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Ultrasonic sensors for in-situ monitoring of manufacturing processes

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MetMap 2019

Advanced Manufacturing Research Centre, Sheffield

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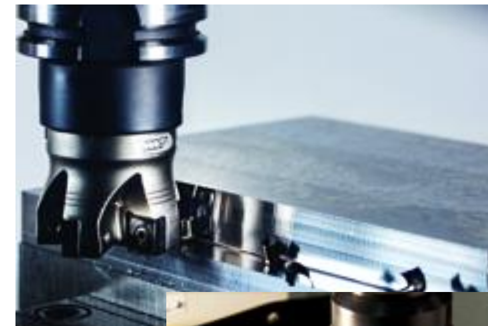
Monitoring a Manufacturing Process

- What might we want to know
  - Part geometry
  - Surface roughness/integrity
  - Friction at the interface
  - Tool wear/life
- Advantages of in-situ over ex-situ measurements
  - Ex-situ - CMM, profilometer etc.
  - In-situ – dyno, load cells, force sensors, AE, vibration
- Interfaces and Tribology are important
  - Presence of a surface film (lubricant)
  - Contact stress/pressure



Contents

- Ultrasound and Interfaces (basic principles)
- Developing an Interface Sensor
- 3 Case (Pilot) Studies
  - Metal Rolling
  - Cutting tool monitoring
  - Incremental sheet forming

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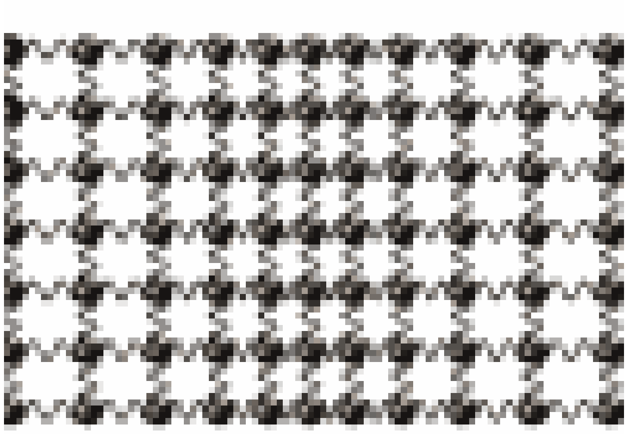
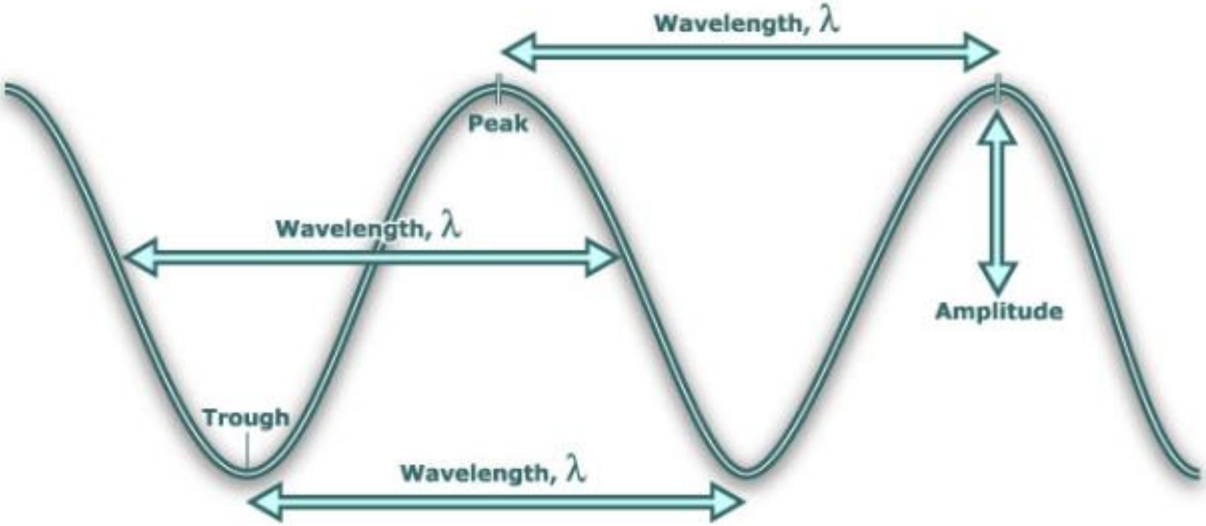
Ultrasound and Interfaces

Ultrasound and Waves

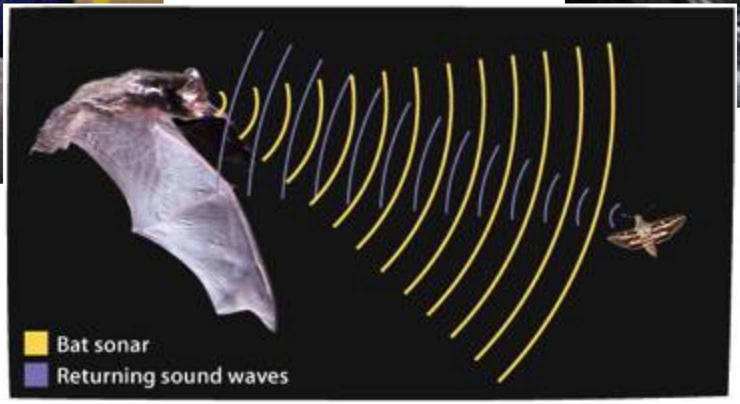
- Ultrasound are small mechanical vibrations (>20kHz)
- Elastic waves in a solid or liquid – tiny amplitude
- The particles don't travel – they just oscillate
- Wavelength, frequency, amplitude





Ultrasonic Reflection

- Ultrasound can travel through a medium
- Ultrasound *reflects* from boundaries – echoes
- We can measure the frequency, time of flight and amplitude



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Generating Ultrasound #1

- Usually generated by piezo electric transducers
- Apply a voltage pulse (10 – 100V)
- Frequency of vibration depends on thickness

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Laptop & Labview

Instrument control and signal processing

Pulser

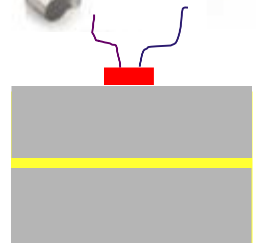
Generates short duration voltage pulses

Piezo-electric element

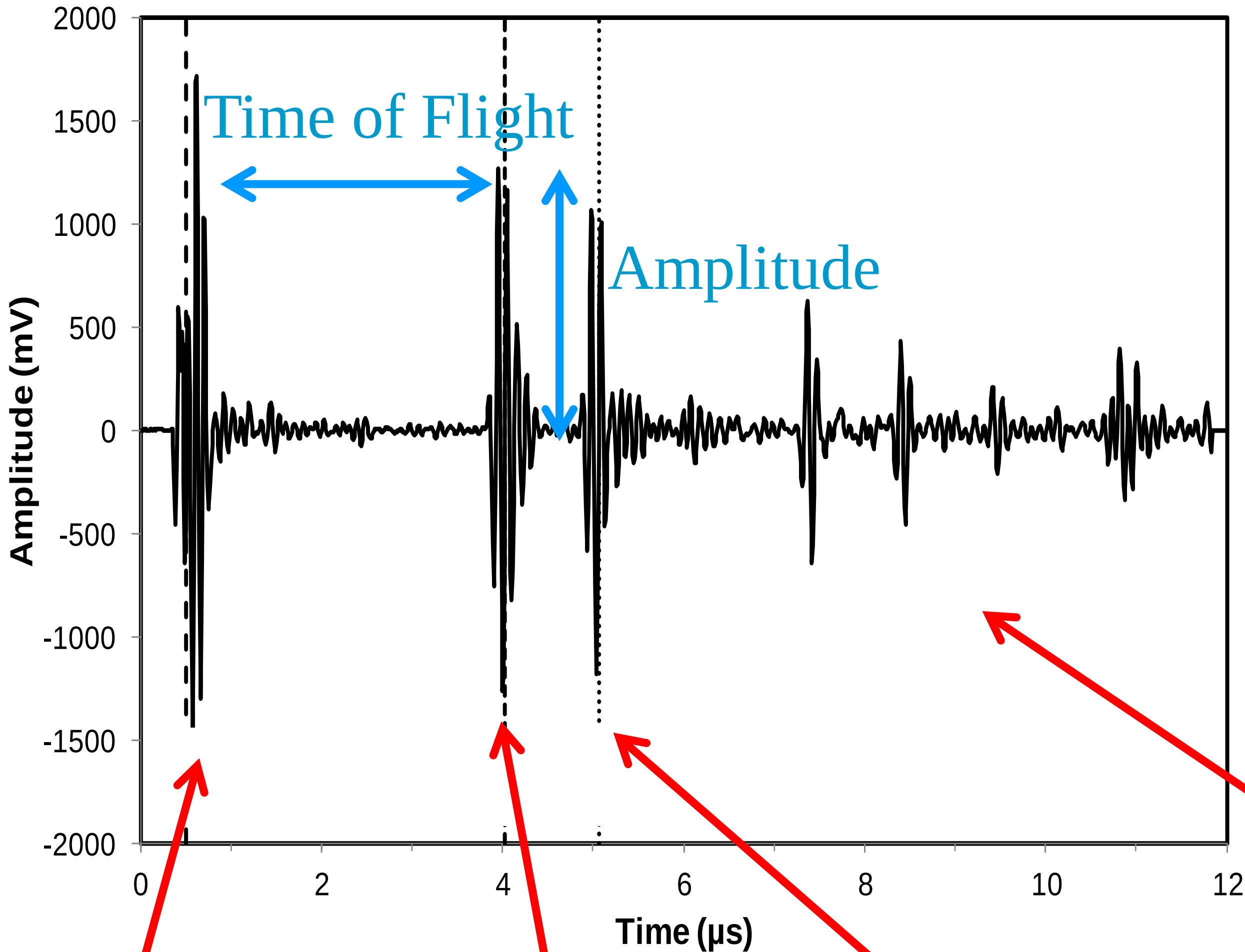
Converts voltage to deflection (and vice versa)

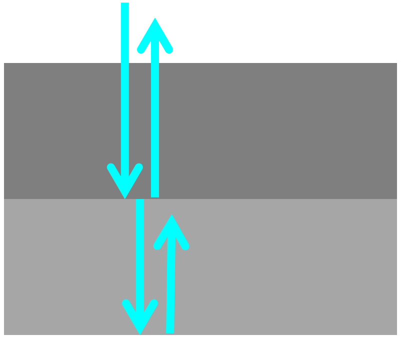
Digitiser

Converts received pulses to digital signal



Anatomy of a Waveform





Other echoes

Sensor reflection

Contact reflection

Back face reflection

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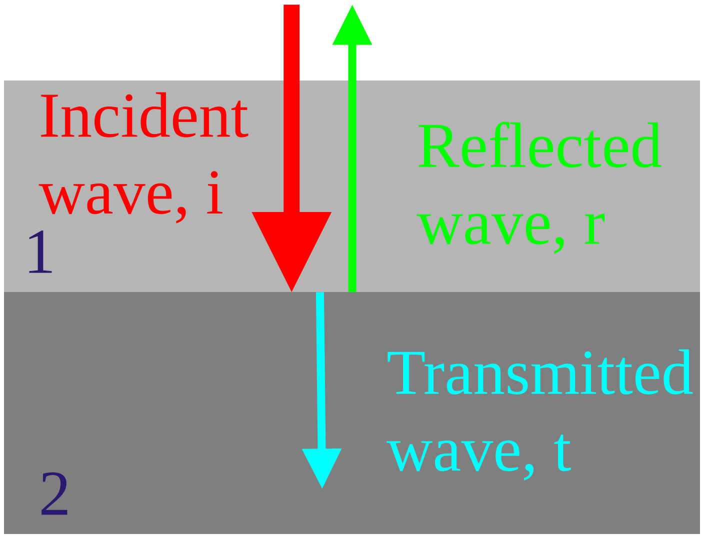
Ultrasonic Reflection

