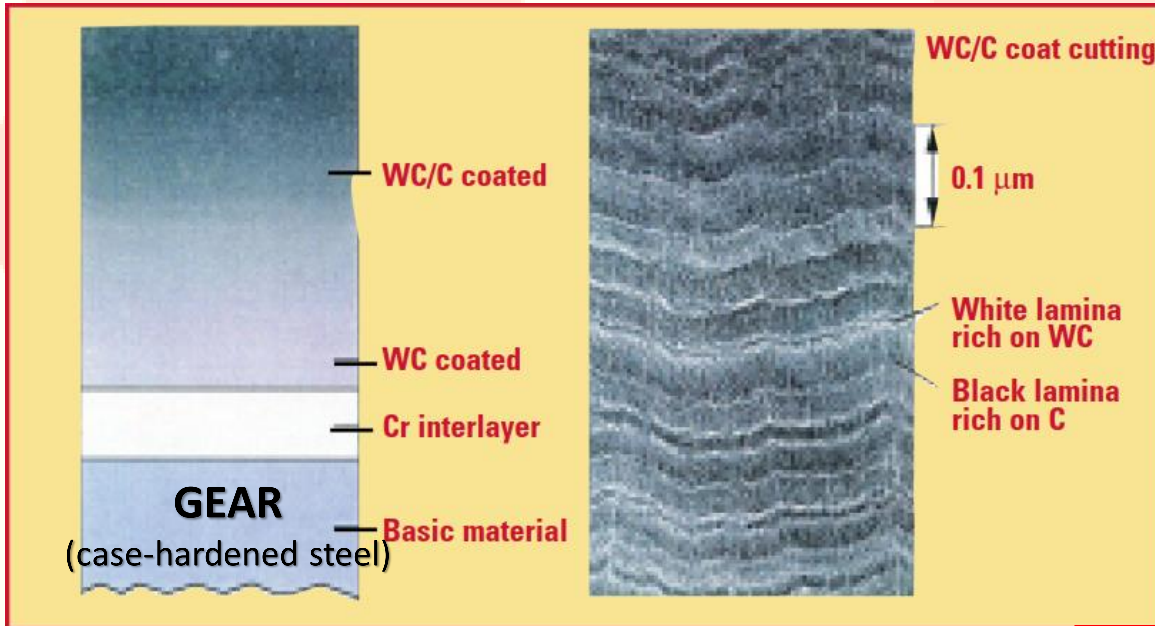
SOLUTION 2

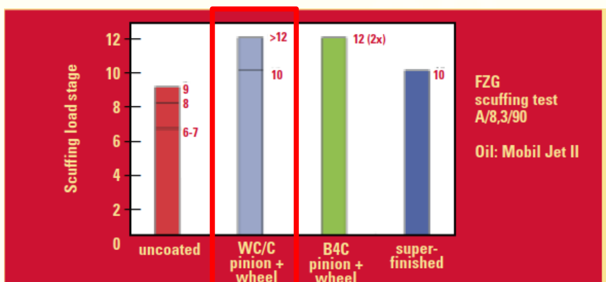
A «state of the art» advanced WC/C film is usually a multilayer, where <u>both PVD and PECVD processes are combined together</u> *in the same deposition chamber*.

F. Joachim et al., Influence of coatings and Surface improvements on the Lifetime of gears, July/August 2004, Gear Technology

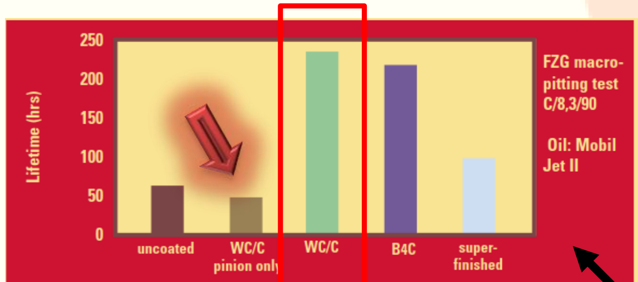
Sputtering PVD & PECVD *- a **WC target** is eroded by Ar^+ ions and simultaneously **C_2H_2 (acetylene)** is introduced and the molecule broken*

