Tribology and Surfaces Interactions Summer School
Viège, 28 Juillet 2025

Dr. Mousab Hadad

Content

1. Objective
2. Wear rate
3. Fundamentals of erosive and abrasive wear
4. Wear events and approaches
5. Several techniques to minimize wear
6. Coating solutions: thermal spray coatings
7. Coating solution against erosion wear: case study
8. Wear of thermal spray coatings
9. Adhesion of thermal spray coating

Content

Wednesday 27 August		Speakers
09:00-09:45	Experimental techniques for tribology	**N. Randall**
09:45-10:30	Experimental techniques for tribology	**N. Randall**
10:30 - 11:00	**BREAK**	
11:00 - 11:45	Tribology of materials	**A. Igual**
11:45 - 12:30	Tribology of materials	**A. Igual**
	LUNCH	
14:00 - 14:45	Surface treatments for tribology	**M. Hadad**
14:45 - 15:30	Surface treatments for tribology	**M. Hadad**
15:30 - 16:00	**BREAK**	
17:30	Rock tribology	**G. Mollon**
18:15-19:00	Rock tribology	**G. Mollon**
19:30	**DINNER**	

1. Objective

The main objective is to explore many potential techniques to minimize

severe wear

2. Wear rate

If you have the mechanical properties of a tribo-pair, can you calculate/foresee the wear rate?

3. Fundamentals of erosive and abrasive wear

3.1 Abrasive wear by plastic deformation

$$\frac{w_v}{s} = k_{ab} \cdot \frac{F_N}{H} \quad *$$

$$k_{ab} = \frac{2.f_{ab} \tan\alpha}{\pi} \quad **$$

$$\frac{k_{ab}}{H} = K \Rightarrow K = \frac{w_v}{S.F_N} \quad \left[\frac{mm^3}{m.N}\right]$$

W_v : the volume loss due to wear, s is the sliding distance

F_N : the normal load on the conical particle

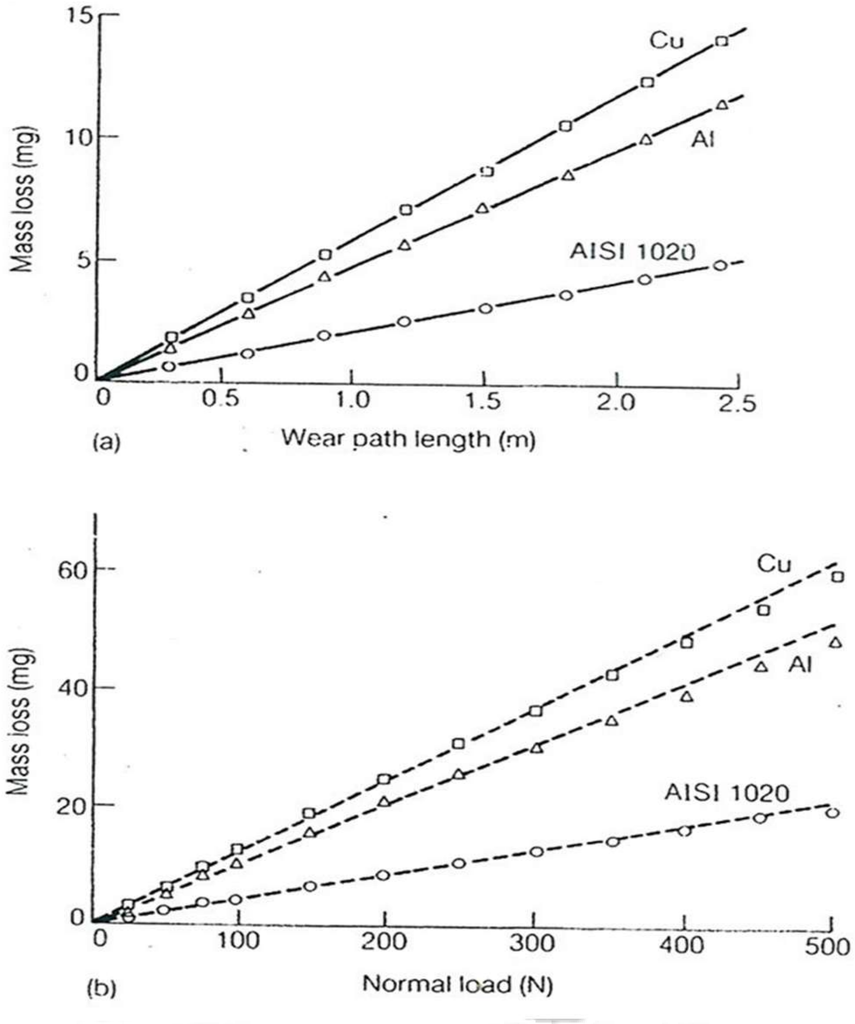
H : the hardness of the wearing surface

α : the attack angle of the abrasive particle

K_{ab} : the wear coefficient (dimensionless)

K : Wear rate $\left[\frac{mm^3}{m.N}\right]$

$$f_{ab} = 1 - \frac{A_1 + A_2}{A_v}$$



* Rabinowich 1965

* Zum Gahr 1987

3. Fundamentals of erosive and abrasive wear

3.2. Abrasive wear by brittle fracture

$$\frac{w_v}{S} = \alpha \cdot \frac{F_N^{5/4}}{K_C^{1/2} \cdot H^{5/8}}$$ **

W_v : the volume loss due to wear

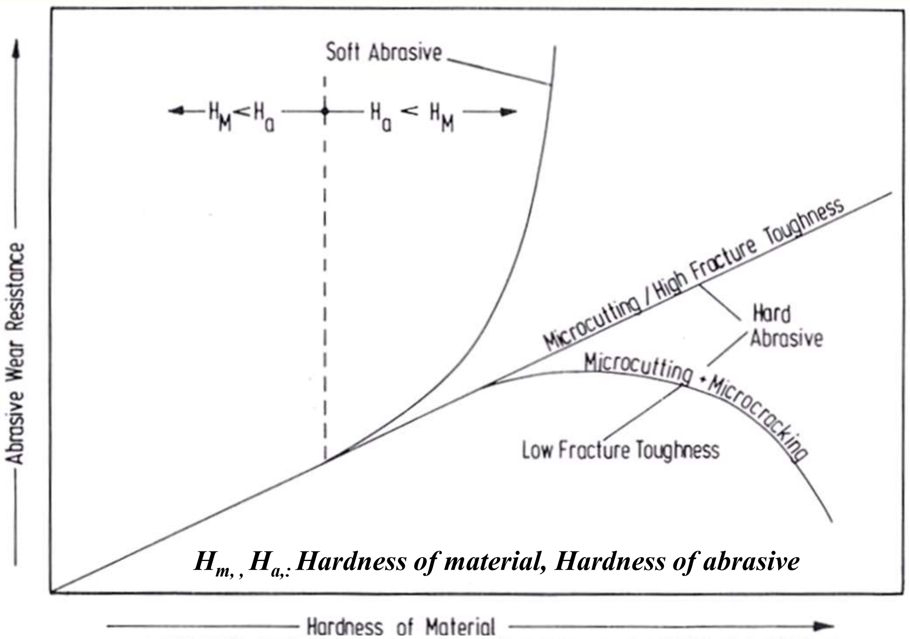
S: the sliding distance

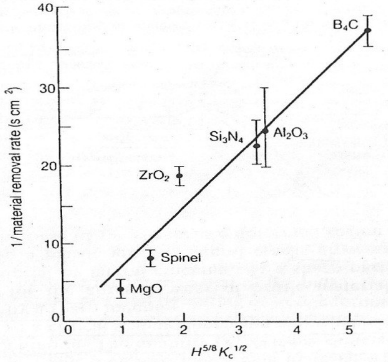
F_N : the normal load on the conical particle

H : the hardness of the wearing surface

α : constant depends on the geometrical conditions

K_c : the fracture toughness of material





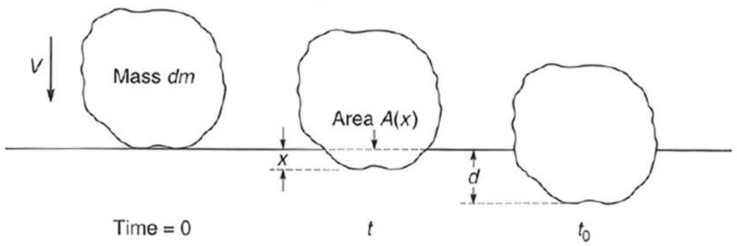
Correlation between the reciprocal of material removal rate in abrasive machining (i.e. two-body abrasion) and the quantity $H^{5/8} K_c^{1/2}$, for several ceramic materials (from Evans A G and Marshall D B, in Rigney D. A. (Ed.), *Fundamentals of Friction and Wear of Materials*, ASM, 1981, pp. 439–452)

* Zum Gahr 1987
** Hutchings 1992

3. Fundamentals of erosive and abrasive wear

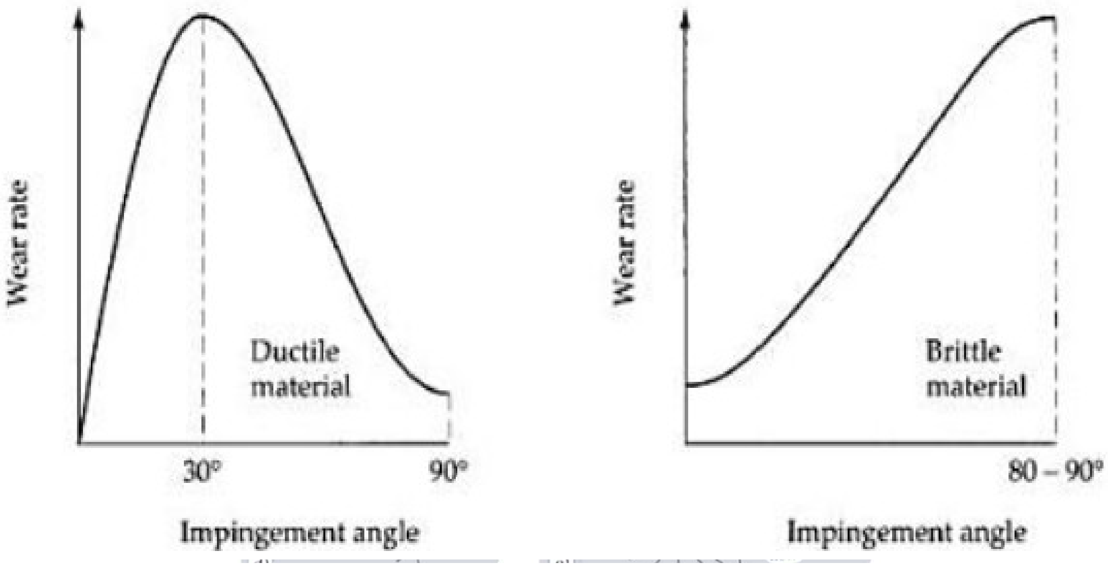
3.3. Erosion wear by plastic deformation

$$w_v = \frac{m_{er}.U^2}{2.H}^{*}$$



$$E = \frac{\text{mass of material removed}}{\text{mass of erosive particles striking}} = \frac{K}{H}.\left[\frac{\rho.U^2}{2}\right]$$

$$E = \frac{K_1.\rho.U^2}{H}.f(\alpha)$$



m_{er} : mass of erodent particle

W_v : the volume loss due to wear

U : Particle velocity

H: Material hardness

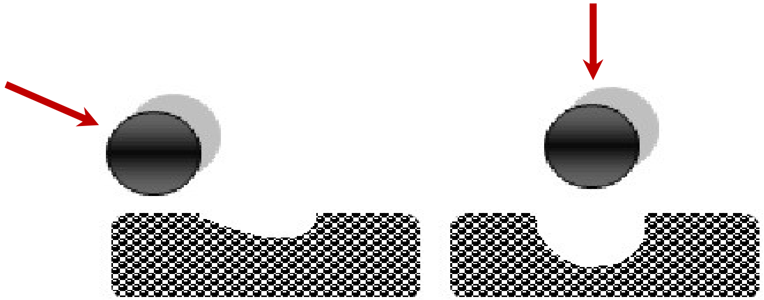
K : dimensionless wear coefficient

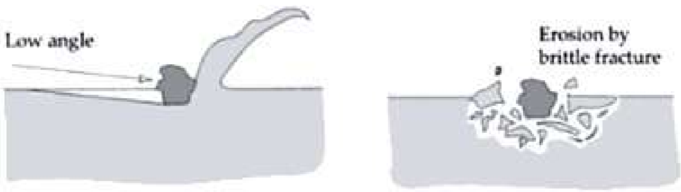
ρ : mass density wear material

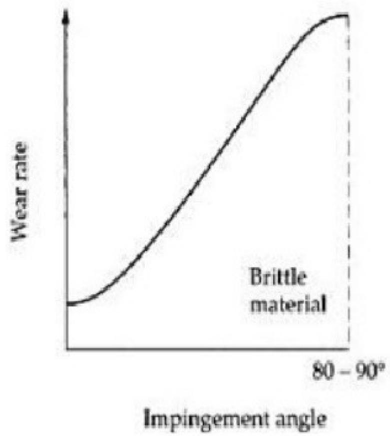
* Hutchings 1992

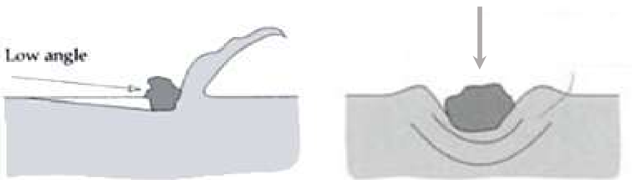
Engineering Tribology (3rd Edition). Gwidon W. Stachowiak and Andrew W. Batchelor. Butterworth-Heinemann, Boston, 2001- Chapter 11