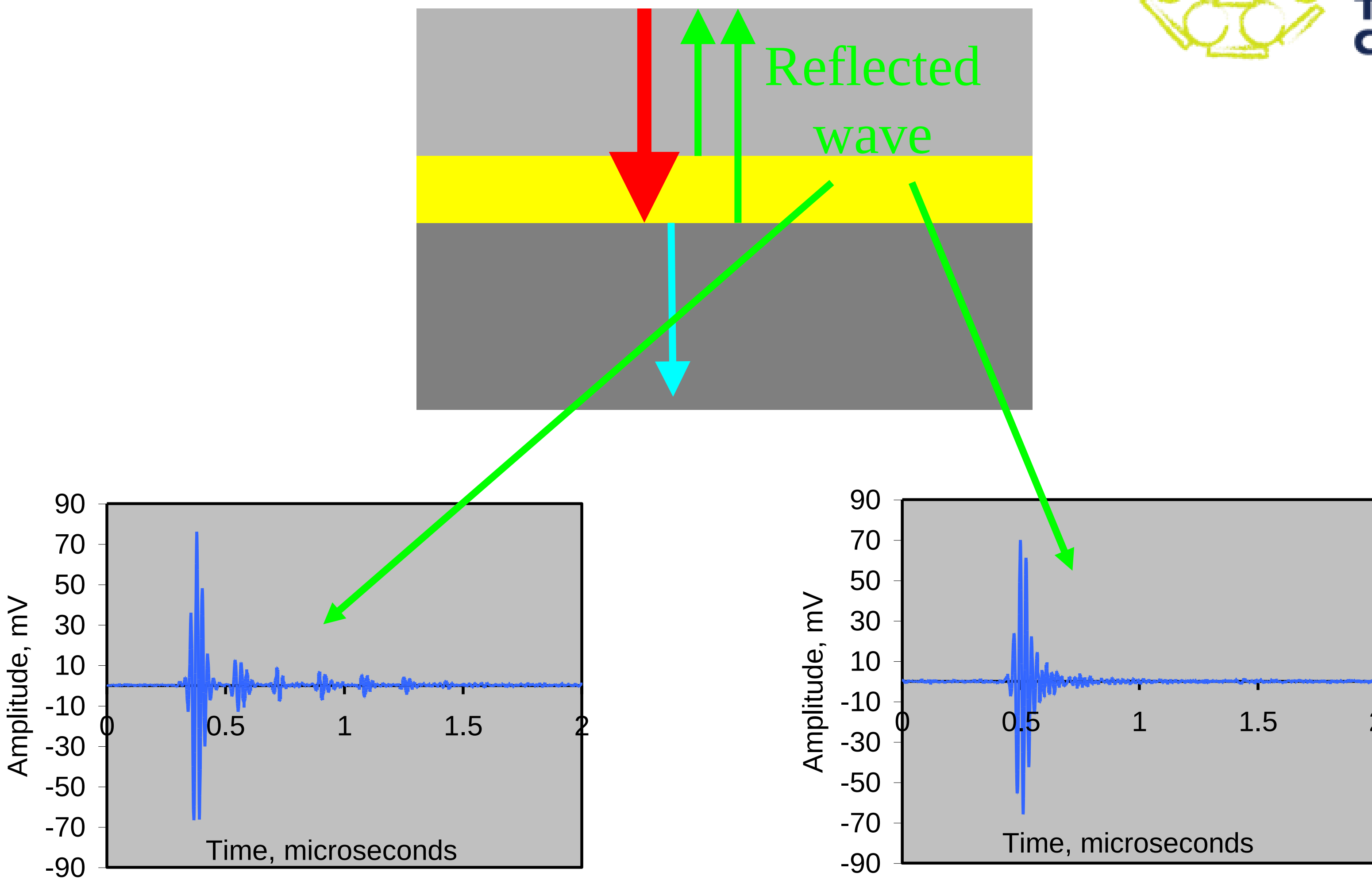


$$R = \frac{z_2 - z_1}{z_2 + z_1}$$

- *Reflection Coefficient, R*
- *R=Amplitude r / Amplitude i*
- The *acoustic impedance* is important;
  - $z = \rho c$

Steel - steel	R=0
Steel - brass	R=0.4
Steel - oil	R=0.85
Steel - air	R=0.999999

An Imbedded Layer



Thick film
time of flight method

Thin film
<100μm

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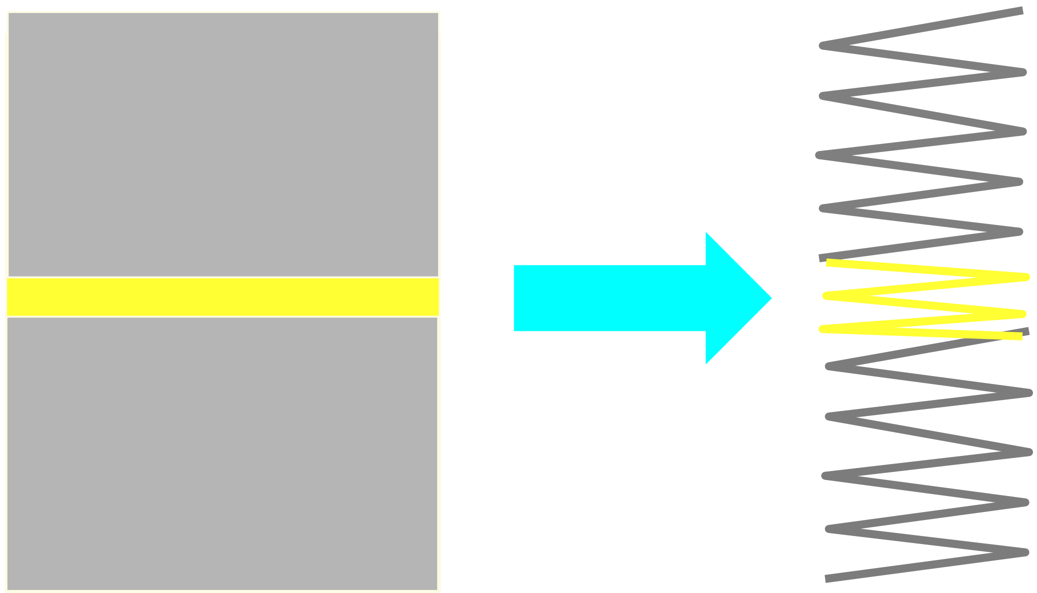
A Simple Spring Model (oil film)

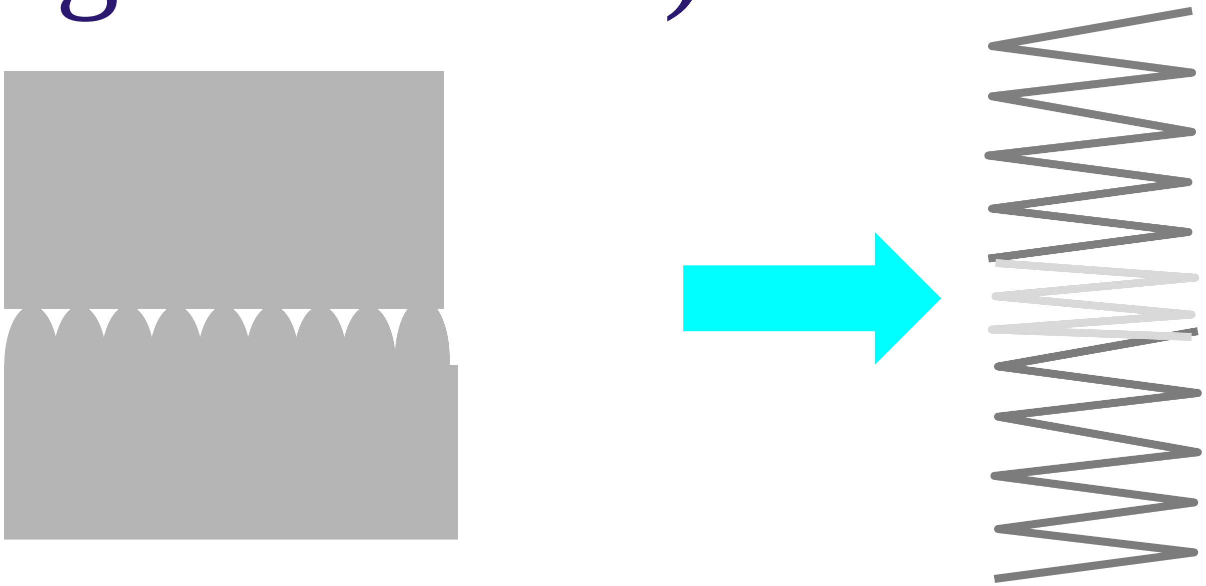


$$|R| = \frac{1}{\sqrt{1+(2K/\omega z)^2}}$$

frequency of the wave (=2πf)

stiffness of oil film = B/h
(bulk modulus / oil film thickness)

A Simple Spring Model (rough interface)

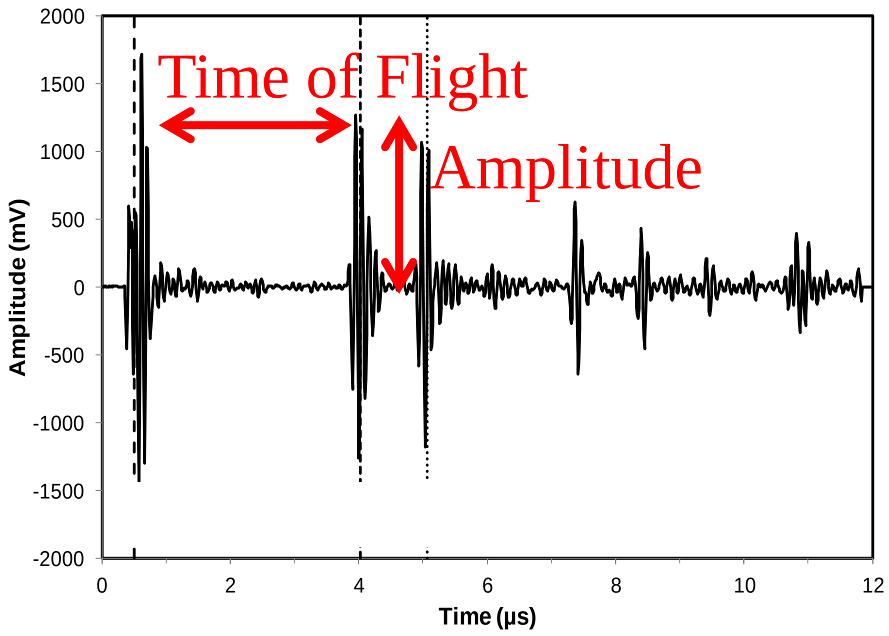


$$|R| = \frac{1}{\sqrt{1+(2K/\omega z)^2}}$$

w=frequency of the wave (=2pf)

z=acoustic impedance of the solids

In Basic Terms



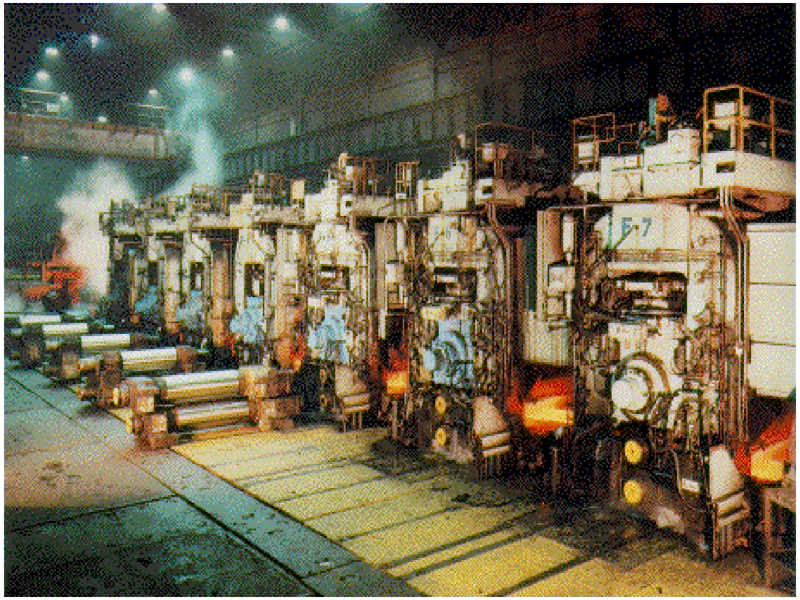
- Time of Flight will tell us about the geometry of the part (compression)

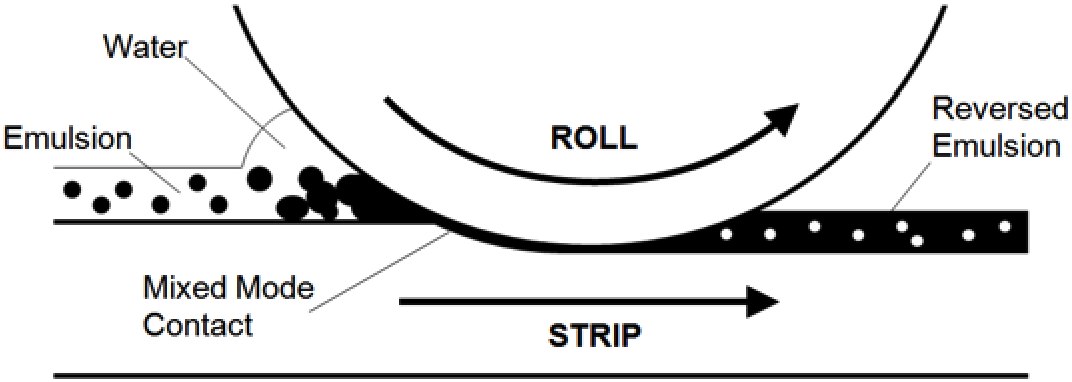
- Amplitude will tell us about the interface (an oil film, close contact)
  - R is small – very thin film of lots of contact
  - R is big – thick oil film little contact
  - R=1 no oil no contact

Three Examples

metal rolling
cutting tool contacts
incremental sheet forming

Metal Rolling & the Rollbite





- A very complicated tribological contact
  - Rough, plastic, mixed regime lubrication, two phase lubricant
- Stress, elongation, strip thickness, lubricant film
- RollGap Sensors EU Project (RFCS scheme)