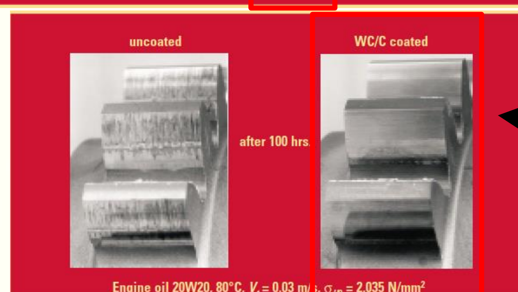
Sputtering PVD *- a **Cr target** is eroded by Ar^+ ions to deposit the adhesion layer*





SCUFFING





MACROPITTING – MICROPITTING

LOW SPEED WEAR RATE

NOTE: ***superfinishing*** of hardened steel + coating ➔ service life * 10-15

SOLUTION 2

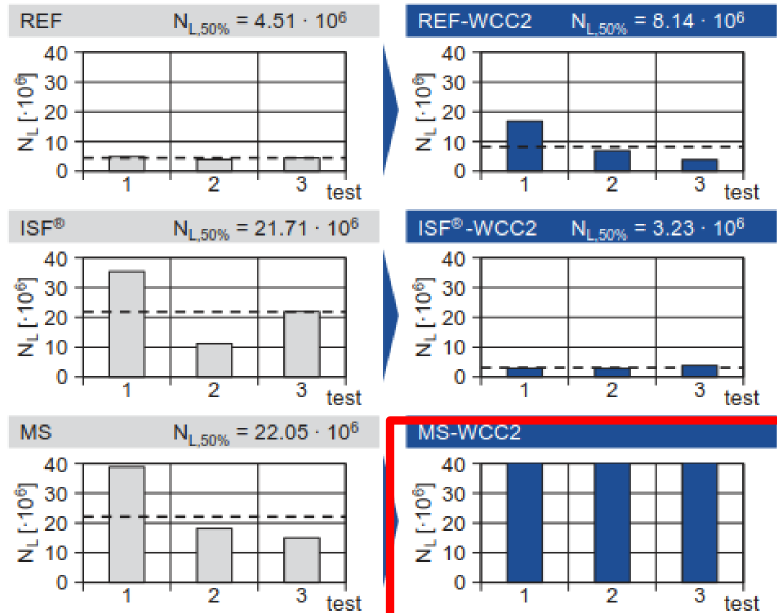
WC/C FILMS COATED GEARS

Back-To-Back Test Rig

case hardened

- **Test Gears**
  - Type: FZG-C_{mod}
  - Material: 16MnCr5E
- **Test Conditions**
  - n_1 = 2250 min^{-1}
  - T_1 = 450 Nm
  - T_{Oil} = 90 ± 3 °C (sump)
  - Oil: SAE 75W add.
- **Surface Finishing**
  - REF = Profile Grinding
  - ISF® = Isotr. Super Finishing
  - MS = Blast Cleaning
- **PVD-Coating**
  - Pinion: WCC = Balinit C
  - Gear: WCC = Balinit C