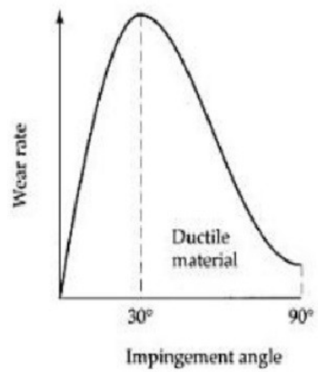
3. Fundamentals of erosive and abrasive wear









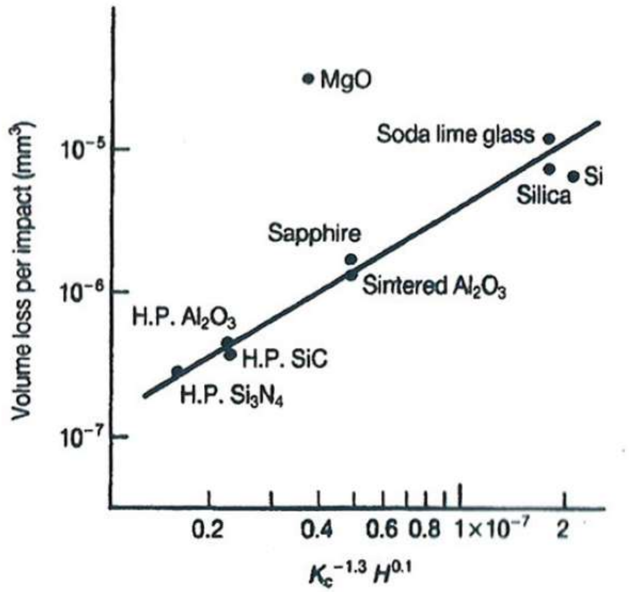


3. Fundamentals of erosive and abrasive wear

3.4. Erosion wear by brittle fracture (semi-empirical)

$$\frac{E}{\rho} \propto r^{0.7}.U^{2.4}.\frac{\sigma^{0.6}.H^{0.1}}{K_c^{1.3}}\ ^{*}$$

r : radius of particle
U : Particle velocity
σ : density of erosive particle in time unite
H: Material hardness
Kc : the fracture toughness of material
ρ : mass density of particle
E: erosion rate (dimensionless)



** As for abrasion, a correlation with function of H and K_{IC}.*
(this hold only for erodent particles which hard enough to cause a lateral fracture)

* Hutchings 1992

3. Fundamentals of erosive and abrasive wear

- ***Parameters selected in erosion wear models (Meng 1995)***

Parameters selected in erosion wear models

	1	2	3	4	5	6		7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22		23	24	25	26	27	28
Density										×							×	×	×				×	×	×	×			×	×
Hardness						×	×					×																		
Moment of inertia									×																					
Roundness						×	×					×			×															
Single mass									×																					
Size			×					×	×	×	×			×			×	×	×	×	×					×			×	×
Velocity	×	×	×	×	×	×	×	×	×	×	×	×	×	×		×	×	×	×	×	×	×	×	×	×	×			×	×
Rebound velocity				×																										
Kinetic energy (KE) of particle																											×			
Density	×	×	×	×		×	×	×	×	×		×			×		×	×	×			×	×		×	×	×		×	×
Hardness						×	×			×		×					×	×	×			×	×	×	×	×			×	
Flow stress	×								×													×								
Young modulus																											×		×	
Fracture toughness																	×	×	×							×	×		×	×
Critical strain																						×						×		
Depth of deformation																												×		
Incremental strain per impact																												×		
Thermal conductivity															×															
Melting temperature															×								×							
Enthalpy of melting															×															
Cutting energy		×		×																										
Deformation energy		×		×																										
Erosion resistance						×	×					×																		
Heat capacity																							×	×						
Grain molecular weight															×															
Weibull flaw parameter			×					×																						
Lamé constant																		×	×											
Grain diameter																											×			
Impact angle	×	×	90	×		×	×	90	×			×	×	×							×	90	90		×					
Impact angle max. wear													×																	
KE transfer from particle to target															×															×
Temperature																							×							
Constant	2	3	3	1	2	10	1	3	2	1	6	1	4	4	1	1	1	1	1	1	4	1	8	1	1	1	[illegible]	[illegible]	[illegible]	[illegible]

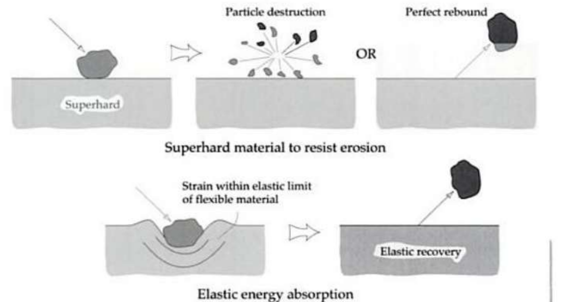


FIGURE 11.37 Comparison of the high and low elastic modulus modes of erosive wear

H.C. Meng, K.C. Ludema, Wear models and predictive equations: their form and content, Wear 181-183 (1995) 443-457

3. Fundamentals of erosive and abrasive wear

	Abrasion	Erosion	
Ductile	$\frac{w_v}{s} = k_{ab}.\frac{F_N}{H}$	$E = \frac{K_1.\rho.U^2}{H}.f(\alpha)$	Hardness
Brittle	$\frac{w_v}{S} = \alpha.\frac{F_N^{5/4}}{K_C^{1/2}.H^{5/8}}$	$\frac{E}{\rho} \propto r^{0.7}.U^{2.4}.\frac{\sigma^{0.6}}{H^{-0.1}.K_c^{1.3}}$	Toughness + Hardness

Hutchings 1992

Rabinowich 1965

Zum Gahr 1987

Engineering Tribology (3rd Edition). Gwidon W. Stachowiak and Andrew W. Batchelor. Butterworth-Heinemann, Boston, 2001-Chapter 11

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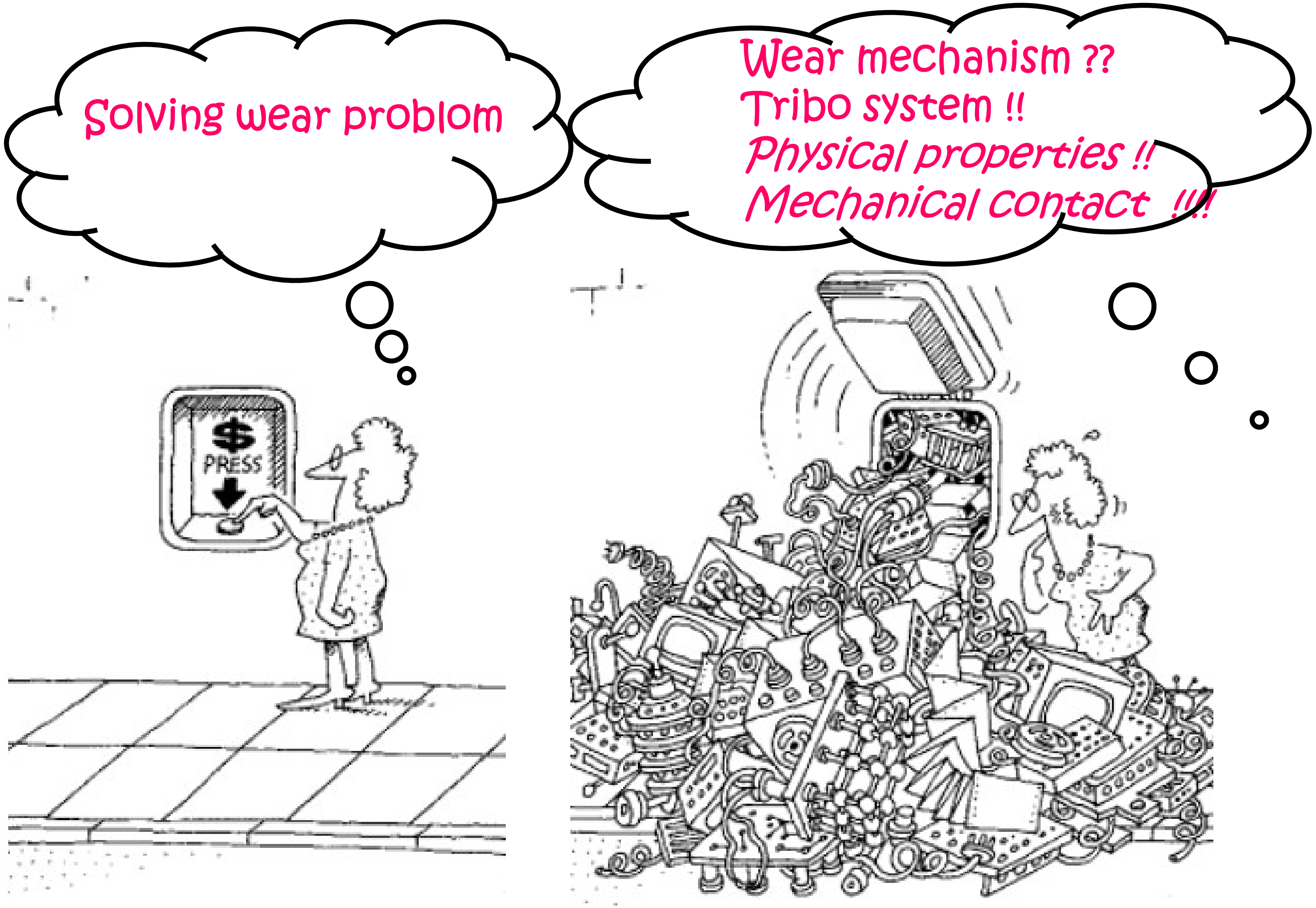
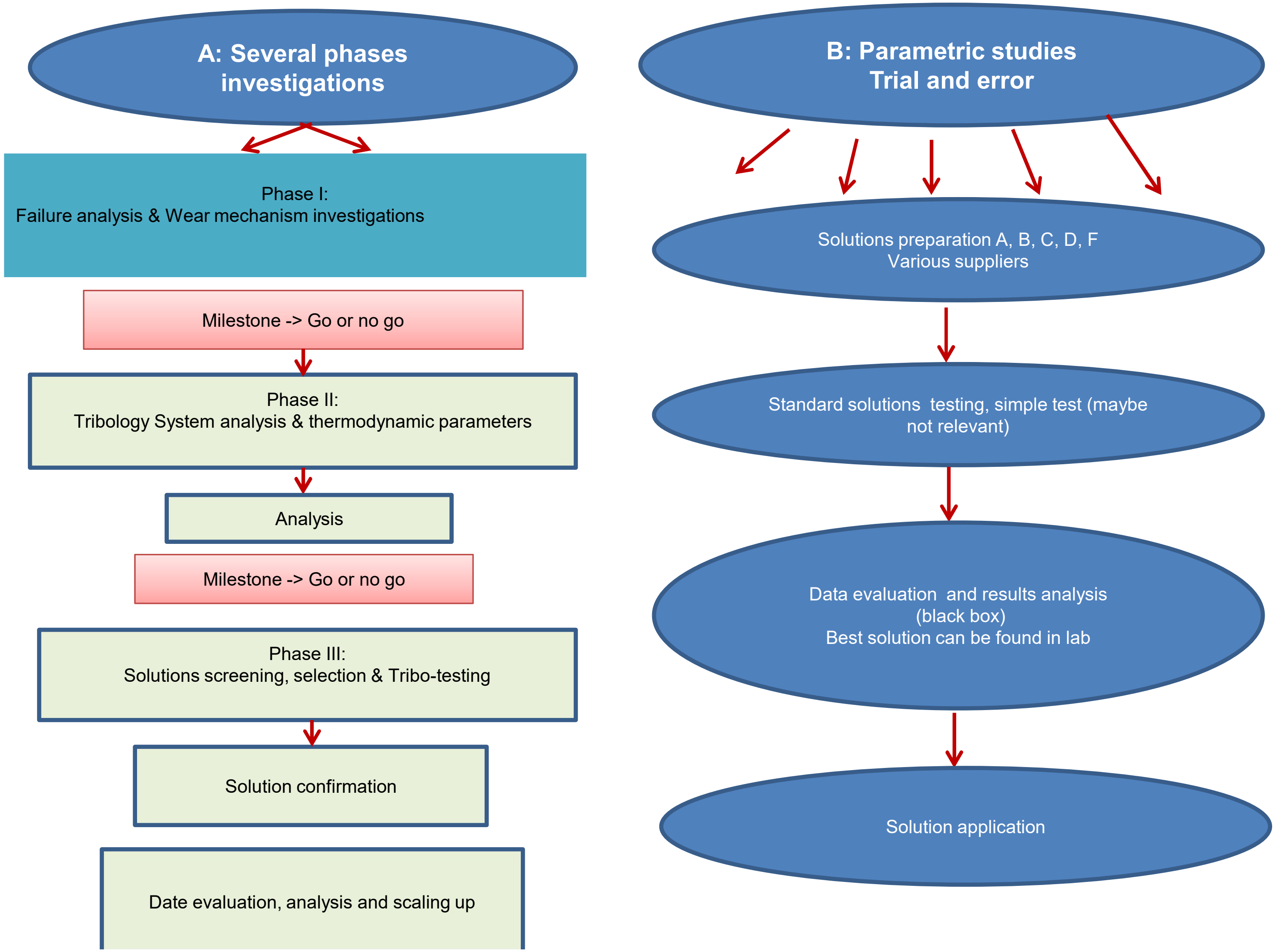
4. Wear events and approaches