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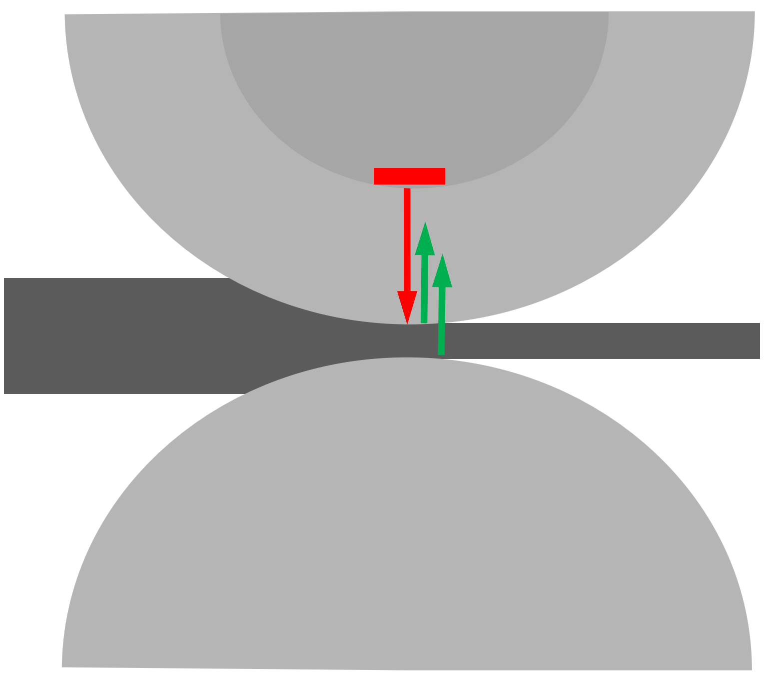
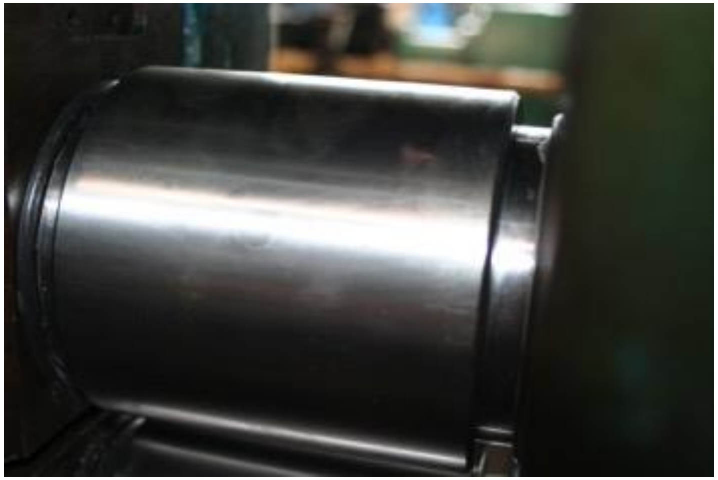
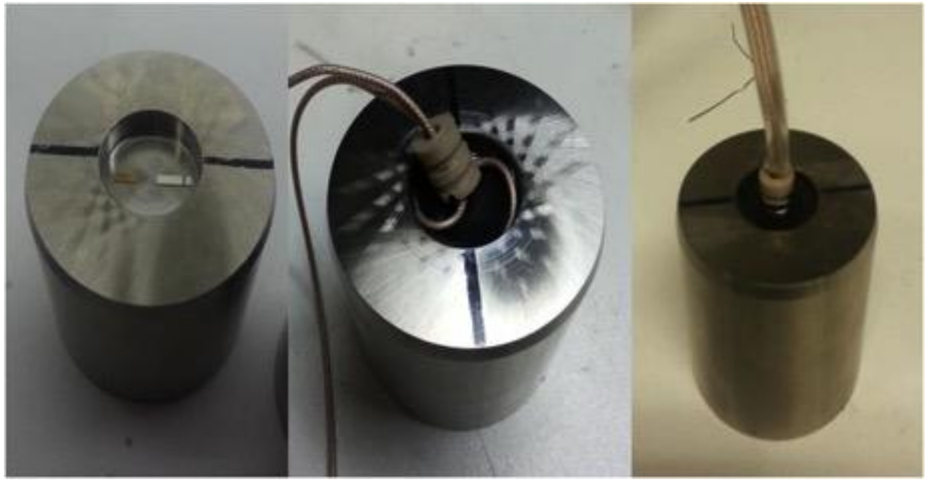
A Sensor Inside the Roll

- Transducer mounted within the roll
- Slip rings to take out the signal
- Ultrasonic pulse towards the roll bite
- Reflected back to same sensor







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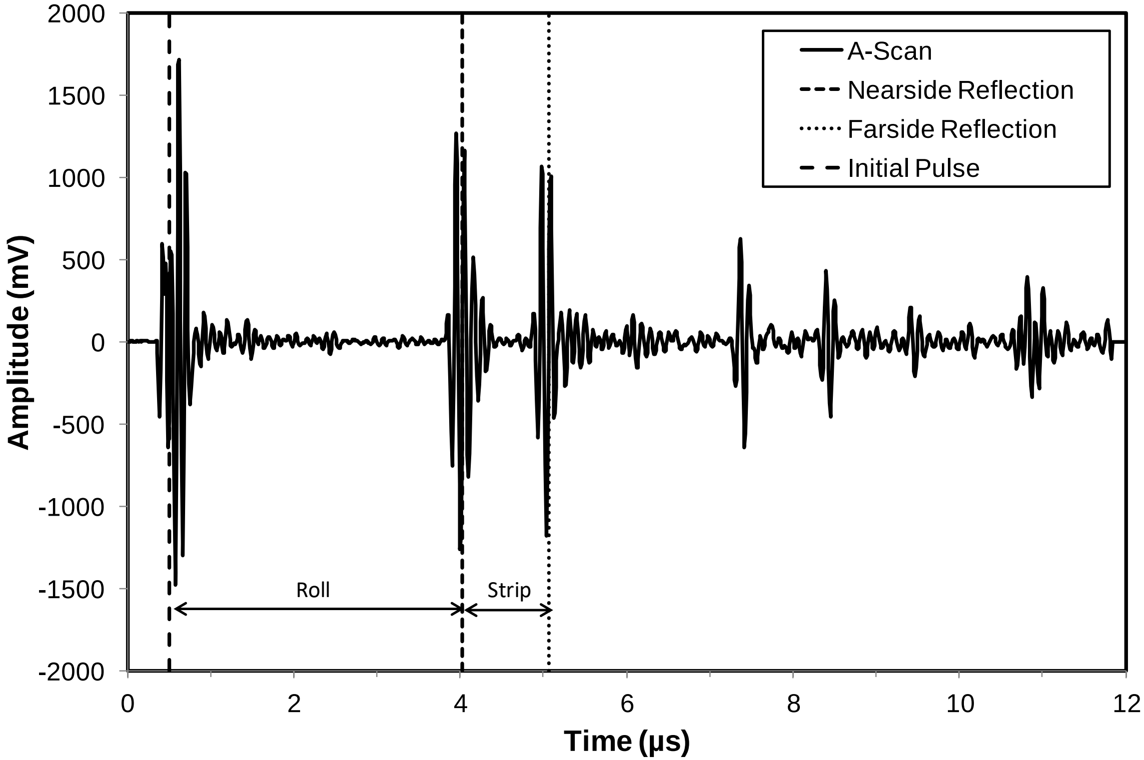
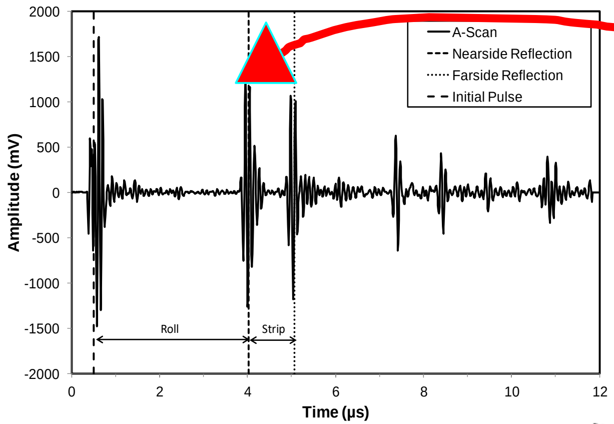
Arcelor Meziers Pilot Mill

Typical Reflected Signal
(when sensor is over the strip)

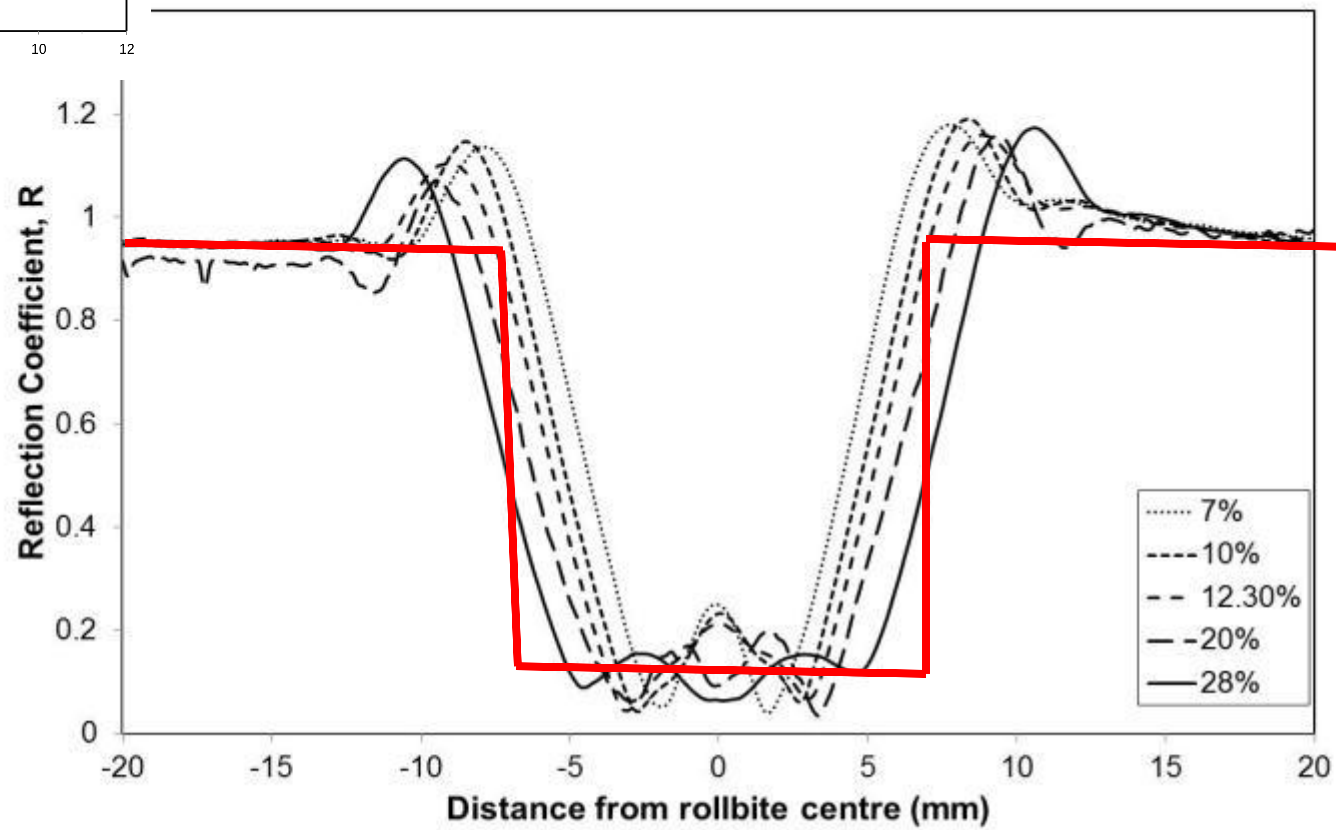


- Analysed to give:
  - Roll bite width
  - Strip thickness
  - Oil film thickness
  - Roll stress