---- $N_{L,50\%}$



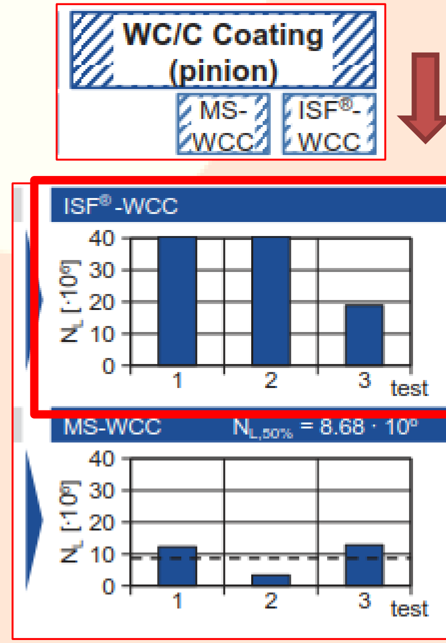
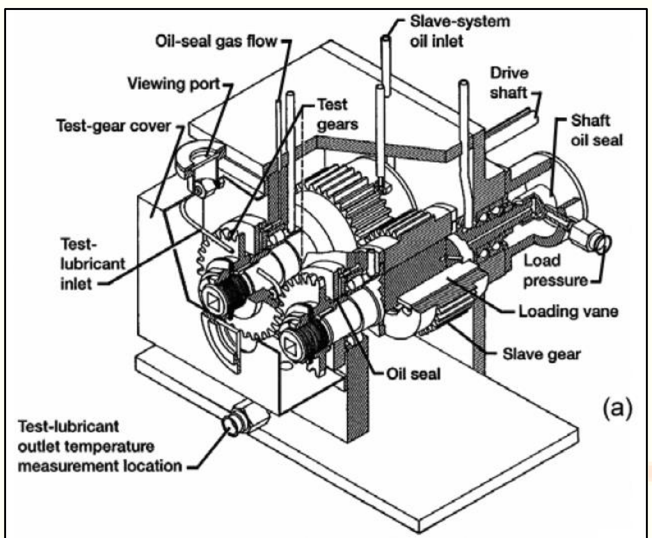


Figure 4: Results from pitting tests with pinion coated

C. Brecher et al., Influence of surface finishing on the load capacity of coated and uncoated gears, AGMA FTM 2015

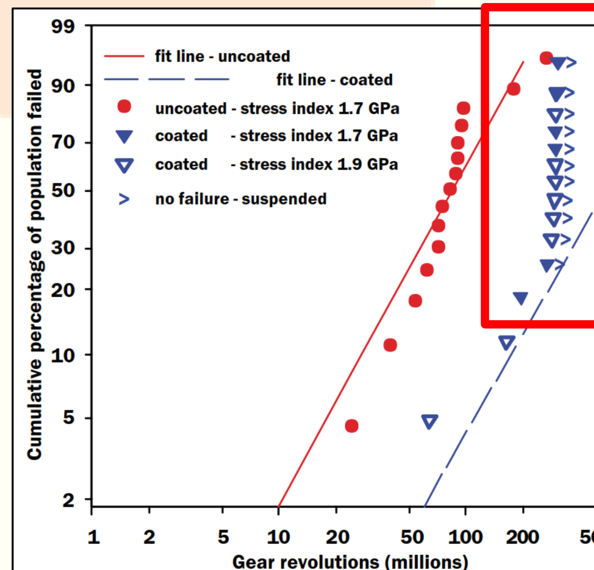


uncoated = carburized

Gear type	Hertz stress index (GPa)	Number of tests	Number of failures	Number without failure (after 275×10^6 revolutions)
uncoated	1.7	15	15	0
coated	1.7	6	1	5
	1.9	8	2	6

TABLE 5: SUMMARY OF TEST RESULTS

Gear type	Weibull slope	Scale (10^6 cycles)	10-percent live (10^6 cycles)	50-percent life (10^6 cycles)
uncoated	1.7*	105	28	83
coated	1.7*	673	180	530