Grady Booch - Object-Oriented Analysis and Design With Applications 2nd ED

4. Wear events and approaches



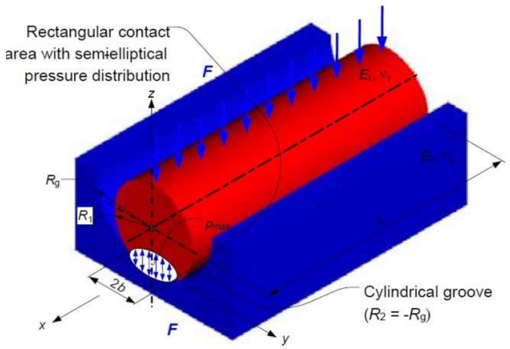
4. Wear events and approaches

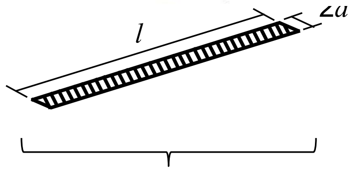
Point of view of the problem provider

Wear is always an unwished event
whatever is the mechanism

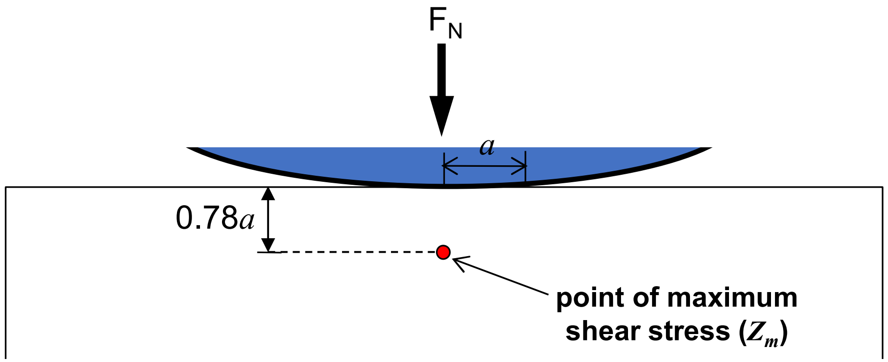
4. Wear events and approaches

Elastic normal contact between a cylinder and a cylinder – Hertz theory





projected contact area



$$a = 1.128\sqrt{\frac{4F}{b} H \frac{R1.R2}{R1 - R2}}$$

Poisson's ratio of cylinder

Poisson's ratio of block

$$\frac{1}{E^*} = \frac{1-\nu_c^2}{E_c} + \frac{1-\nu_b^2}{E_b}$$

reduced elastic modulus

elastic modulus of cylinder

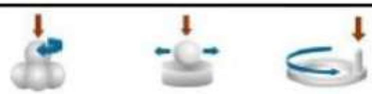
elastic modulus of block

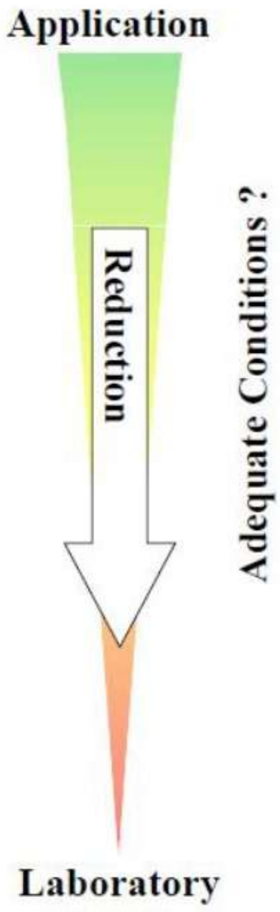
Hertzian Stress	Ph Mpa
Major half axis of contact ellipsis	a mm
Minor half axis of contact ellipsis	b mm
Approach of both bodies	δ mm
Depth for max. shear stress body1	z(τMax_2) mm
Maximal shear stress body 1	τMax_2 Mpa

$$\tau_{\max} = 0.3 p_{\max} \qquad Z_m = 0.78a$$

maximum shear stress

4. Wear events and approaches

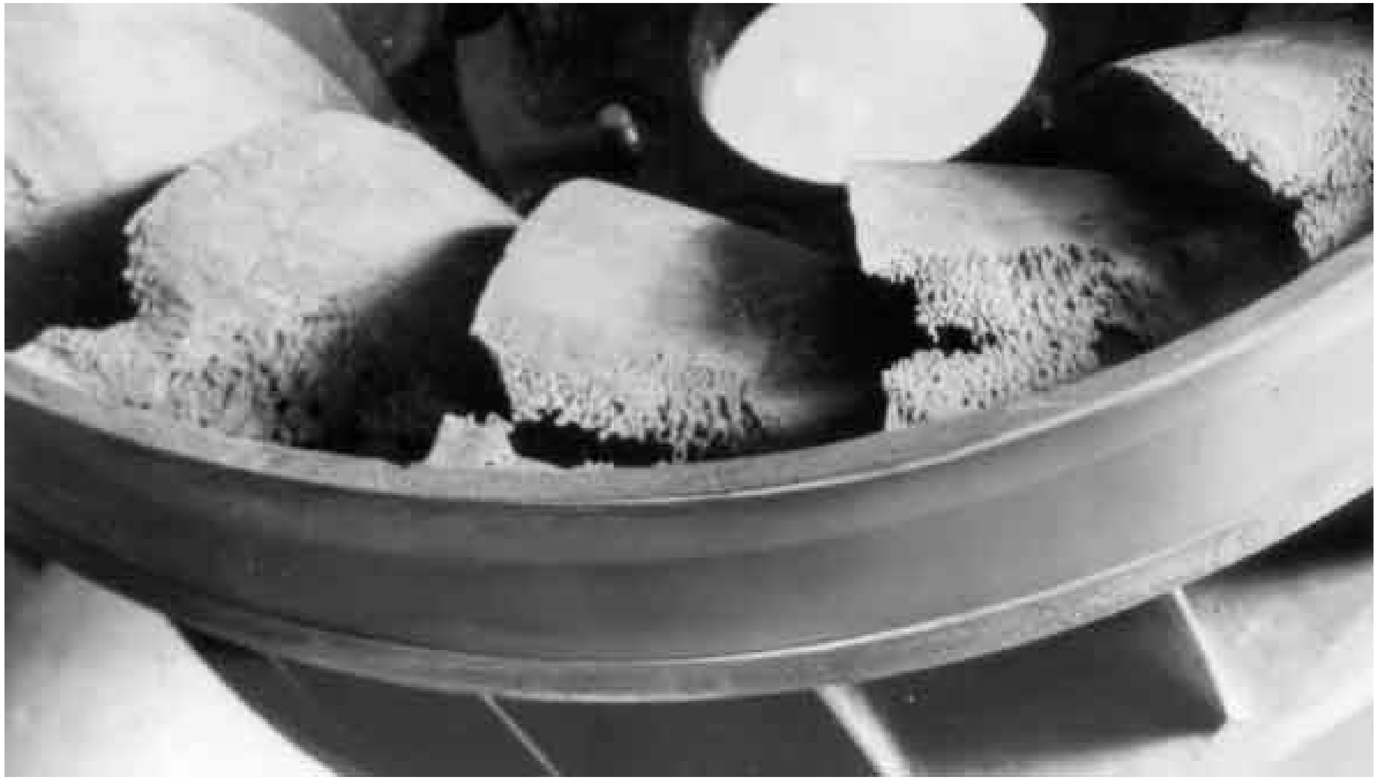
Category	Measurement and Testing Technology		System, Assembly, Model
I	Operational trials and tests that are similar to operation conditions. Original system struture. Stress collective simplified.	field test	
II		bench test	
III		unit test	
IV		component test	
V	Model structure and simple stress.	test specimen test	
VI		model test	



*Jürgen RIGO-V 26, Nr 42, 2018, Sciendo,, PROBLEMS WITH TRIBOLOGICAL TESTINGS OF MARKETABLE OILS USING LABORATORY MODEL TEST RIGS

4. Wear events and approaches

Example of wear events



http://authors.library.caltech.edu/25019/1/chap6.htm

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5. Several techniques to minimize wear

Abrasion wear:

✓Hardness of the stressed body at least 1.3 higher than the counter body

✓Hard phases, e.g. carbides in tough matrix (e.g. cast iron)

✓If counter material is harder: Tougher material

Abrasive wear with brittle behaviour:

✓Material with high toughness and hardness (compromise)

✓Homogeneous materials (e.g. rolling bearing steel)

✓Residual compressive stress in surface areas

5. Several techniques to minimize wear

Adhesive wear:

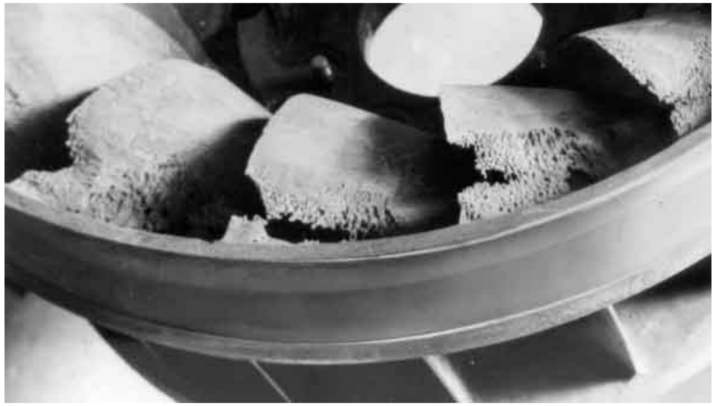
- ✓lubrication (EP additives, avoiding of starving lubricating film, ...)
- ✓avoid metal/metal pairing; instead: plastic/metal, ceramic/metal etc.
- ✓for metallic pairings: CFC with hex cell unite (solubility!)
- ✓materials with heterogeneous microstructure

Tribo-corrosion:

- ➢no metals, at most precious metals
- ➢intermediate materials and surrounding medium without oxidising components

5. Several techniques to minimize wear

The pertinent question is: what kind of coating have we to apply to protect the component? Example in water turbine blades, can we avoid a brittle behaviour?



http://authors.library.caltech.edu/25019/1/chap6.htm

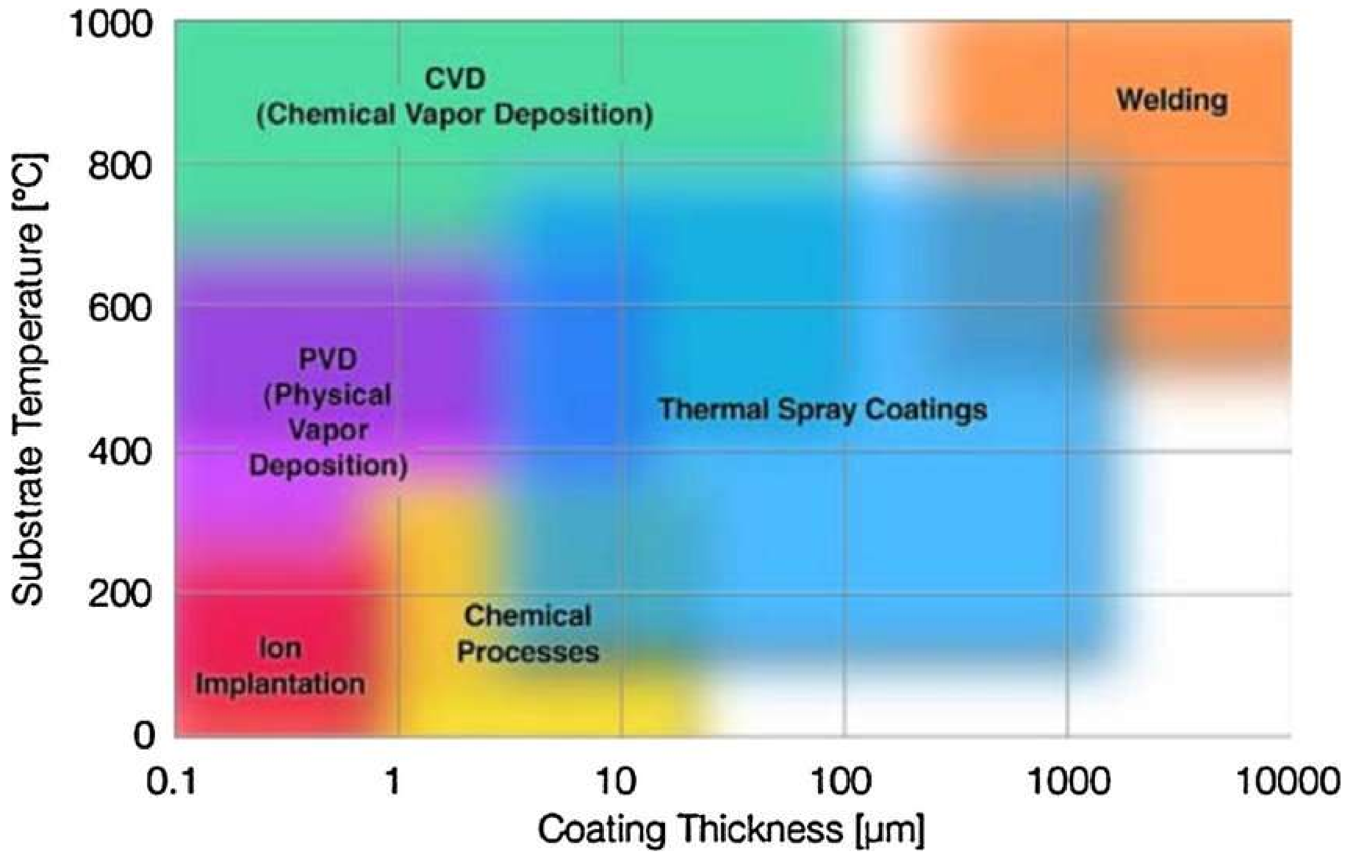
The smart tribologically counter-questions :

I) where to apply it?