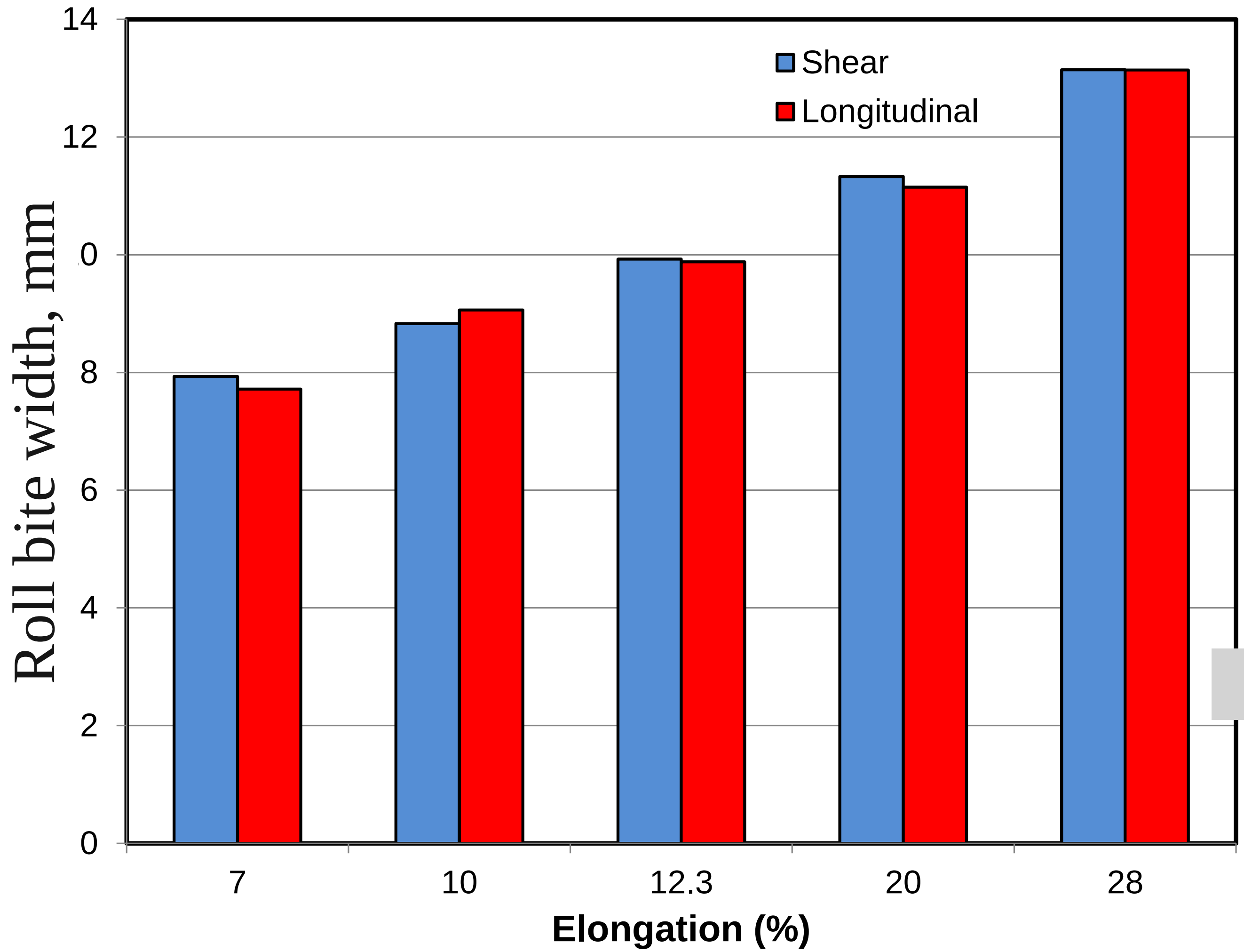
Width of Roll-Bite

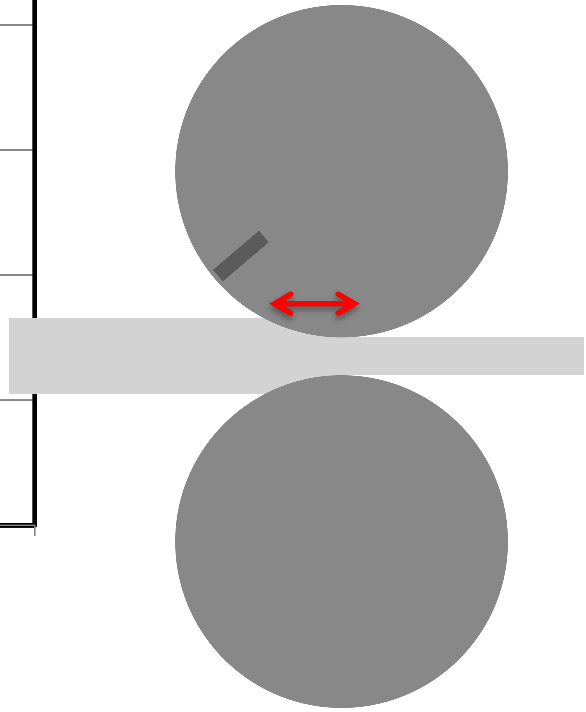


- Amplitude of the first reflection
- If R=1 no contact, R<1 contact
- Showing whether in or out of contact
- Finite sensor resolution

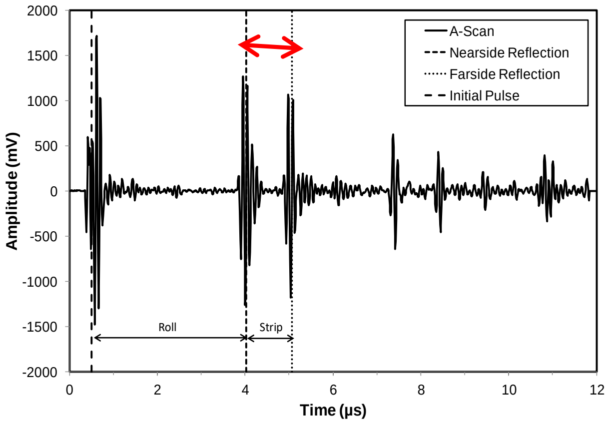


Estimate of Roll-bite Width

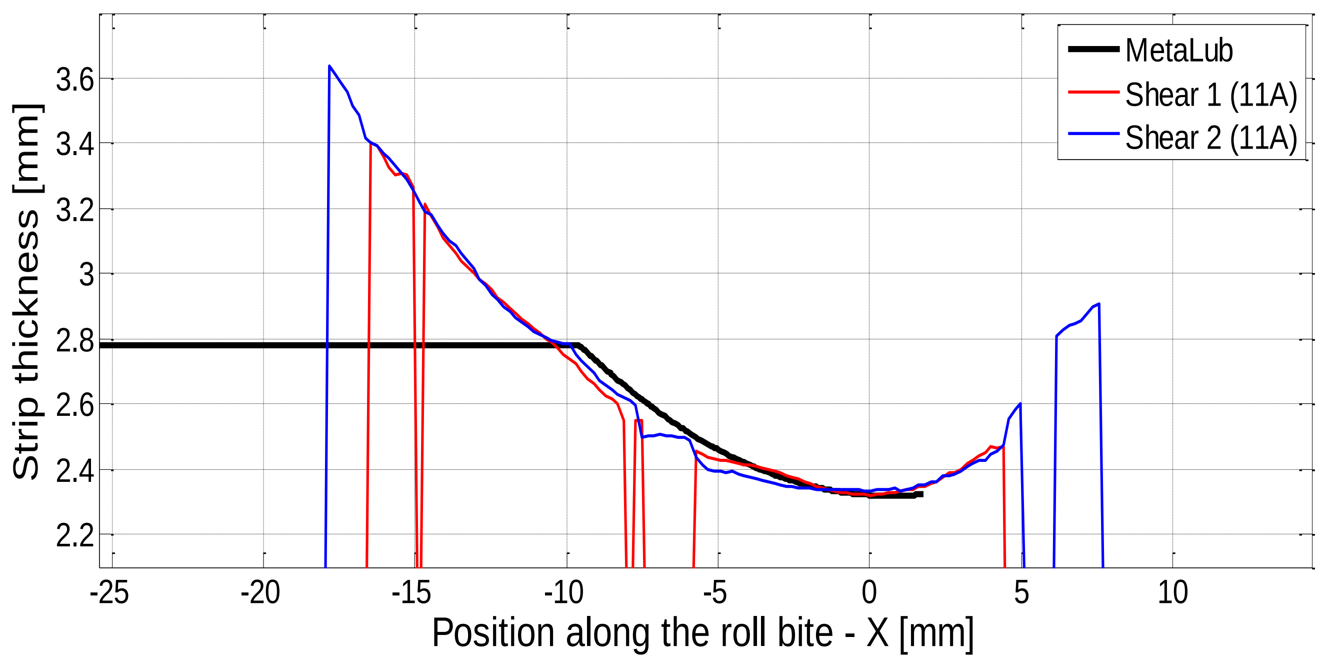




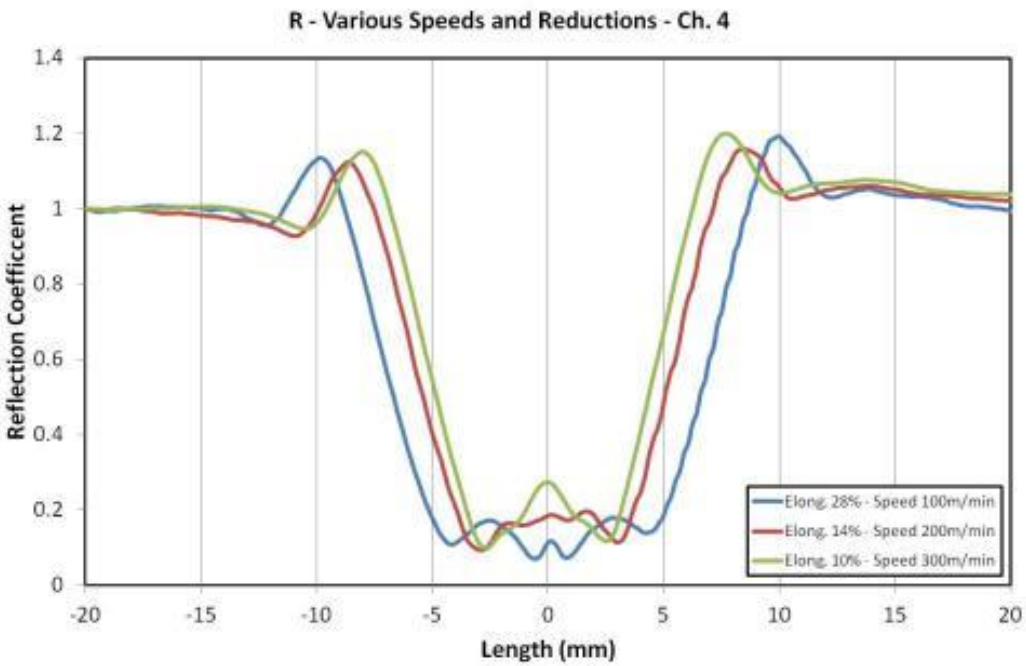
Strip Thickness

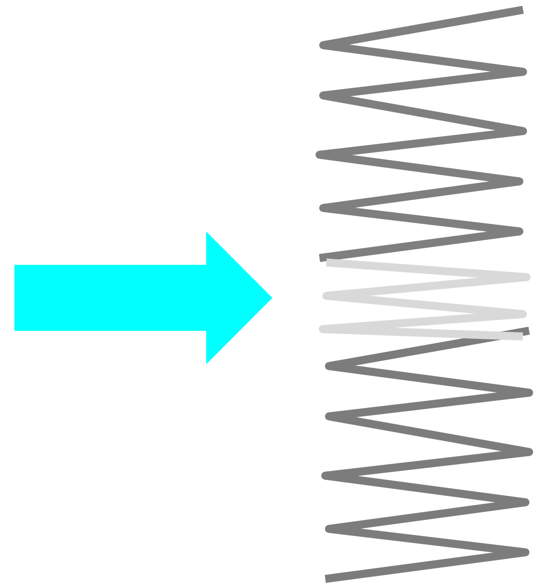


- time difference between strip near-side and far-side reflections
- Compared with prediction from 'Metalub'



Reflection Coefficient

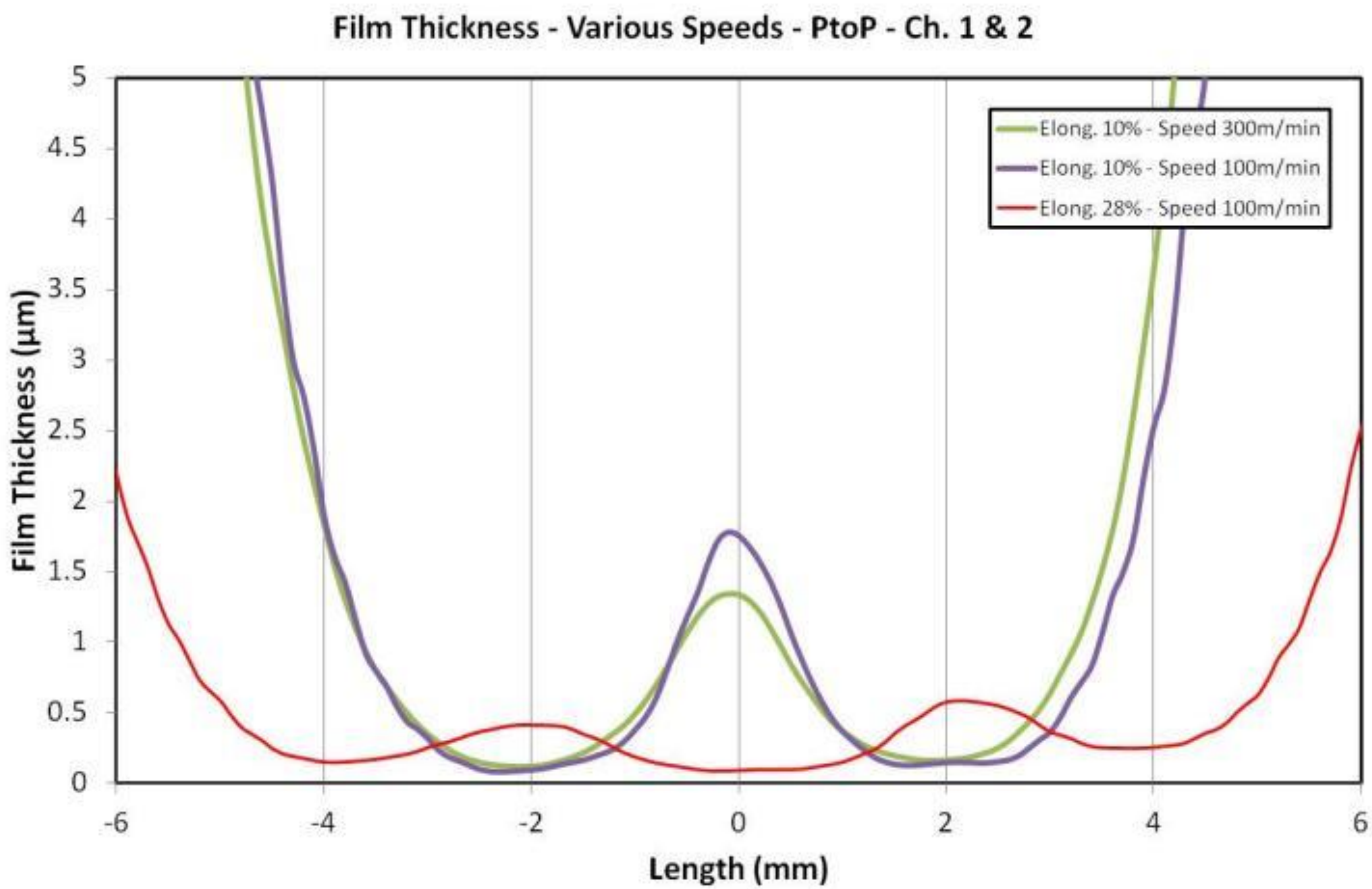




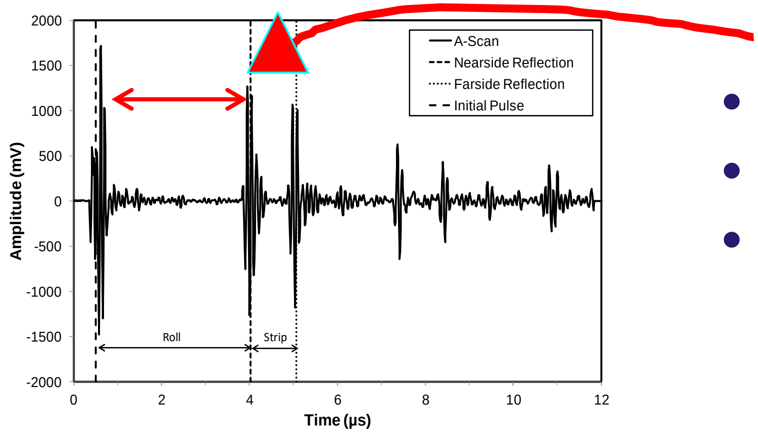
$$|R| = \frac{1}{\sqrt{1 + (2K/\omega z)^2}}$$