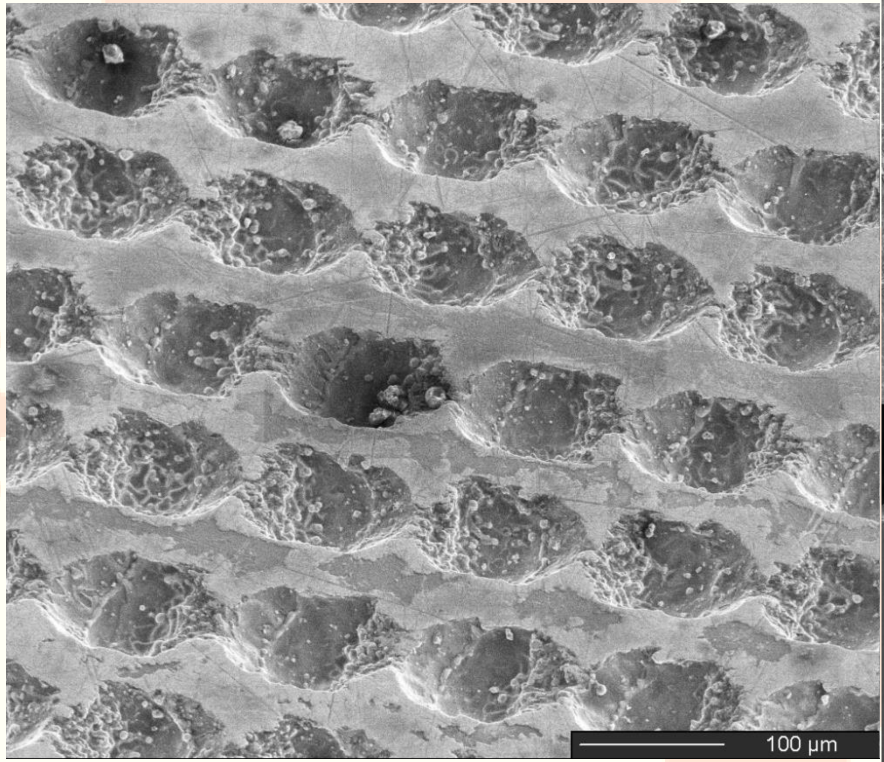
T. L. Krantz et al., Coatings applications for spur gears, Gears solutions, 2007

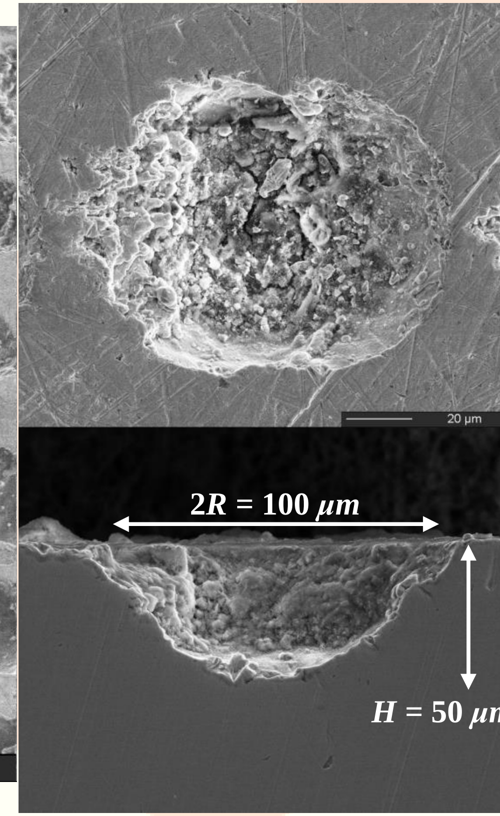
SURFACE TEXTURING

SOLUTION 3

"Artificially generated micro-features could significantly improve friction and wear behaviours of mating surfaces, optimizing the involved lubrication mechanisms" [1-4]

1. Hamilton et al., *J. of Basic Eng.* (1966)
2. Etsion, *J. of Tribology* (2005)
3. Borghi et al., *Wear* (2008)
4. Gualtieri et al., *Trib. Int.* (2009)