II) what is the tribo-system?

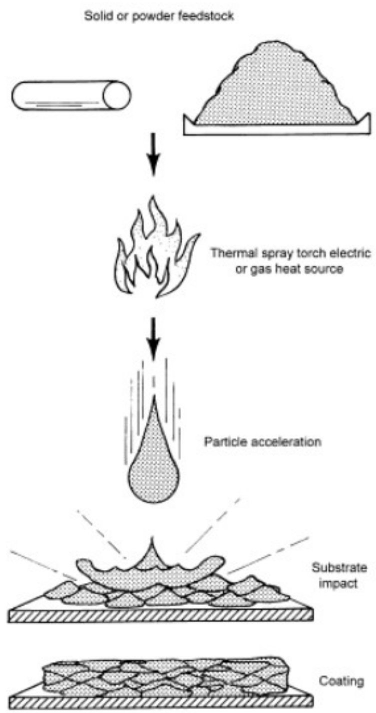
6. Coating solutions: thermal spray coating

Different coating solutions: coating thickness vs. substrate temperature

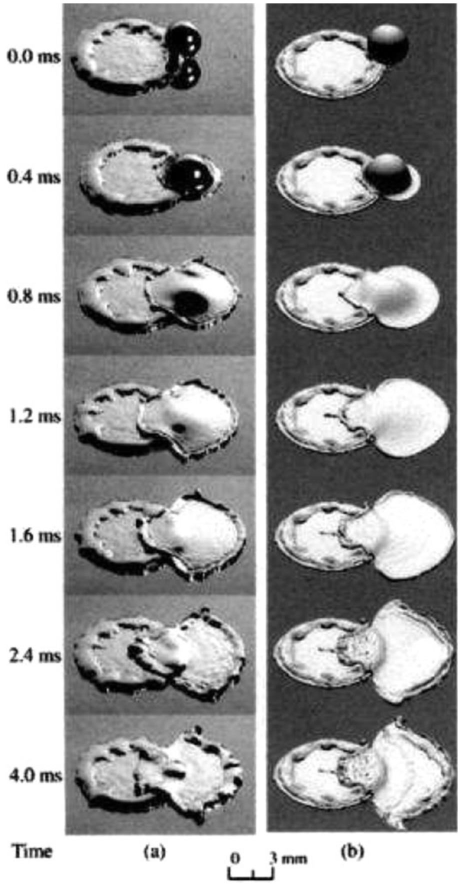


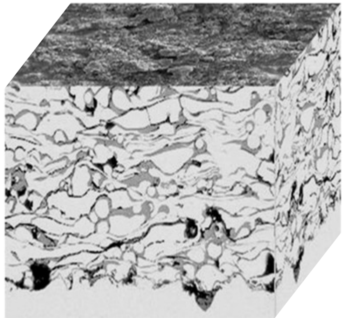
K. E. Schneider, V. Belashchenko, M. Dratwinski, S. Siegmann, A. Zagorski; Thermal Spraying for Power Generation Components, Wiley-VCH, 2006

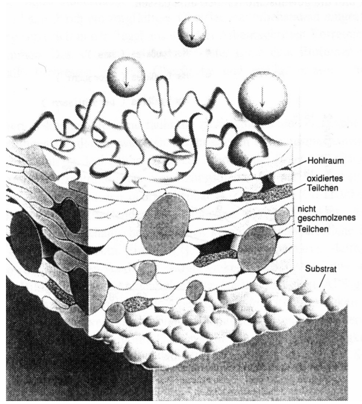
6. Coating solutions: thermal spray coating



schematic presentation of thermal spray process.







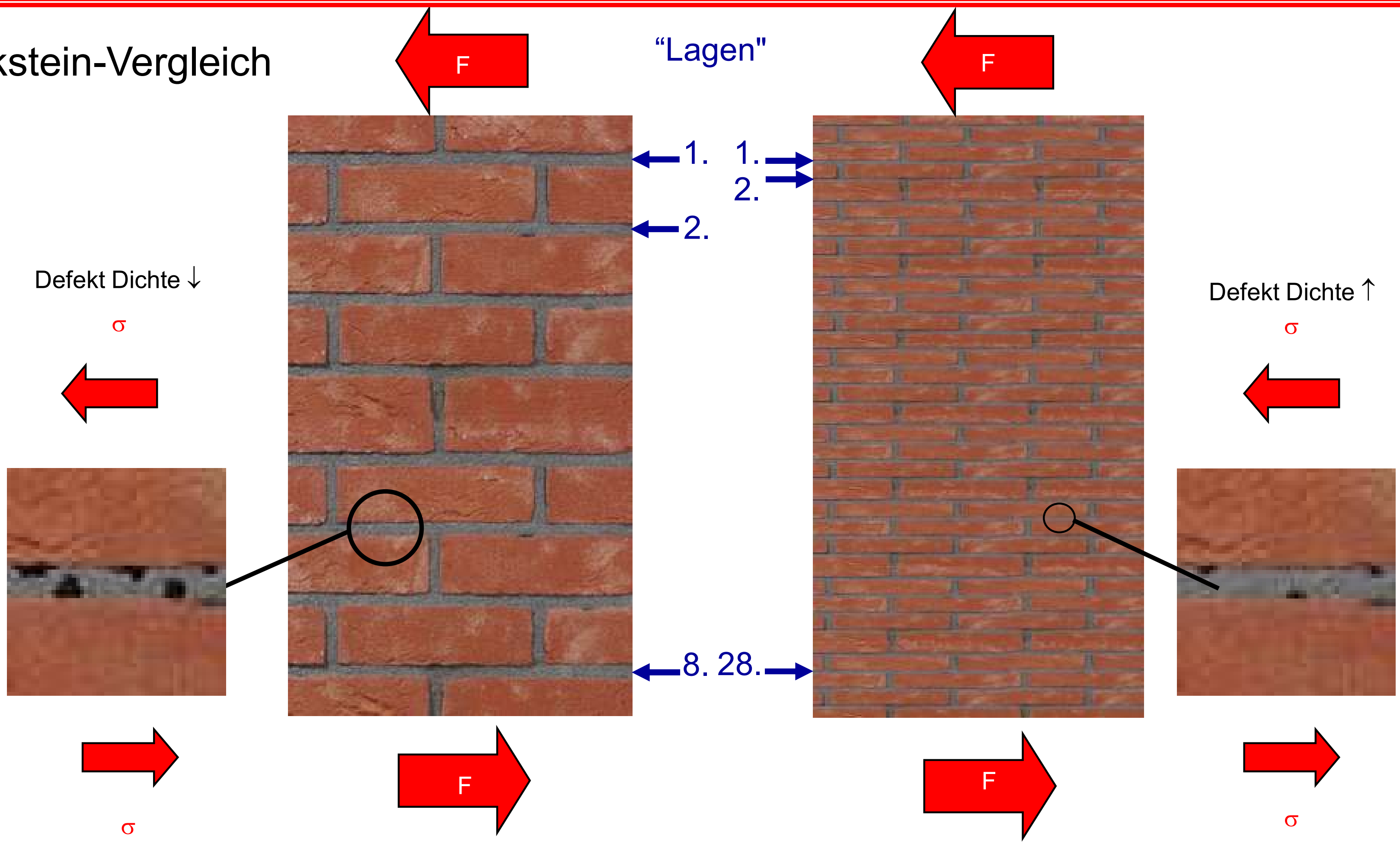
Ref: H. Hermann, Plasmagespritzte Beschichtungen; Spektrum der Wissenschaft, 11 (1988)

Comparison between experimental results (a) and numerical modelling (b) Obtained by Mostaghimi et al.

Hadad, 2010, adhesion and residual stress evaluation of thermally sprayed coatings

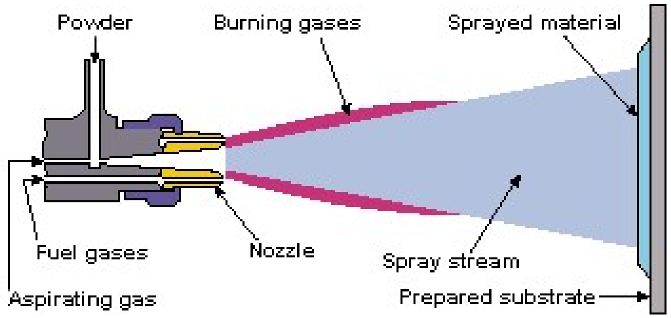
6. Coating solutions: thermal spray coating

“Splat “ – Backstein-Vergleich

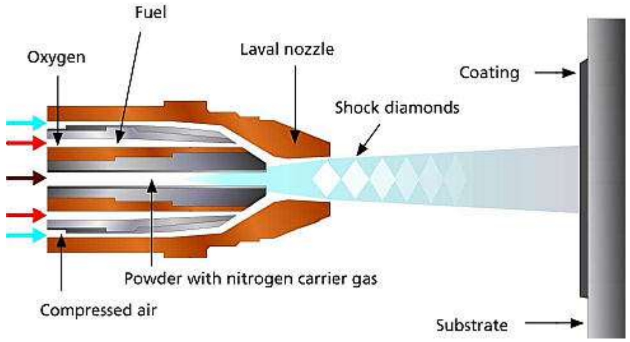


Margadant, N., S. Siegmann, T. Keller, W. Wagner and A. Kulkarni: Proceedings of ITSC 2003 International Thermal Spray Conference - Advancing the Science and Applying the Technology 2 (2003), p. 1053-1061.

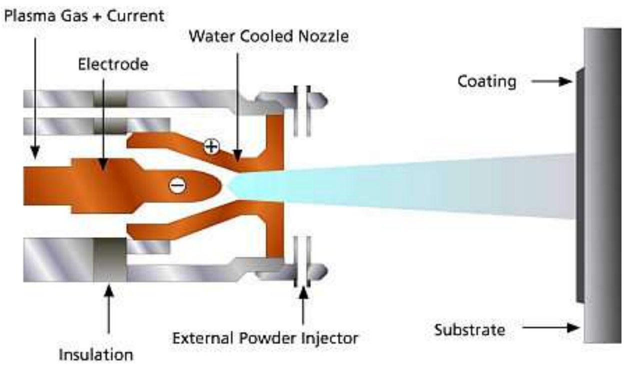
6. Coating solutions: thermal spray coating



Schematic of the powder flame spray process.



schematic presentation of High Velocity Oxy-Fuel spraying process.

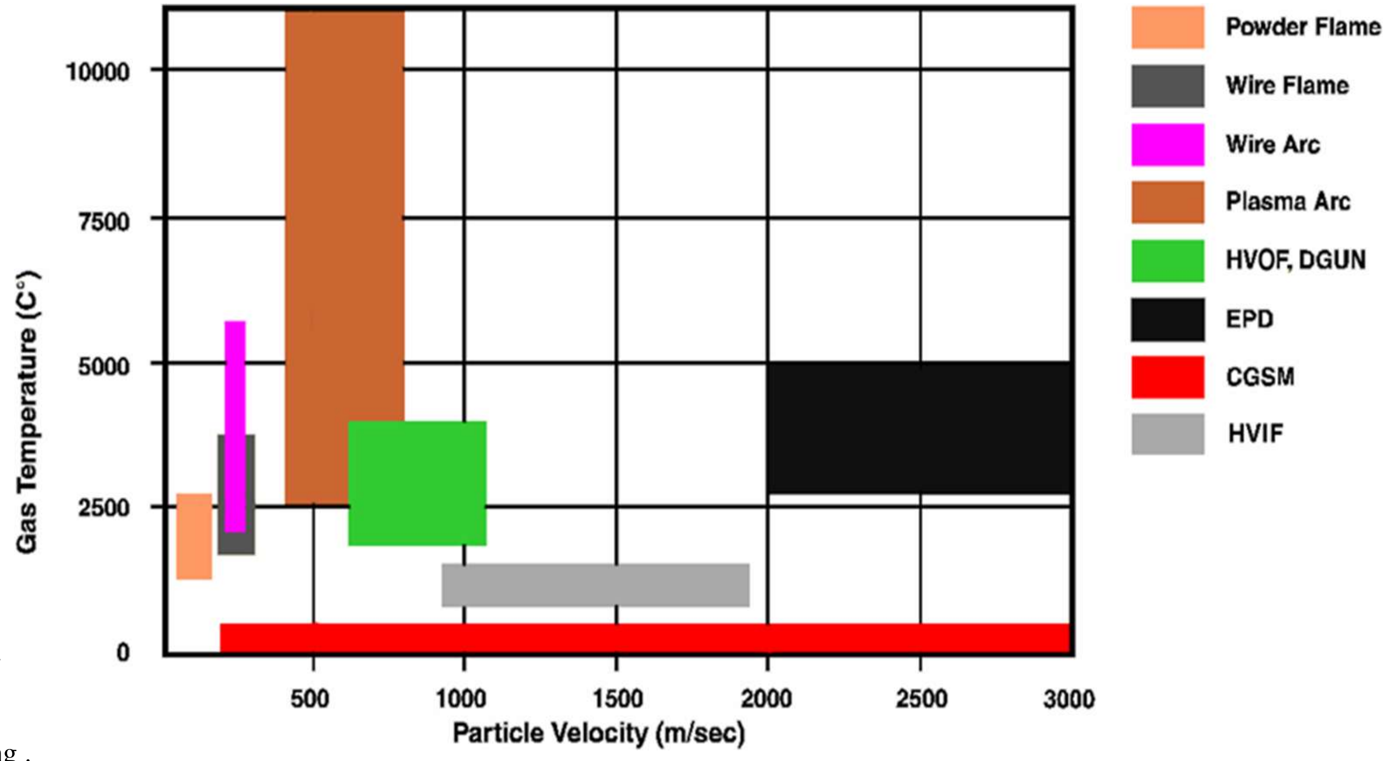


schematic presentation of plasma spray process.