$$K = \frac{B}{h}$$

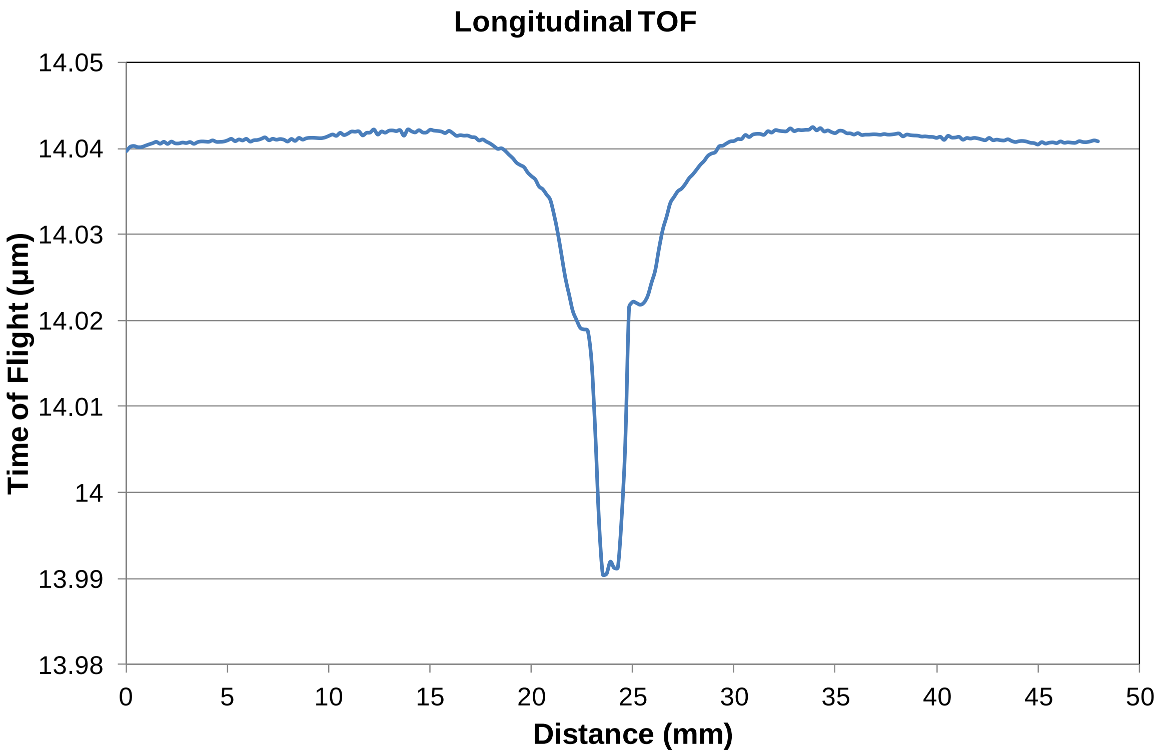
Oil Film Thickness

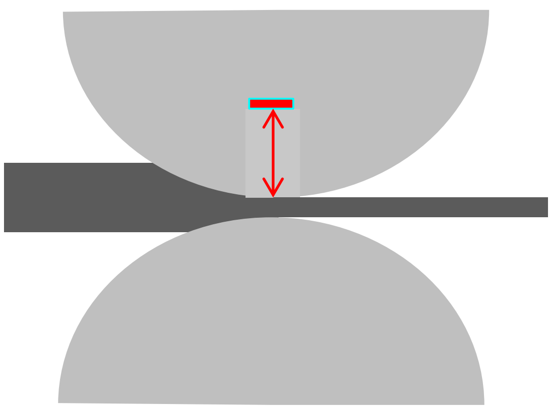


Roll Stress



- time of flight through roll
- as sensor moves over strip
- As roller compresses path is shorter



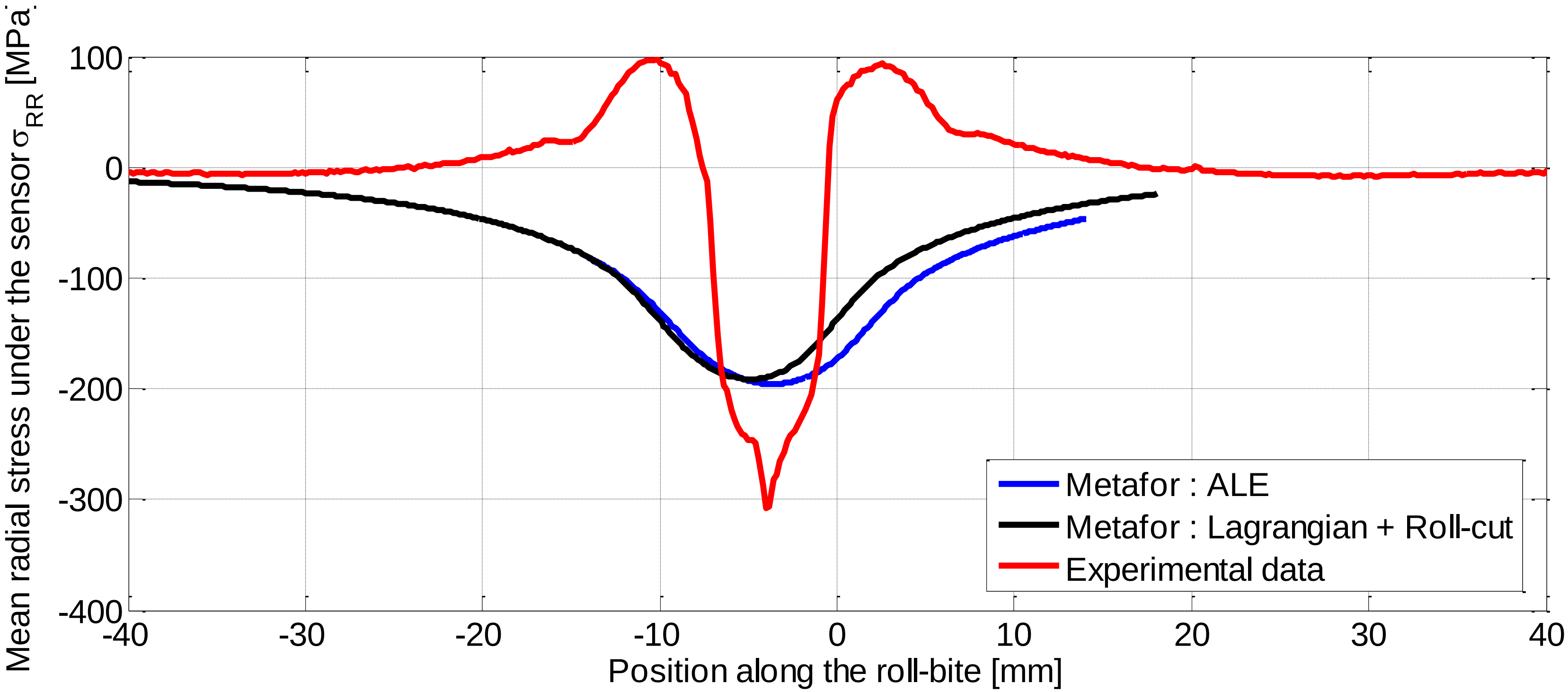


Acousto-elastic Effect

- When a material is under stress its speed of sound changes
- Called the *acousto-elastic* effect
- Means the time of flight will change
- Depends on, α (acousto-elastic constant)

$$V_L = V_{L0}(1 + \alpha_L \sigma)$$

Radial stress : σ_{RR} [MPa]



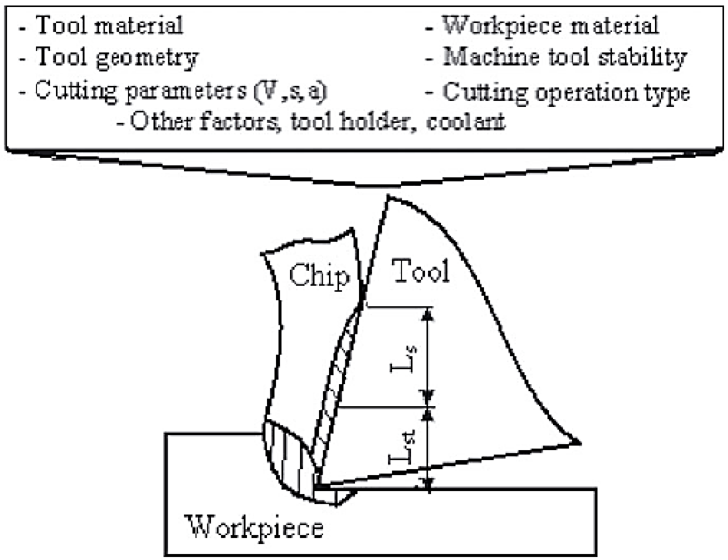
Three Examples

metal rolling

cutting tool contacts

incremental sheet forming

Metal Cutting

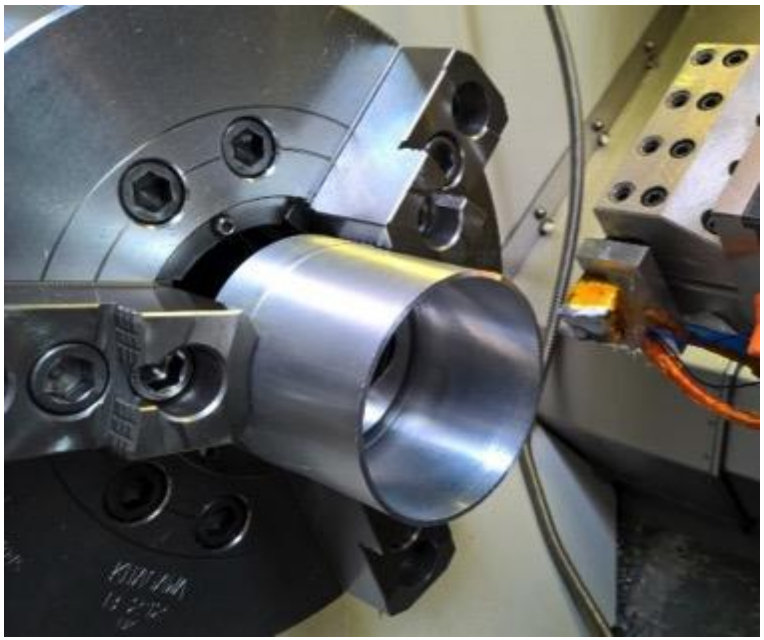


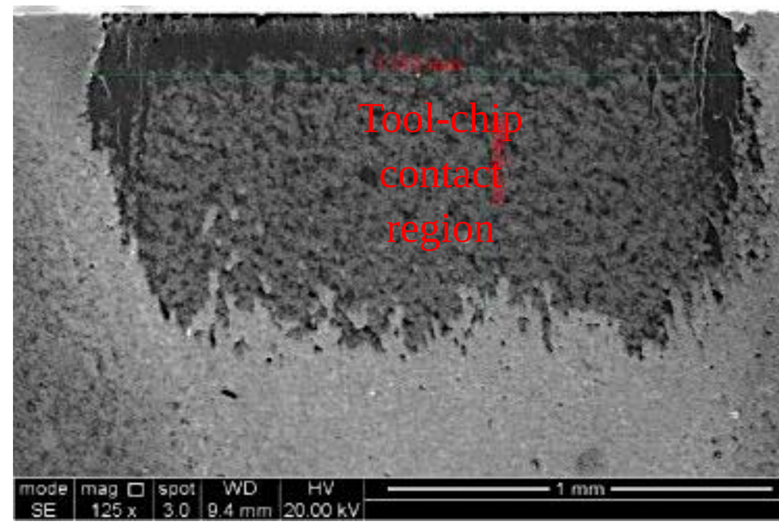
a) Single-point cutting edge

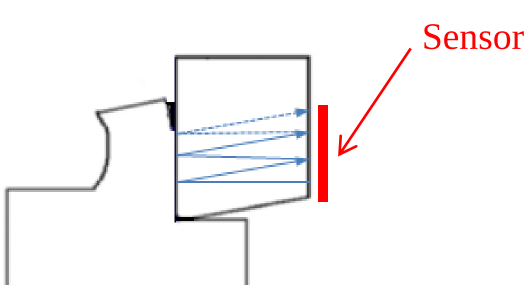
b) Multi-point cutting tool

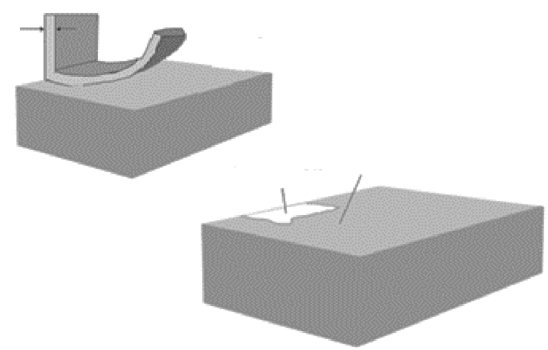
- Effect of machining parameters on
  - ship formation
  - tool wear
  - coolant film formation
  - friction
  - surface finish