ROLES:
- debris *trap*
- lubricant *reservoires*
- hydrodynamic *pockets*

EFFECTS:
- ↓ frictional dissipations
- ↑ service life

BENEFICIAL

ROLES:
- *hedging pressure* sites
- *cavitation* sites

EFFECTS:
- ↓ load-carrying capacity
- ↑ shear stresses

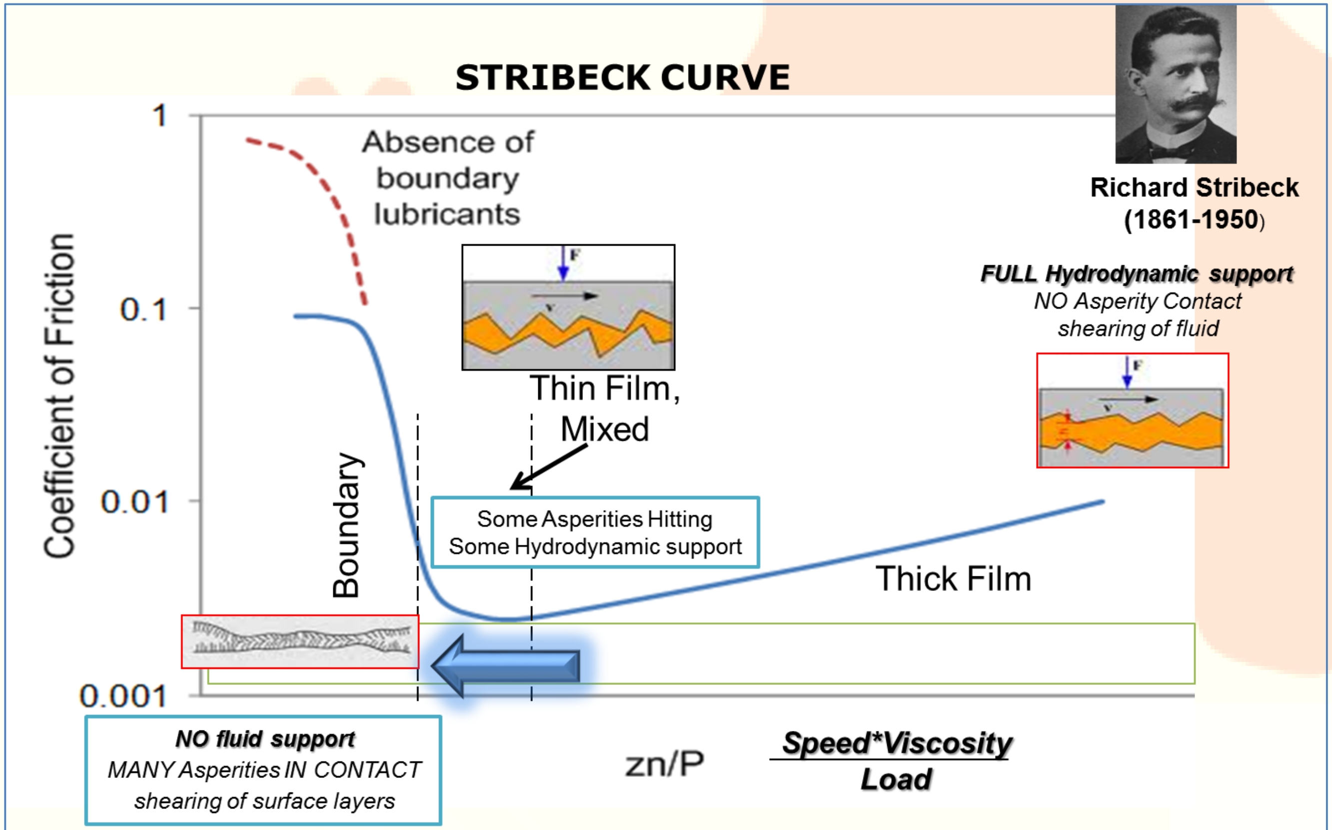
DETRIMENTAL

VS

COMPETITION AMONG SCALING EFFECTS

SURFACE TEXTURING and FRICTION

SOLUTION 3



*A beneficial patterning should shift **the boundary lubrication limit towards lower values***

CRITICAL RISKS

- What about patterning a geometrically complex shape like a gear ? ➔ *Shadowing effects*
- What about surface finishing after patterning ➔ *bulges*

WORK PACKAGE 3 – WORKING FLOW - 2

Summing up, these are the samples which will be studied and tested in MetAGEAR project aiming at an increased performance.

Manufacturing of LABORATORY SAMPLES

Hardening & Tempering

grinding down to 0.4 micron

reference for comparison

Thermochemical treatments
- Carburizing
- Nitriding

2 kinds of samples

grinding down to 0.4 micron

Coated gears
- WC/C-H – «a»
- WC/C-H – «b»

Morphologically modified gears
- Topography «a»
- Topography «b»

Gear test rig (WP 1)

DATA INPUT FOR DATABASE (WP1)

The winning combinations will be applied to COMMERCIAL GEARS to be tested in

Bonfiglioli
Forever Forward

Thank you for your kind attention!

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