Hadad, 2010, adhesion and residual stress evaluation of thermally sprayed coatings

6. Coating solutions: thermal spray coating

Gas temperature in function of particle velocity for different thermal spray processes.



HVOF: High-velocity oxygen/fuel.

HVAF: High-velocity air/fuel.

HVIF: High-velocity impact forging .

CGSM: Cold Gas Spray Method .

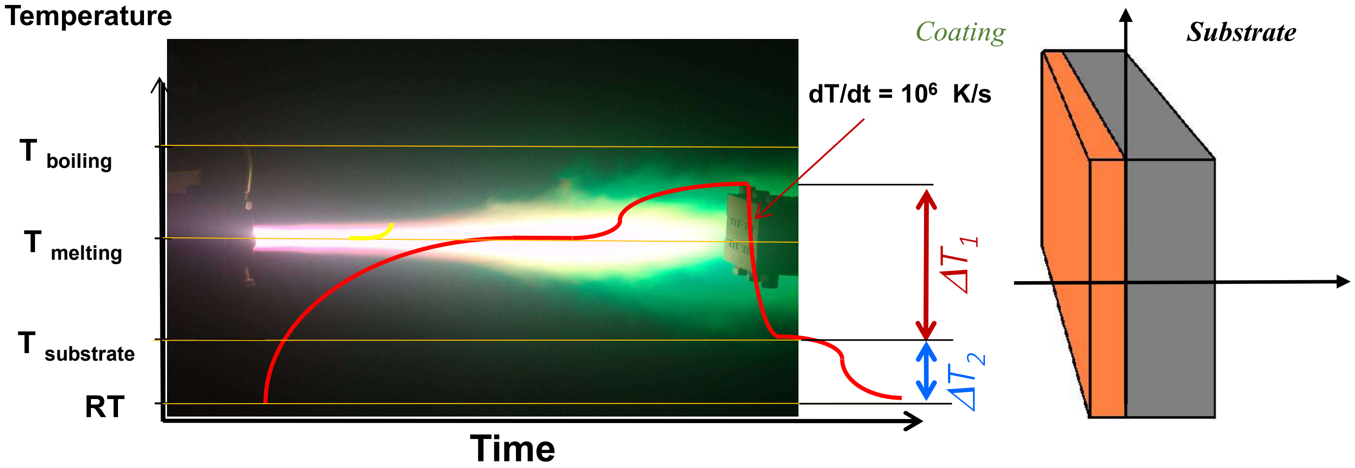
EPD: Electromagnetic Powder Deposition.

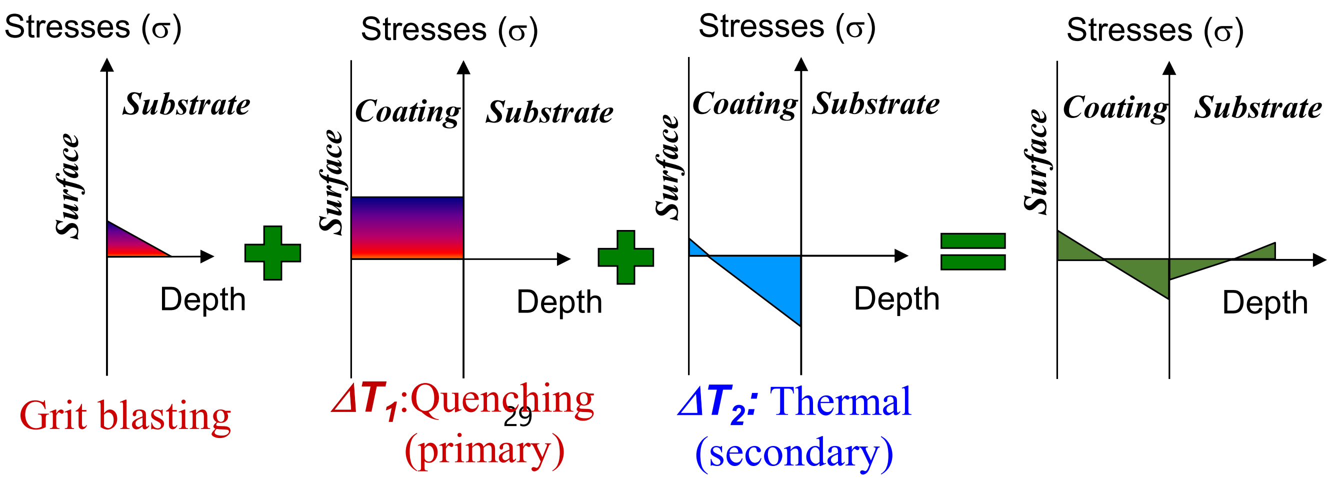
DGUN: Detonation- Gun spraying.

Hadad, 2010, adhesion and residual stress evaluation of thermally sprayed coatings

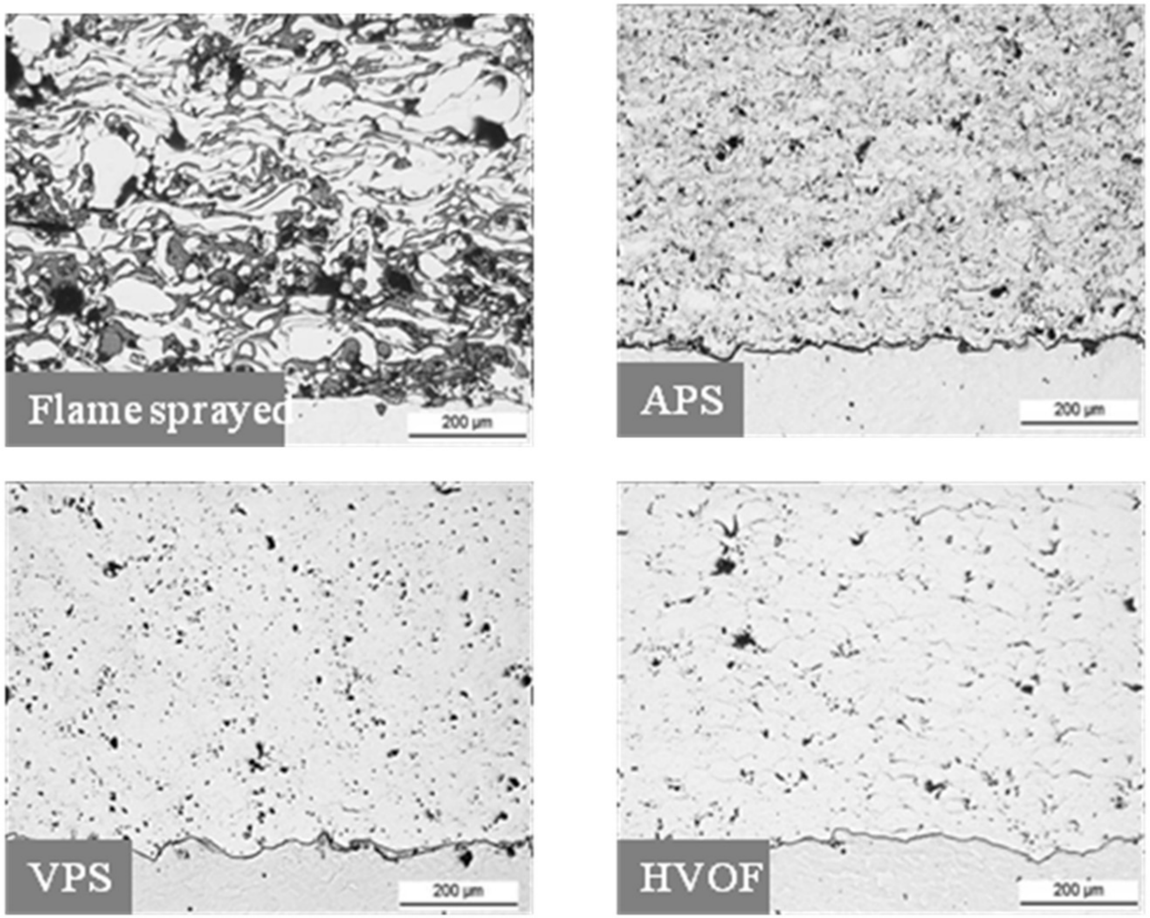
6. Coating solutions: thermal spray coating

Origin of residual stress





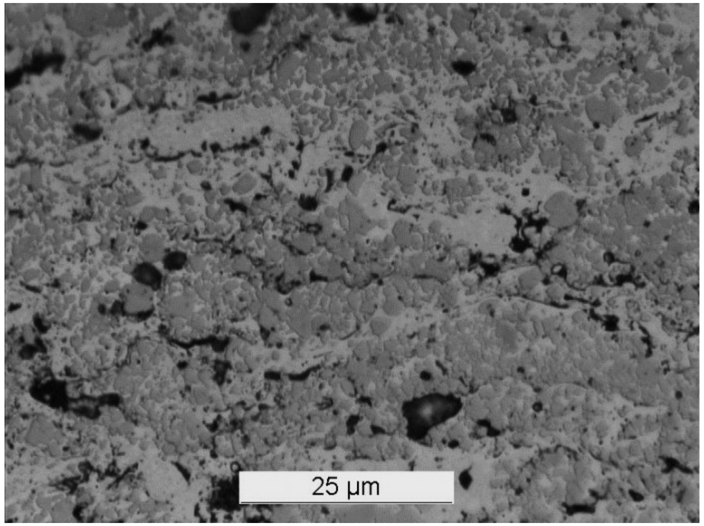
6. Coating solutions: thermal spray coating

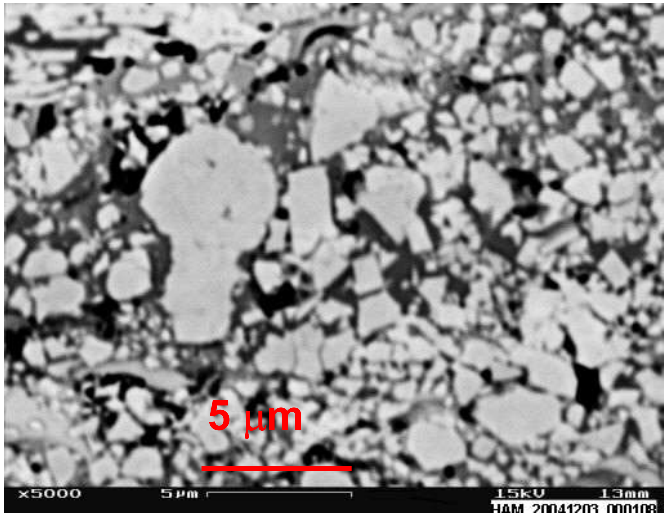


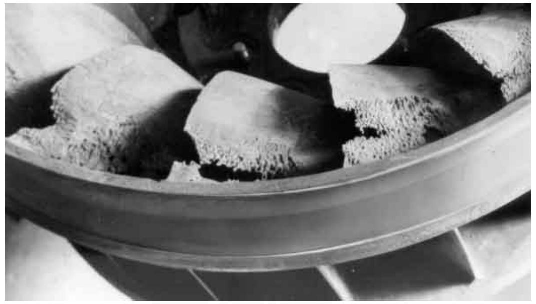
Microstructure of different coatings process of the same powder of NiCr 80-20 and steel substrate.