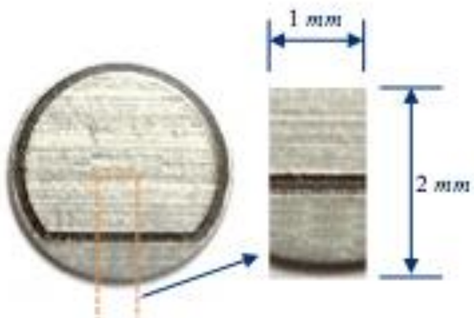
Instrumenting a Cutting Tool

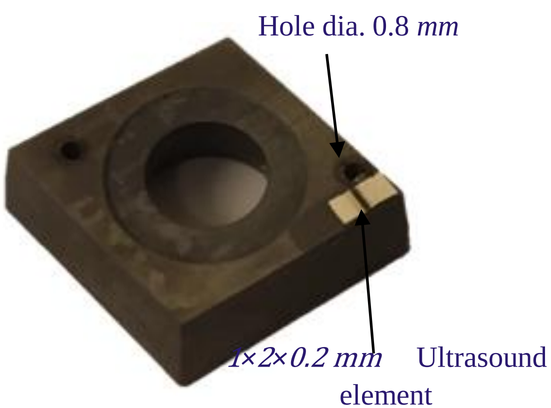


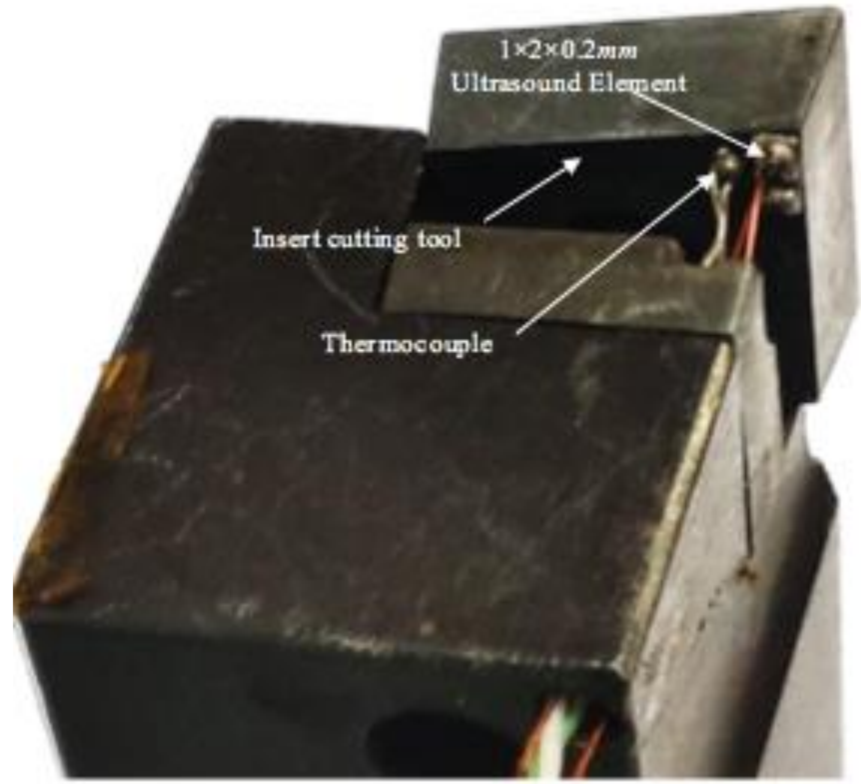







1 mm
2 mm


Hole dia. 0.8 mm
1×2×0.2 mm Ultrasound element


1×2×0.2mm
Ultrasound Element
Insert cutting tool
Thermocouple

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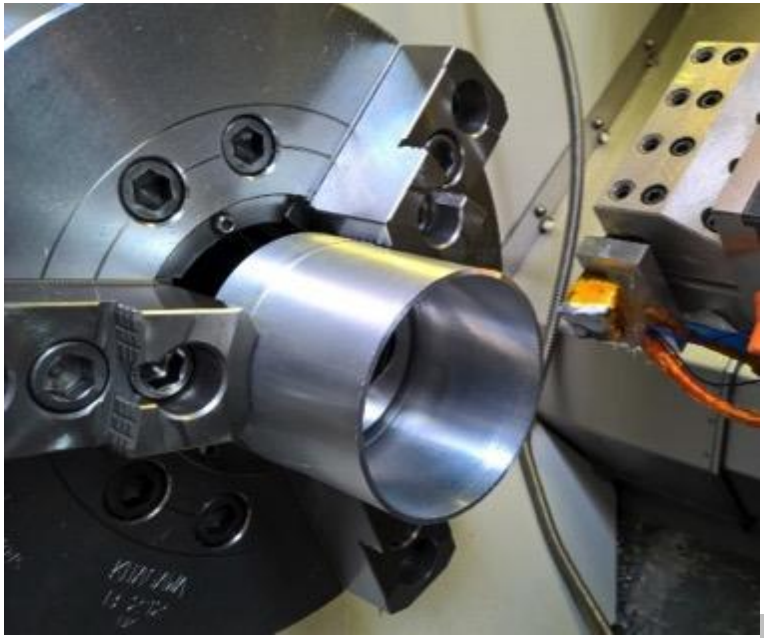
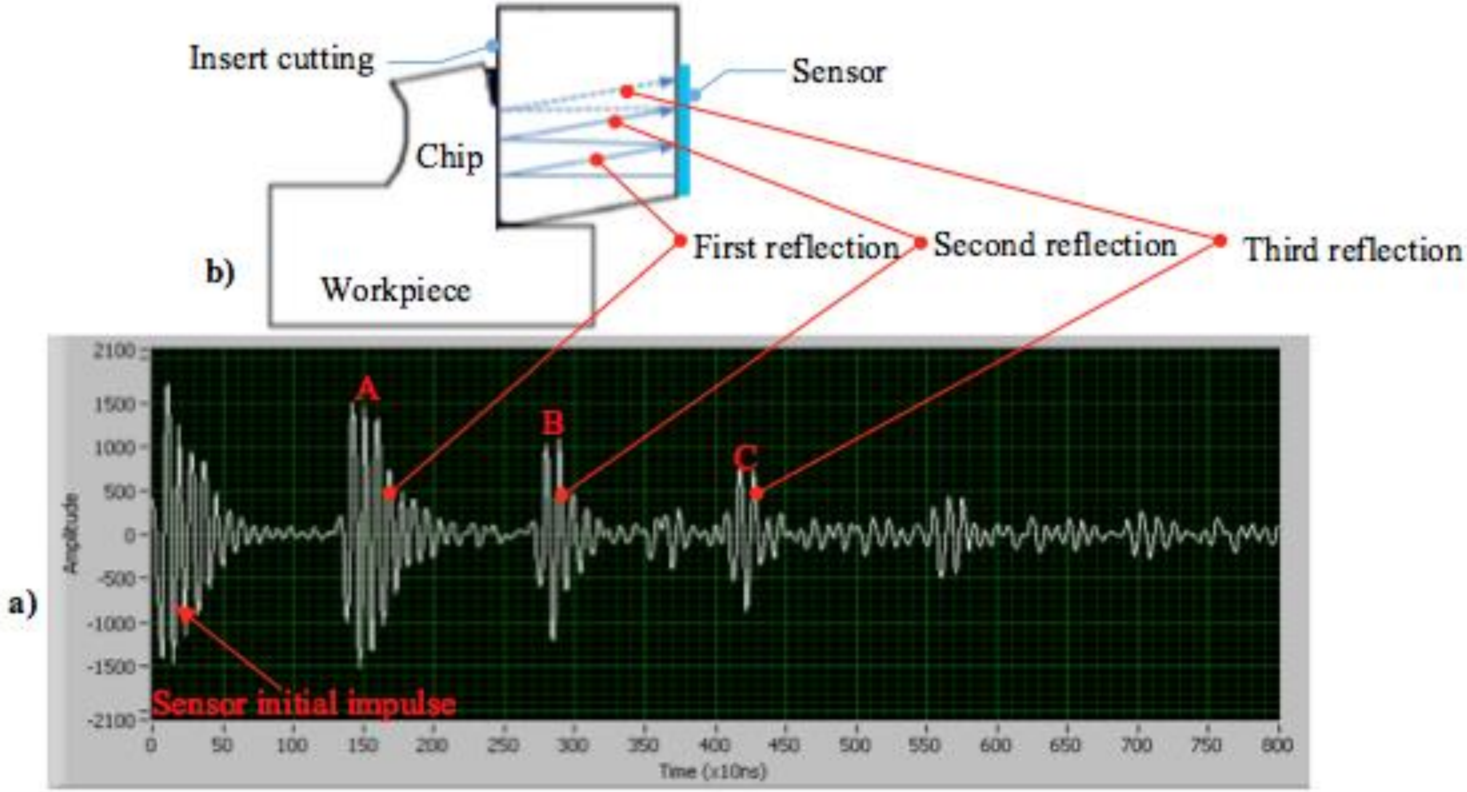
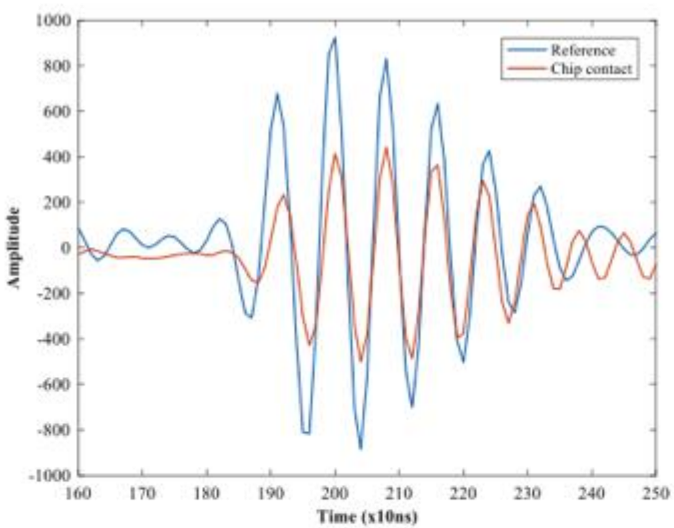


- 6082-T6 Aluminium tube,
- Orthogonal cutting with a Kyocera tool insert uncoated
- CNC Lathe MAG HAWK 300
- Kistler Dyno for cutting forces

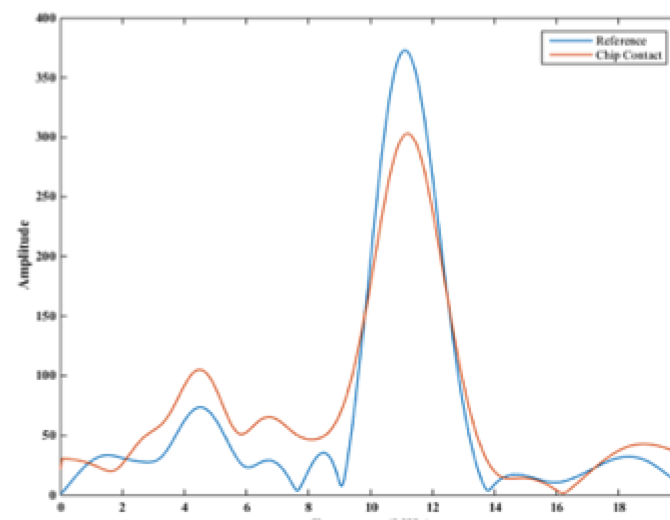
Parameters	Levels				
	1	2	3	4	5
Cutting speed (m/min)	40	60	90	120	140
Depth of cut (mm)	1.2	1.5	2	2.5	2.8
Feed (mm/rev)	0.09	0.12	0.16	0.2	0.23



Insert cutting
Sensor
Chip
Workpiece
b)
First reflection
Second reflection
Third reflection
A
B
C
Sensor initial impulse
a)
Amplitude
Time (x10ns)



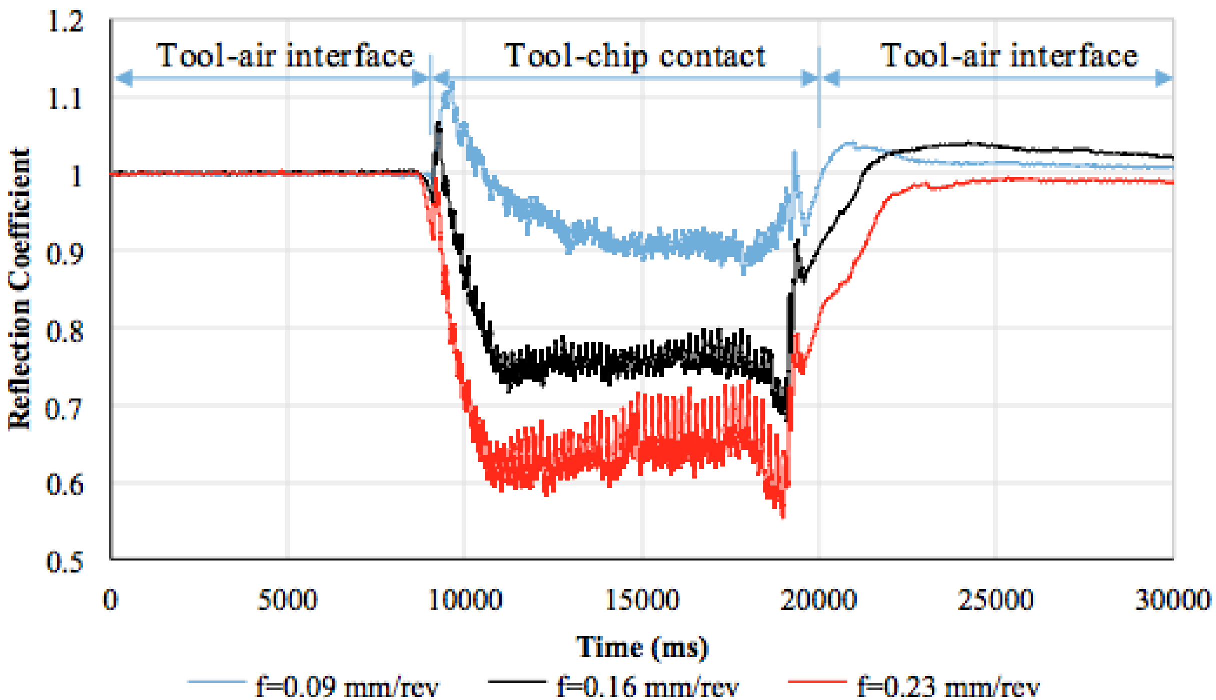
Reference
Chip contact
Amplitude
Time (x10ns)



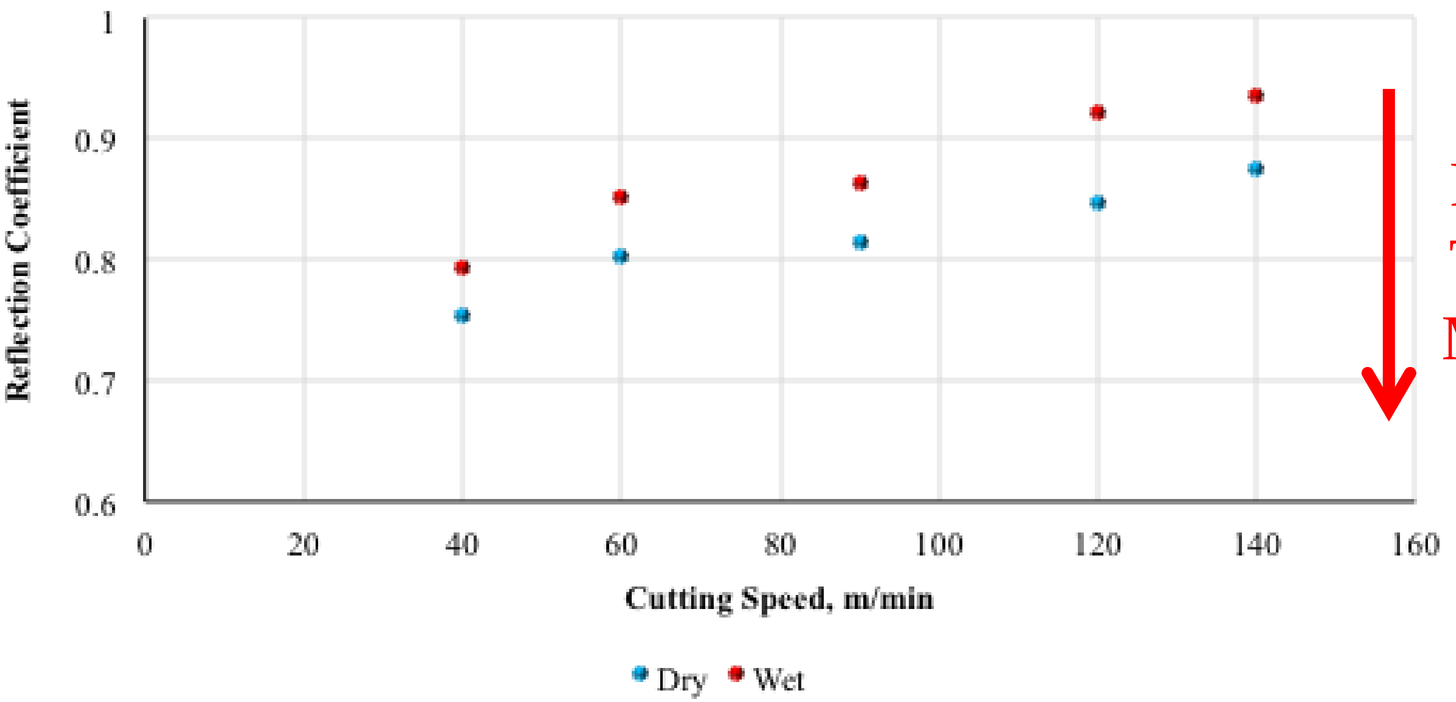
Reference
Chip Contact
Amplitude
Frequency (MHz)

Dry Cutting

- Vary feed with depth and speed constant
- Not immediate engagement
- Increase in chip contact area with feed rate
- High frequency oscillation in the signal (4.77 Hz – corresponds to spindle speed 286rpm)