Hadad, 2010, adhesion and residual stress evaluation of thermally sprayed coatings

7. Coating solution against erosion wear: case study





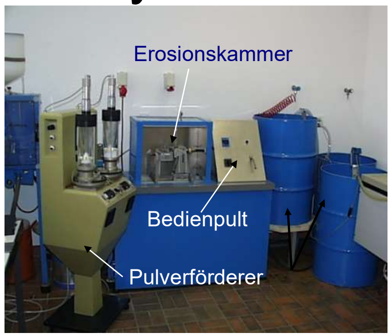


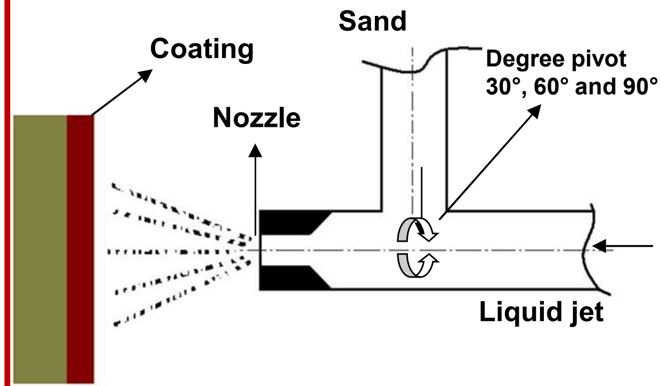
WC-Co thermally sprayed coating on a steel substrate

7. Coating solution against erosion wear: case study

Test	Erodent material	Erodent size µm	Flow rate (water) l/min	Flow rate (erodent) g/min	Velocity m/s	Stand off distance mm	Nozzle diameter mm	Pressure bar	Exposure time min
Slurry erosion	Al_2O_3	**45-75**	13.6	9.52	147	100	1.4	250	38
Dry erosion	Al_2O_3	**500-1000**		378	12	70	7.5	3.5	25

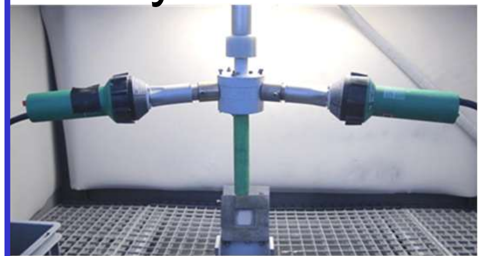
Slurry erosion

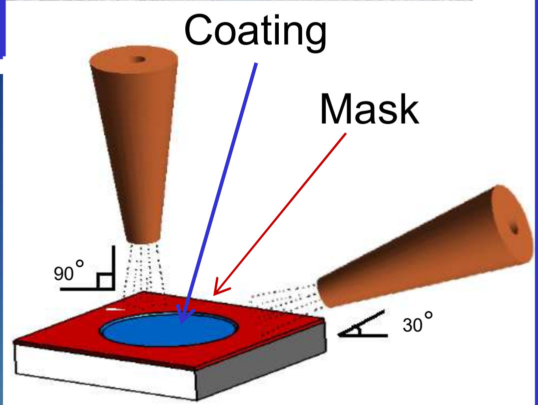




Hadad M, Hitzek R, Siegmann S. Wear 2007;263:691

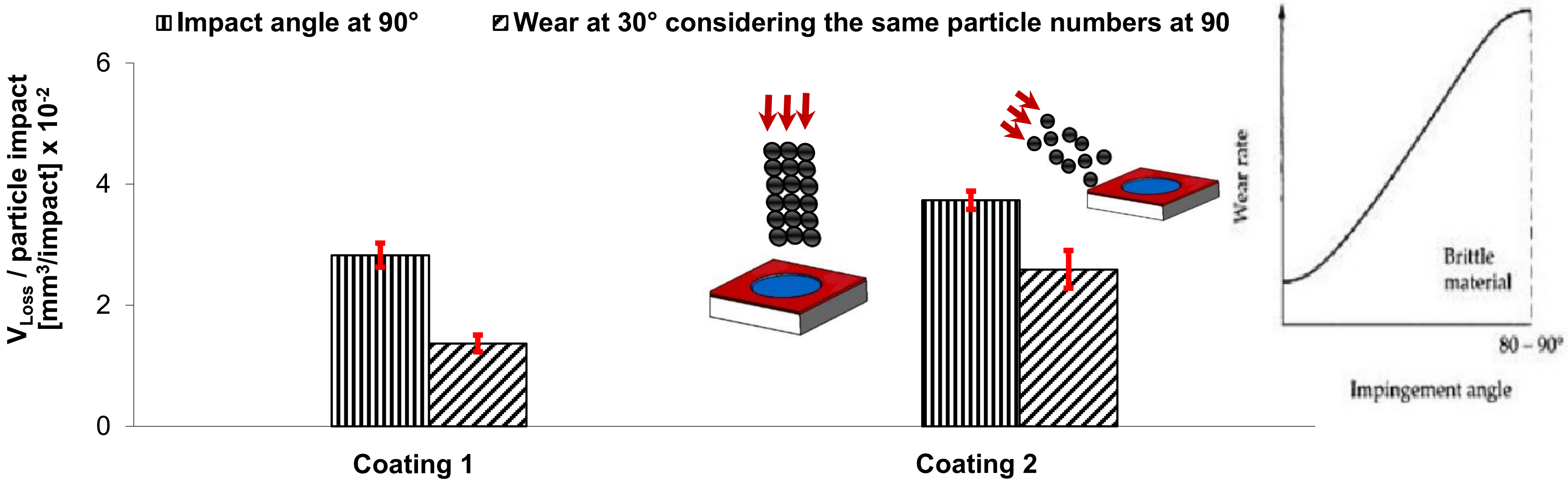
Dry erosion



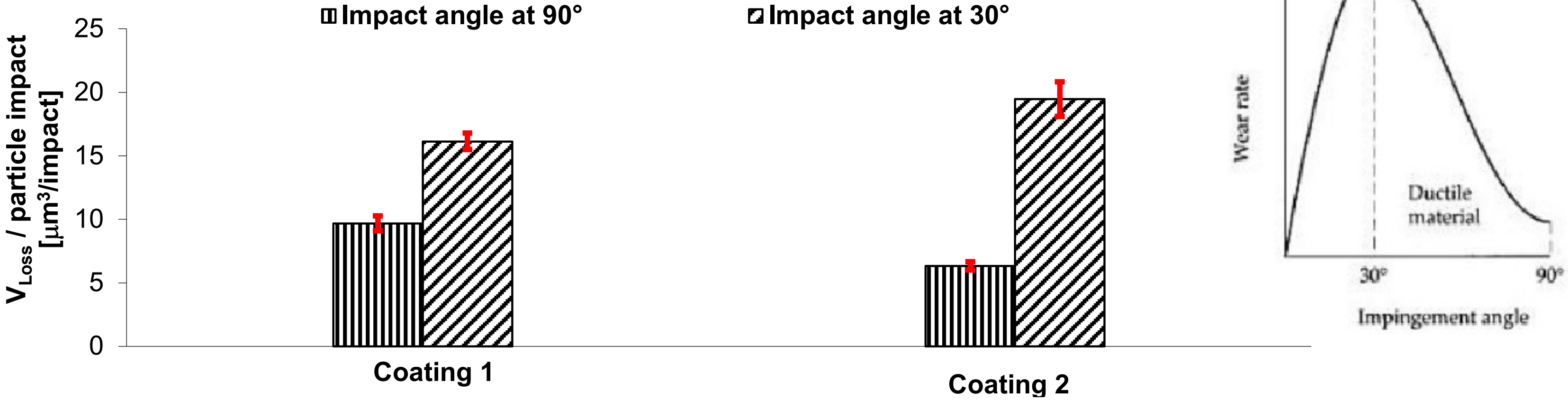


7. Coating solution against erosion wear: case study

Dry erosion results at 30° and 90°

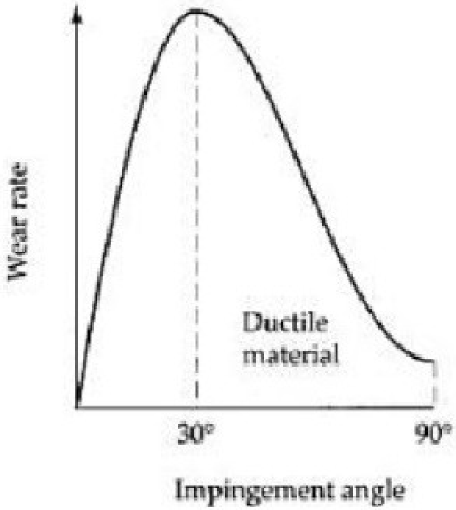


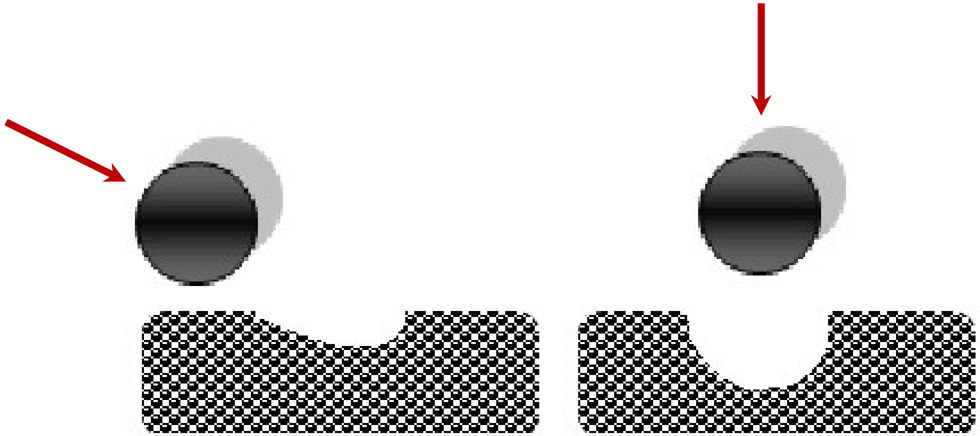
Liquid with solid particle impingement erosion results

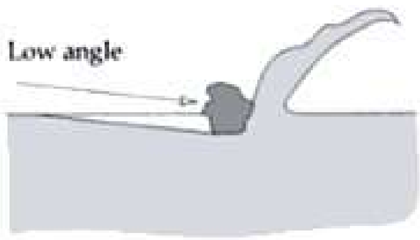


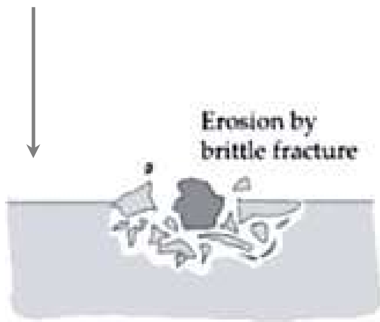
Hadad, 2007, wear

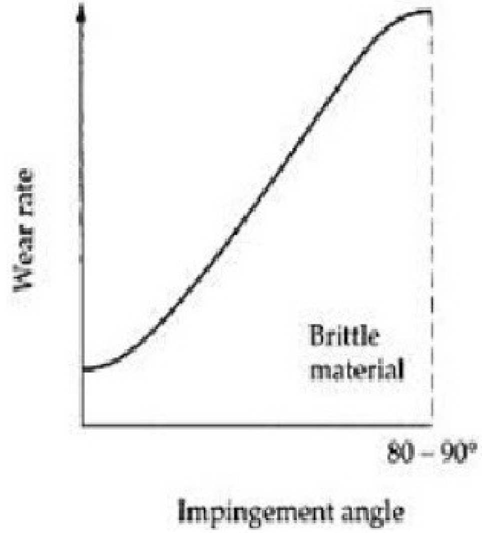
7. Coating solution against erosion wear: case study



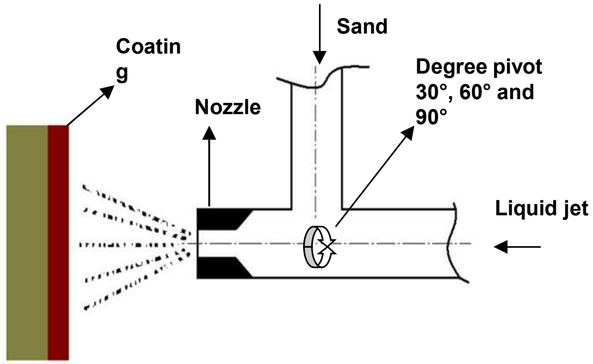


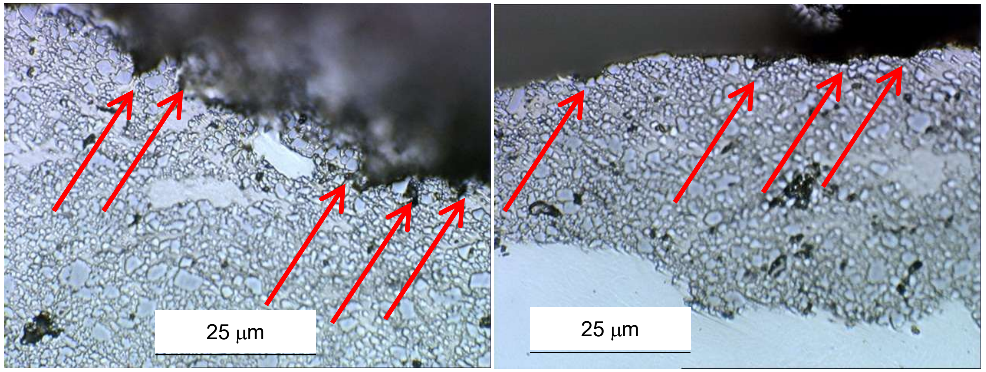


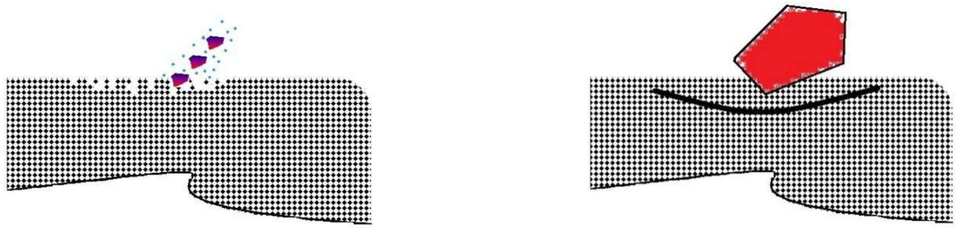


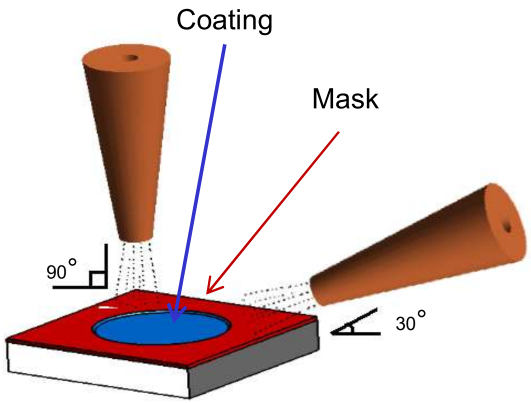


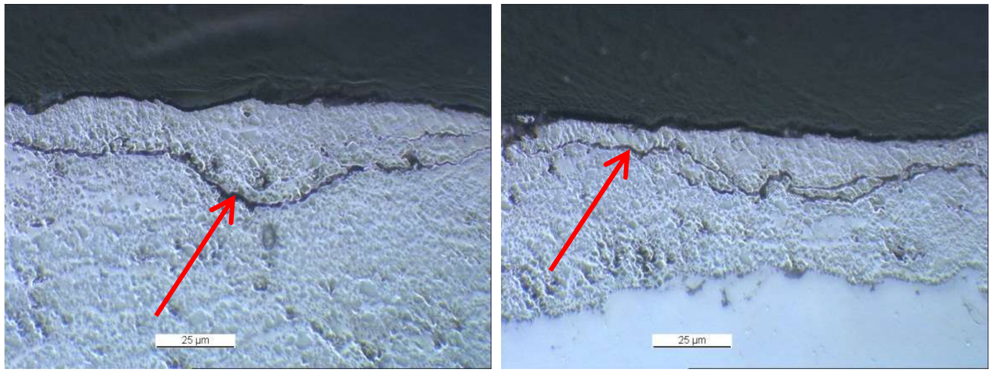
7. Coating solution against erosion wear: case study











Hadad, 2007, wear

7. Coating solution against erosion wear: case study

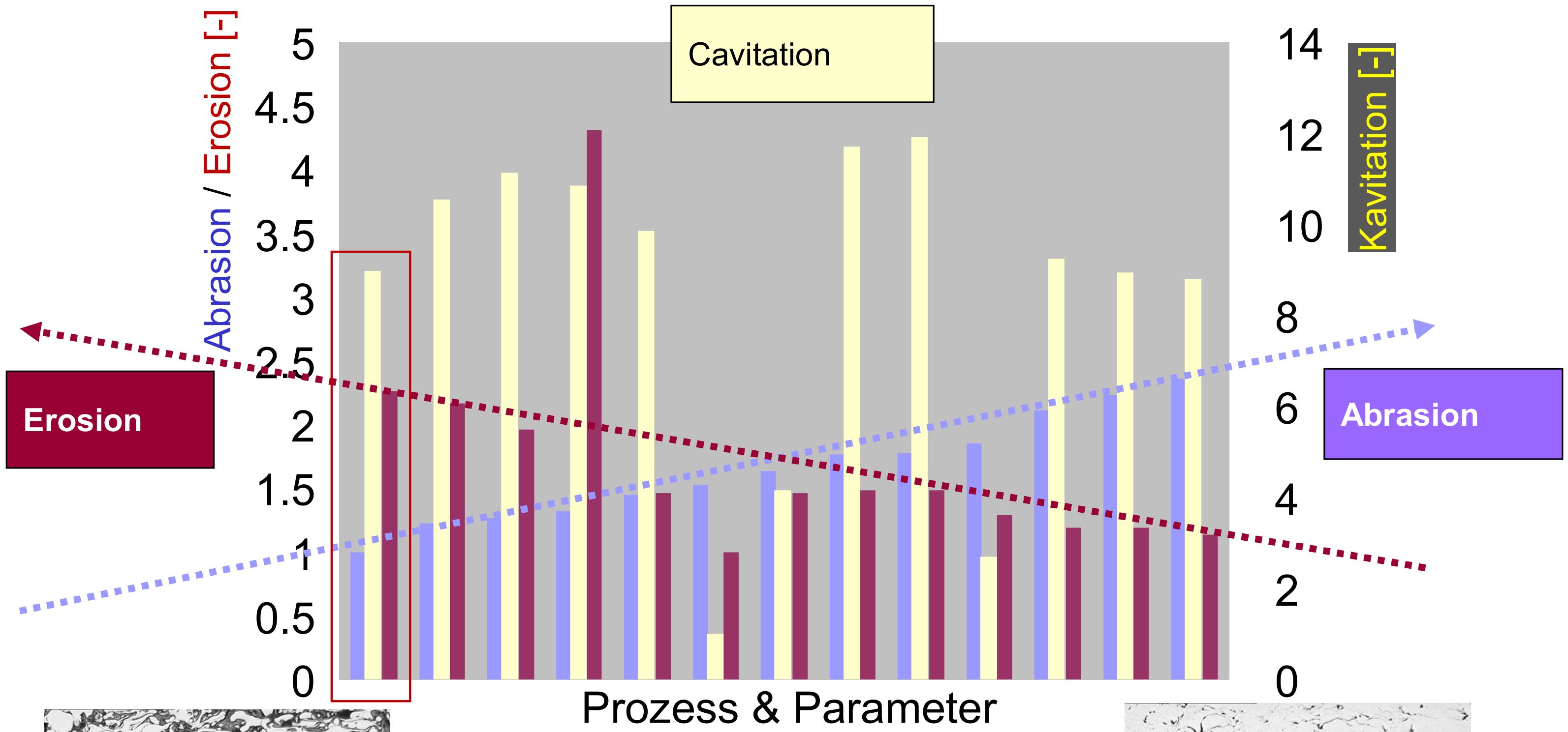
1. **In abrasion:** the microstructural features of the TS coating is dominant in wear acceleration, since the discrete interfaces of inter-splats could lead to weaken the coating cohesion compared to bulk

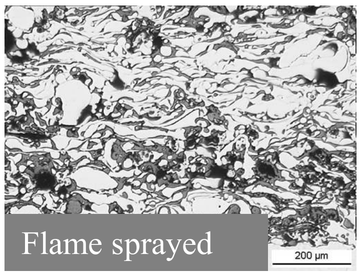
2. **In erosion:** the difference in coating behaviors (ductile/ brittle) subjected to erosion was mainly affected by **tribo-system** (particle size, and speed) and consequently the **wear mechanism**. The mechanical properties of materials showed a minor influence.

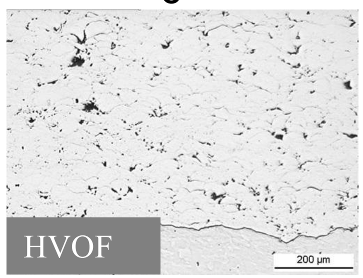
3. These study cases are few extents to show that the wear is not only depending on the mechanical properties, but also strongly on the **thermodynamic parameters** and on the **tribo-system**, **microstructural** features, and **wear mechanism**

8. Wear of thermal spray coatings

Normalized wear rate: abrasion, particle erosion and cavitation wears of NiCrAlY coating



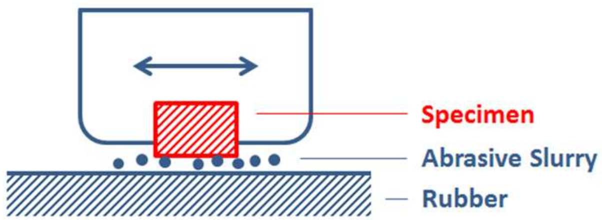


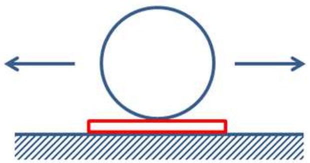


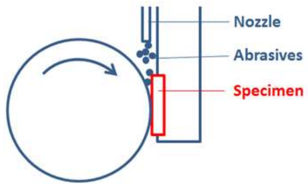
Ref: N. Margadand. N. ITSC 2003

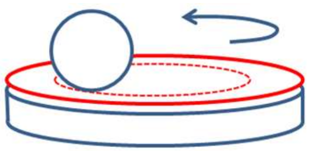
8. Wear of thermal spray coatings

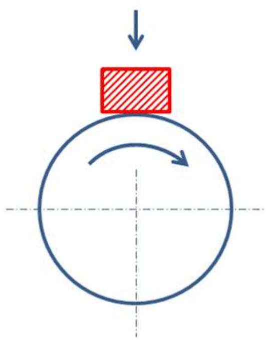
Abrasion



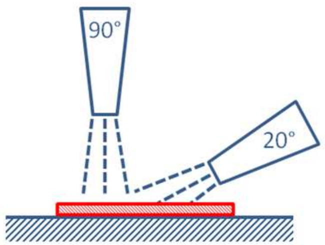


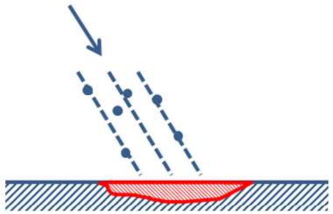




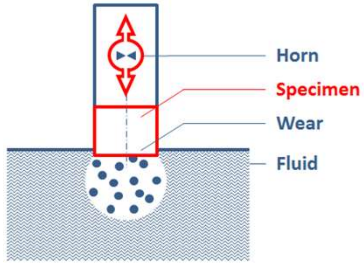


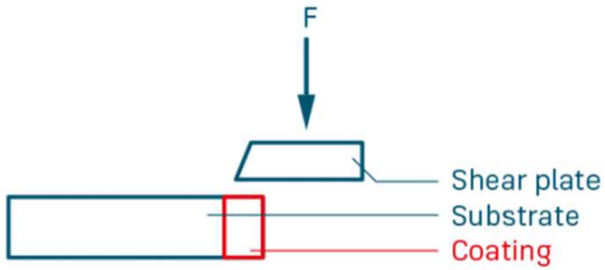
Erosion



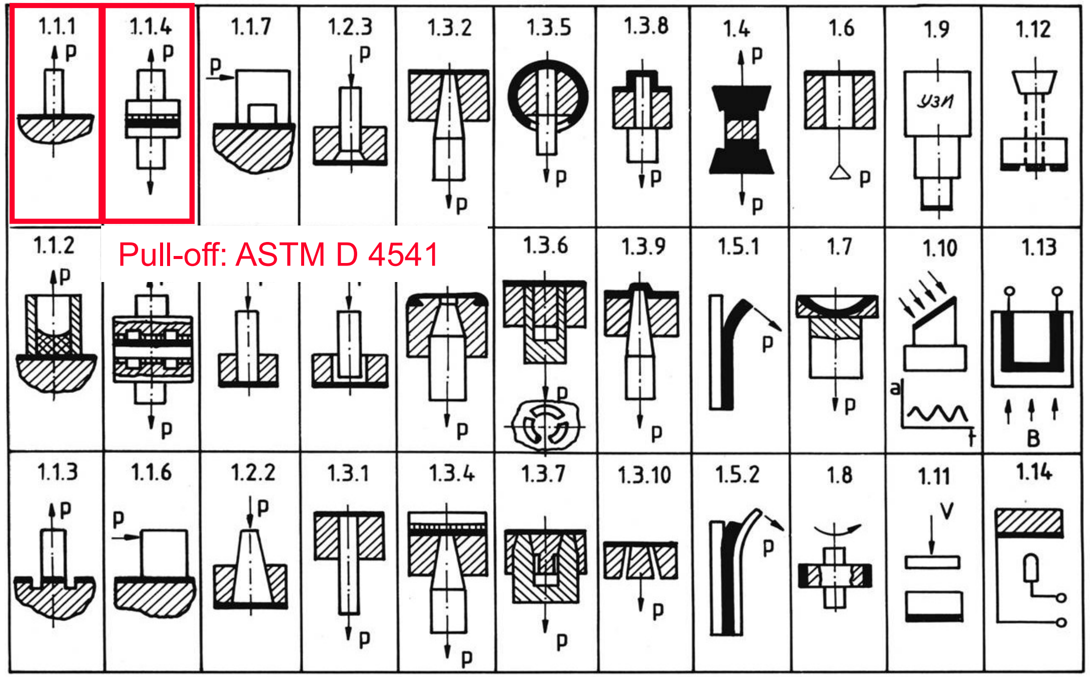


Cavitation



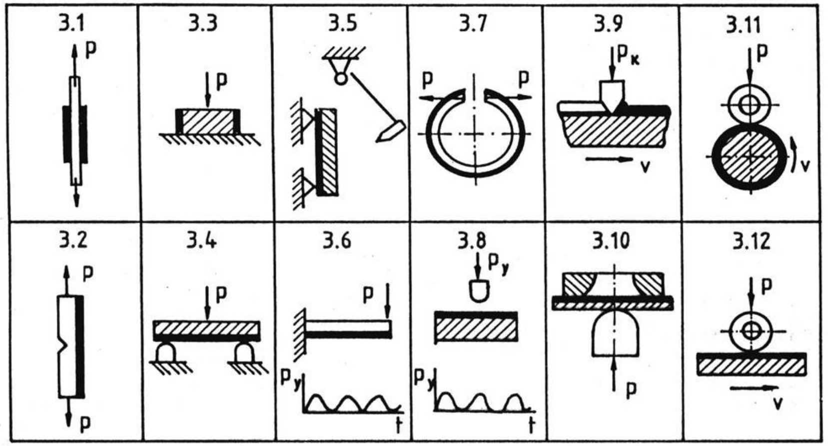


9. Adhesion of thermal spray coatings



Adhäsion: EN 582 / ISO 14916 / ASTM C 633, ASTM F 1147

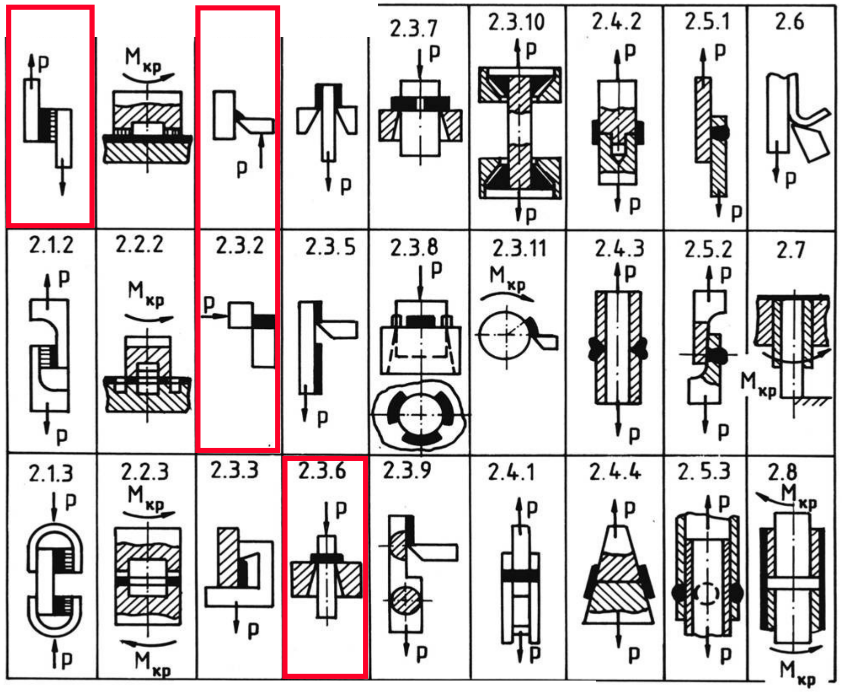
9. Adhesion of thermal spray coatings



Kharlamov, Y. A. Methods of Measurement of the Adhesion Strength of Coatings (Review). Industrial Laboratory, 453-459 (1987)

Scher-Test:

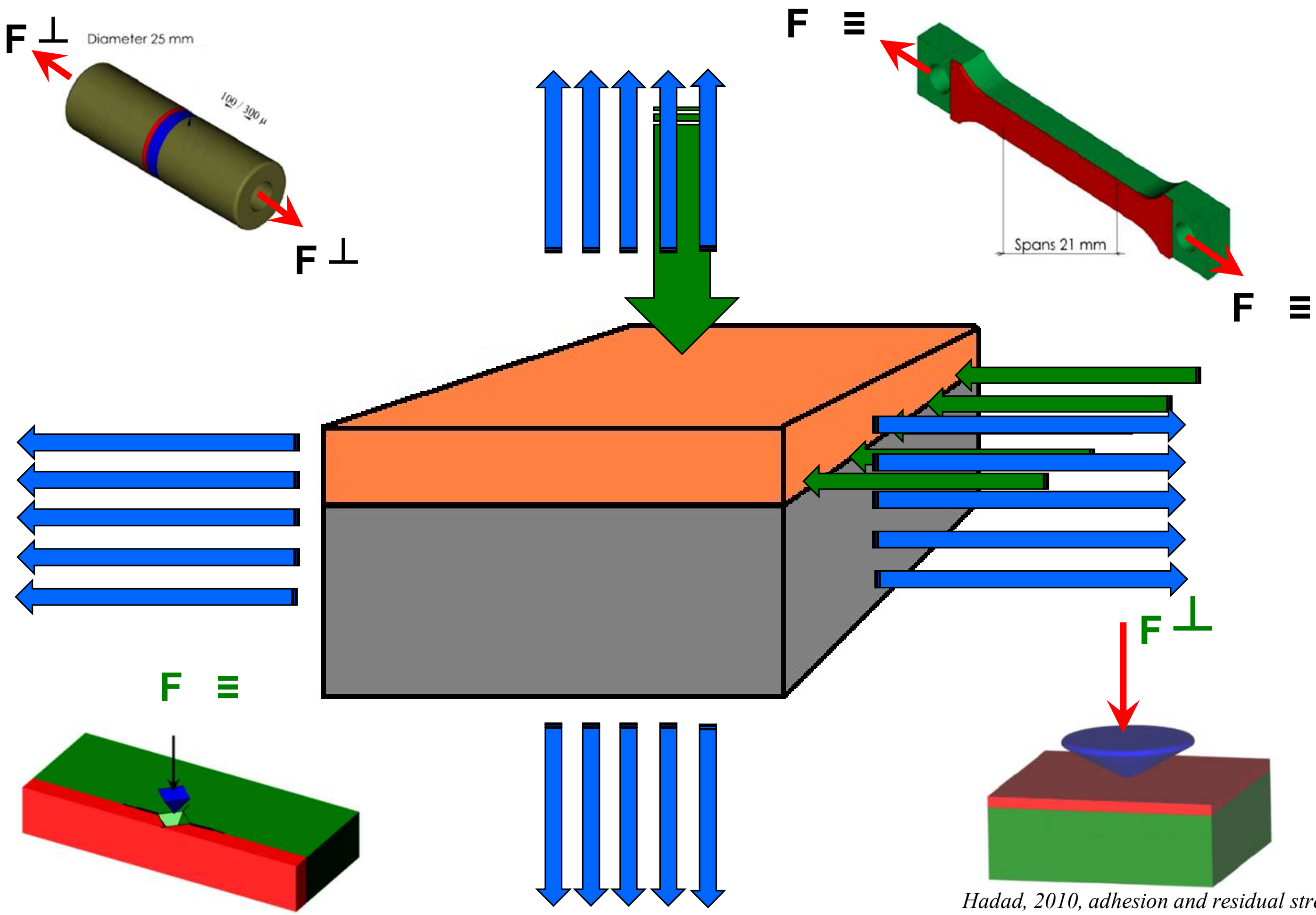
ASTM F 1044 Neuer Schertest prEN 15340



Alter Schertest: DIN 50161

40

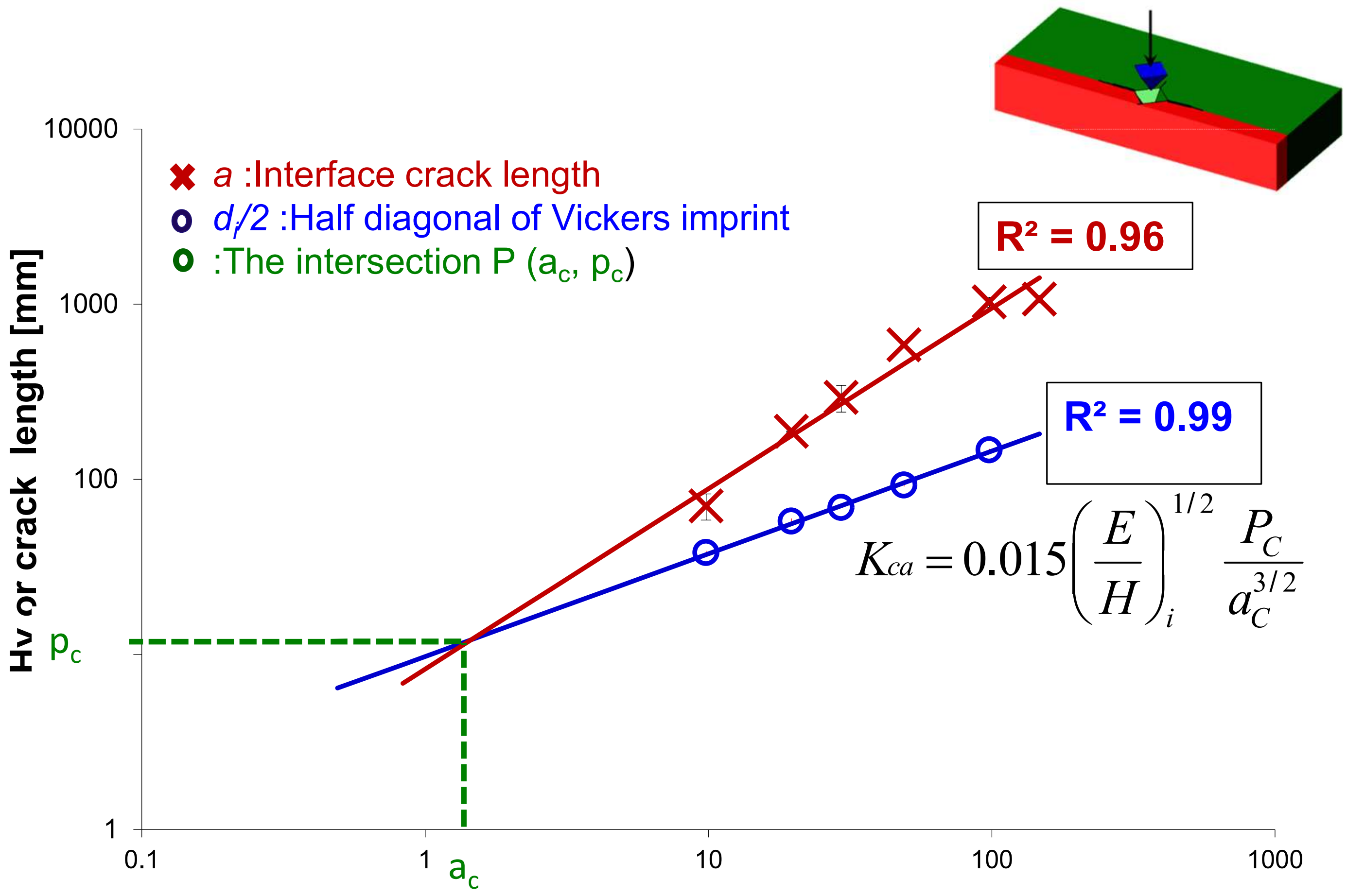
9. Adhesion of thermal spray coatings



Hadad, 2010, adhesion and residual stress evaluation of thermally sprayed coatings

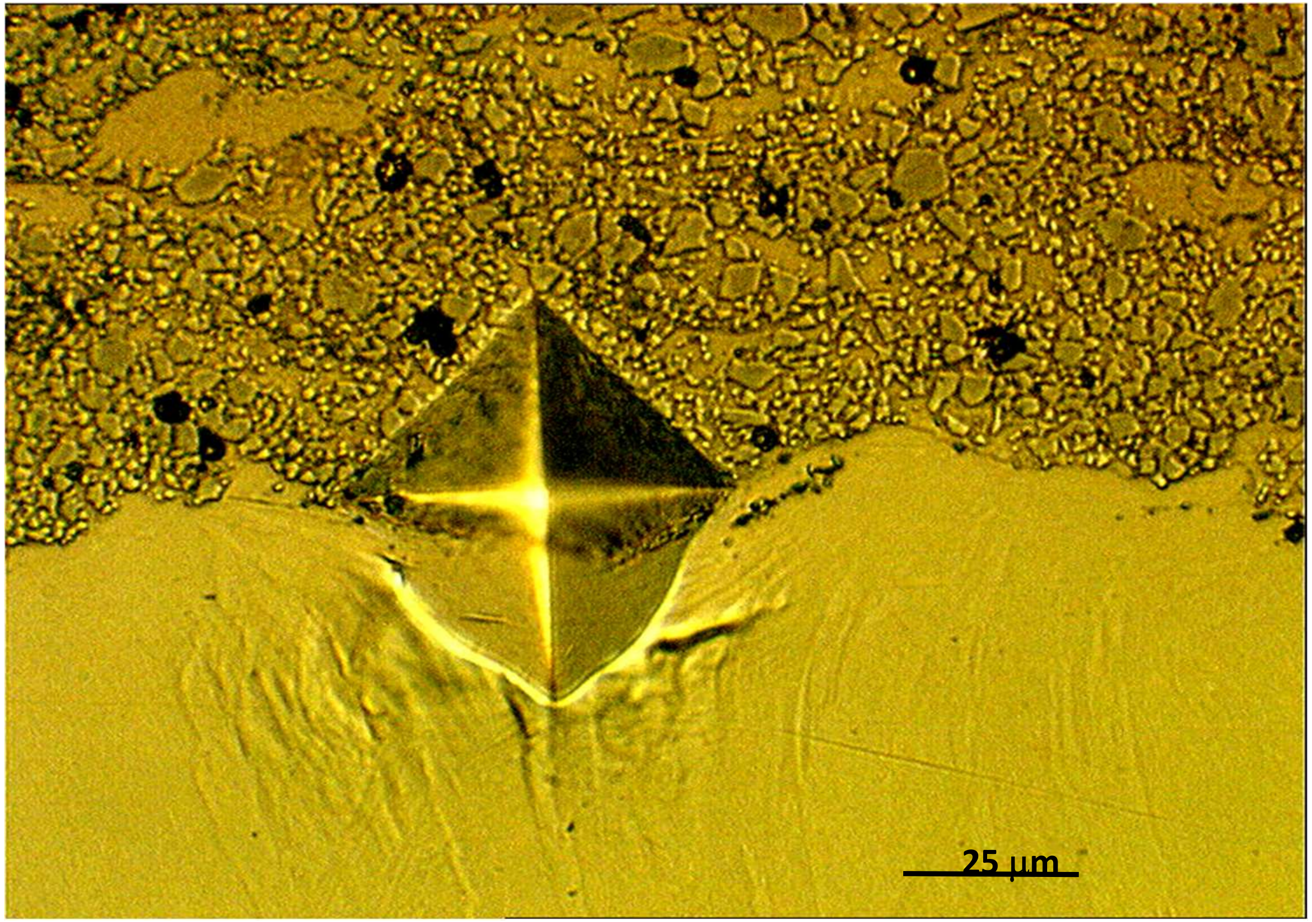
9. Adhesion of thermal spray coatings

Meaningful of adhesion values: Interface indentation tests



Hadad, 2010, adhesion and residual stress evaluation of thermally sprayed coatings

9. Adhesion of thermal spray coatings



Hadad, 2010, adhesion and residual stress evaluation of thermally sprayed coatings

Questions?