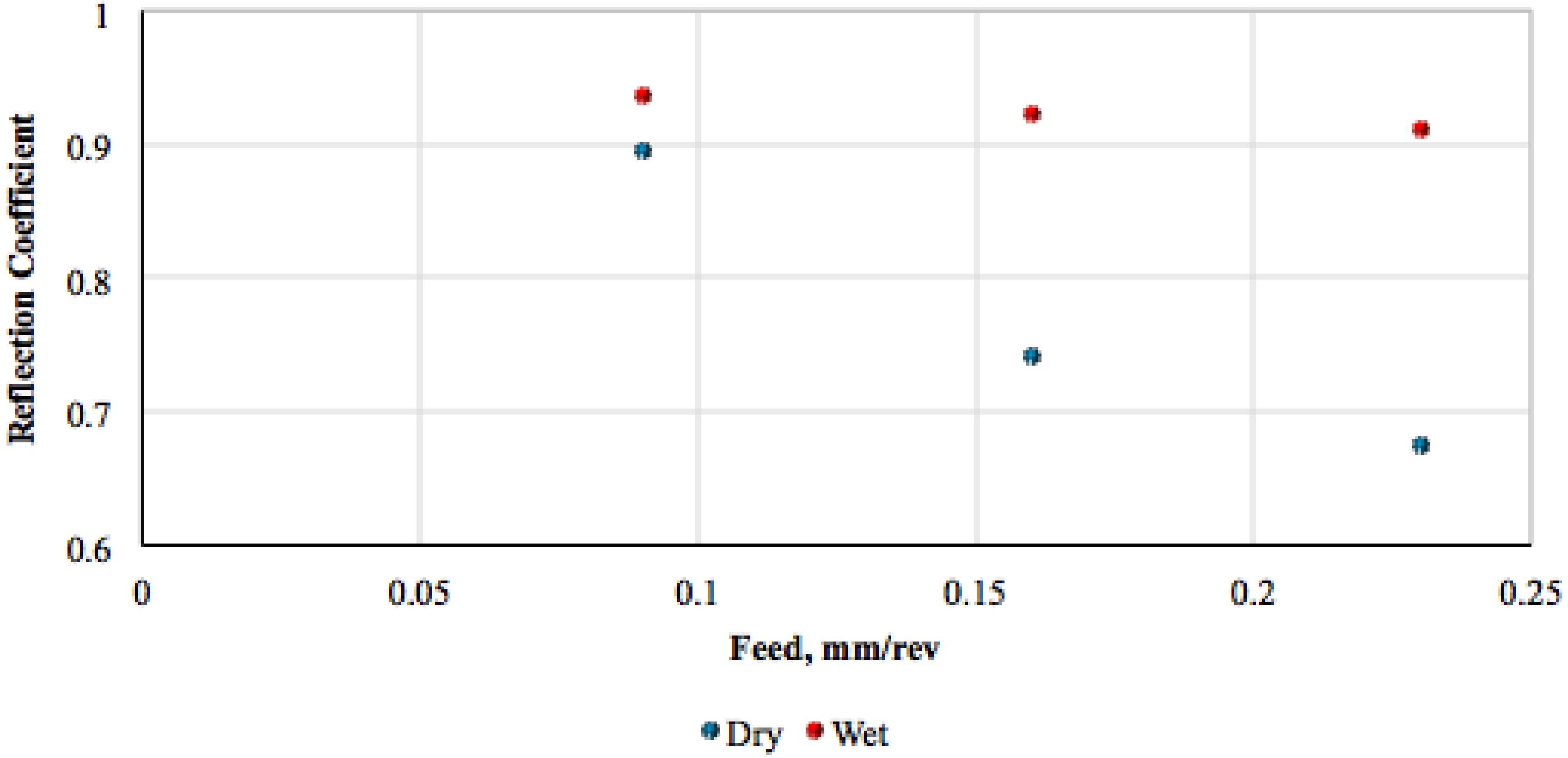


Effect of Cutting Speed

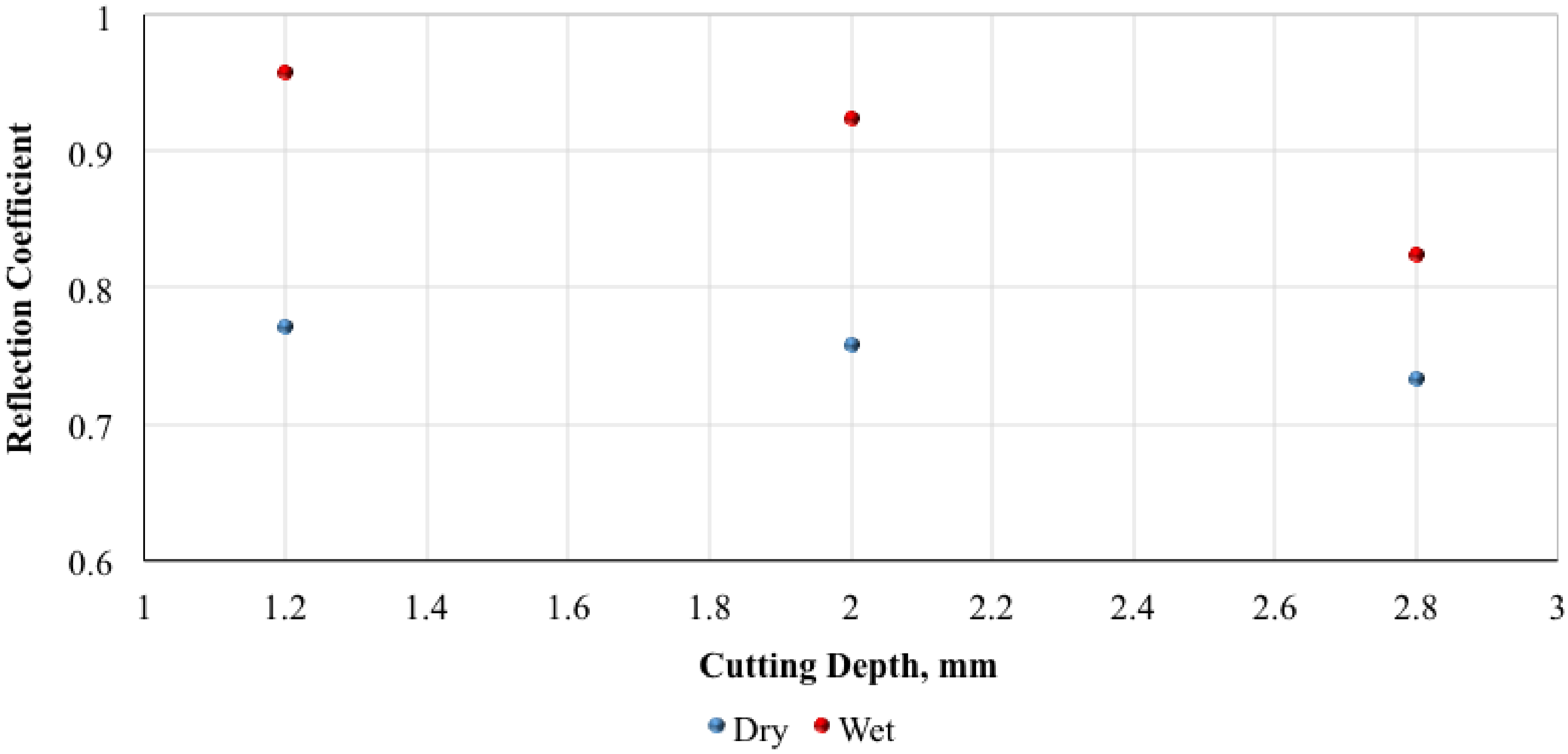


R reduces as
Thinner film
More contact

Effect of Feed Rate



Effect of Cutting Depth



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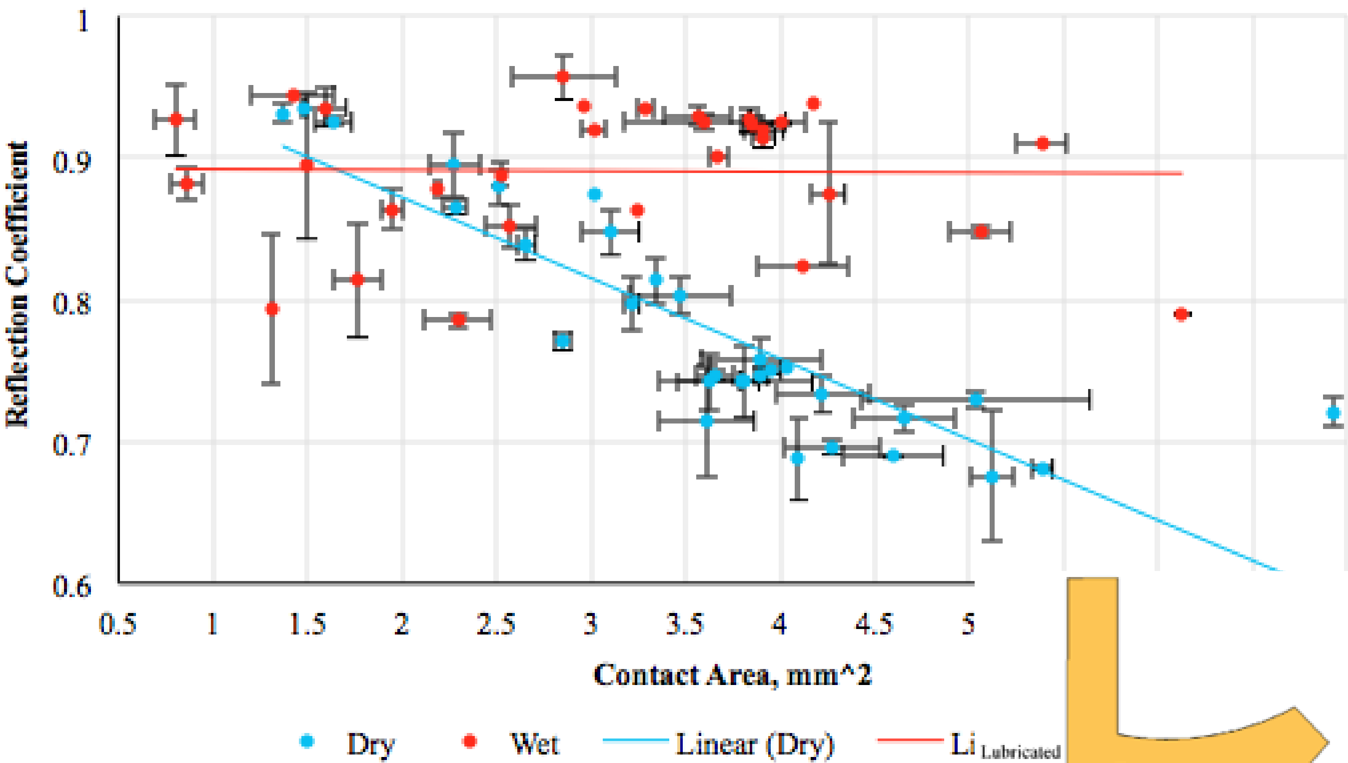
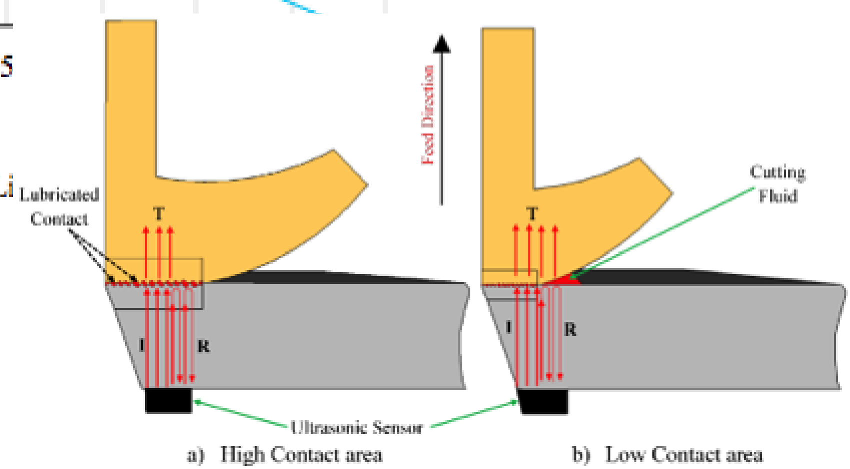
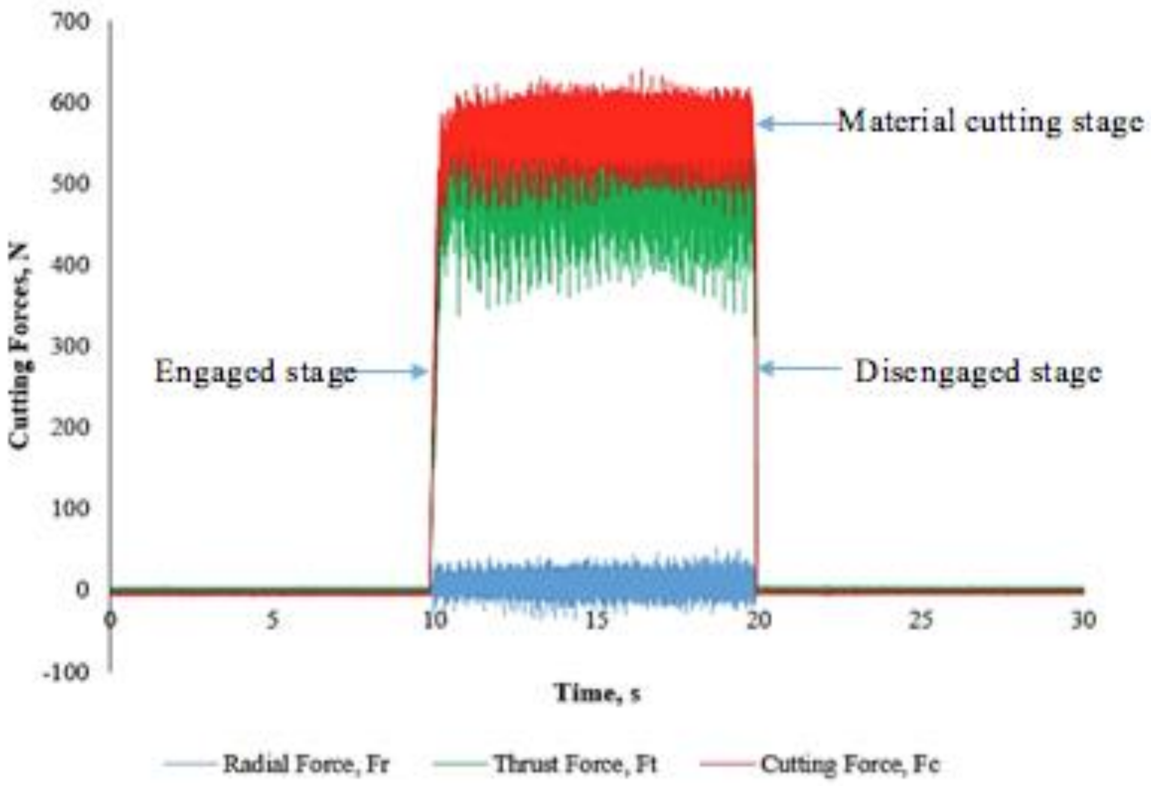
Effect of Oil on ‘Contact Area’

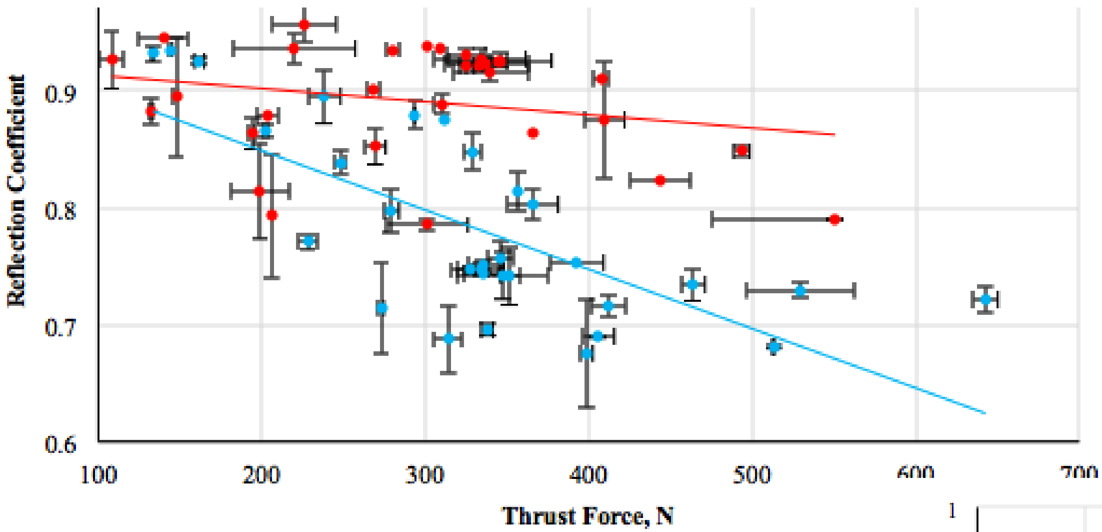


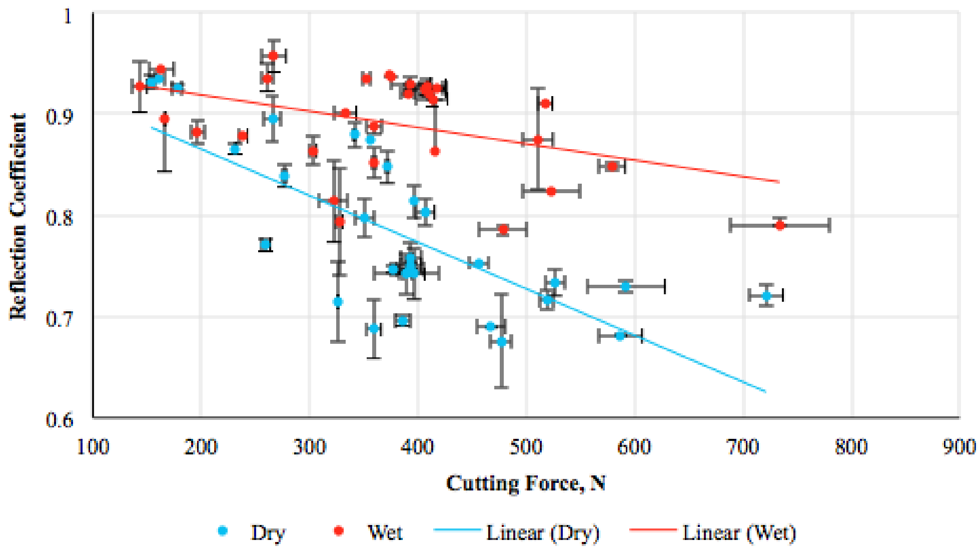


Cutting Forces measured on Dyno



Correlation to Cutting Forces



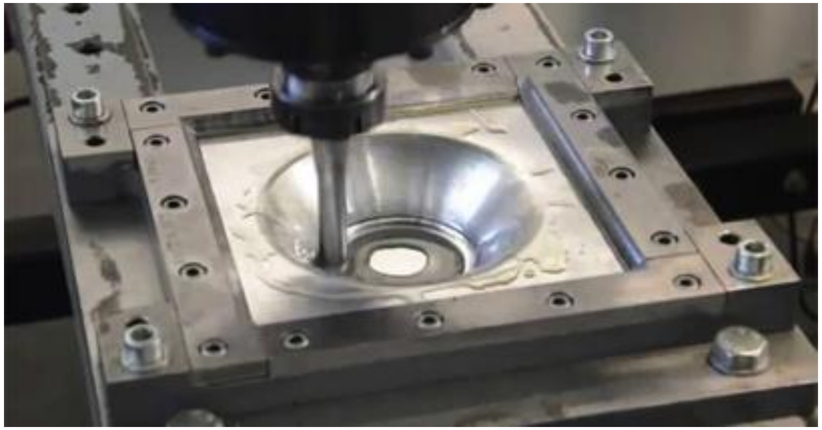


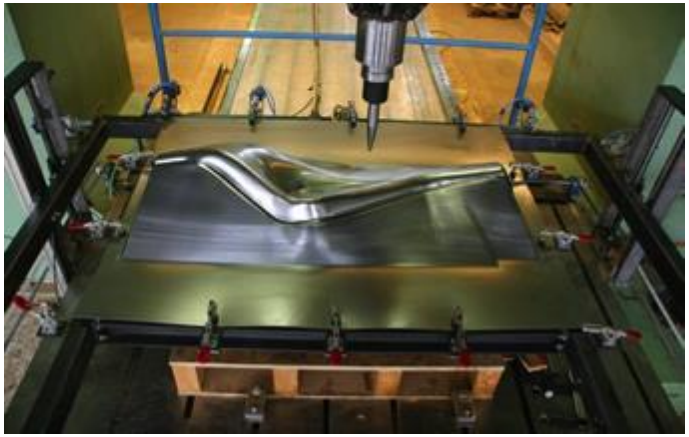
Four Examples

metal rolling
cutting tool contacts
incremental sheet forming

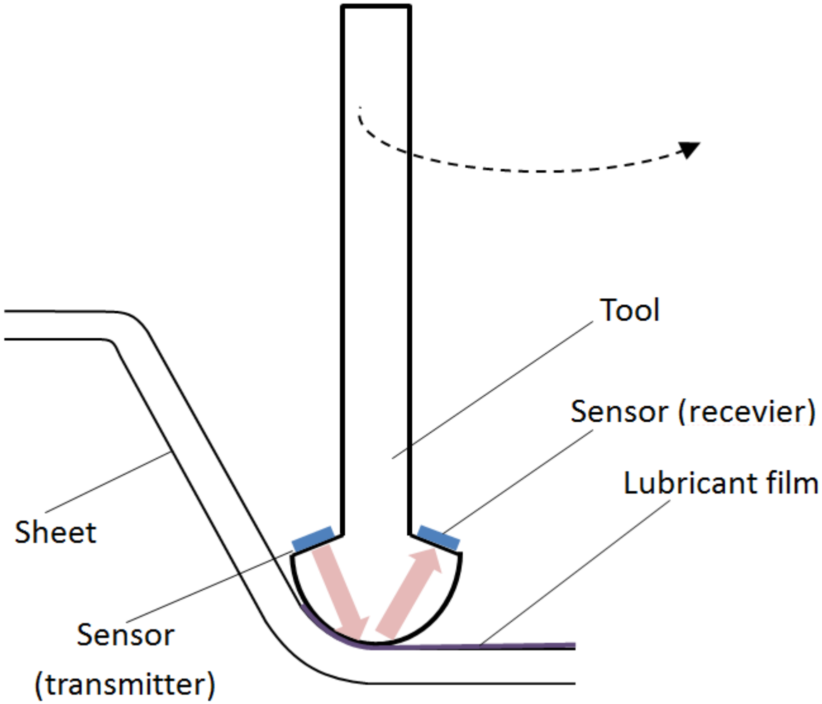
Incremental Sheet Forming

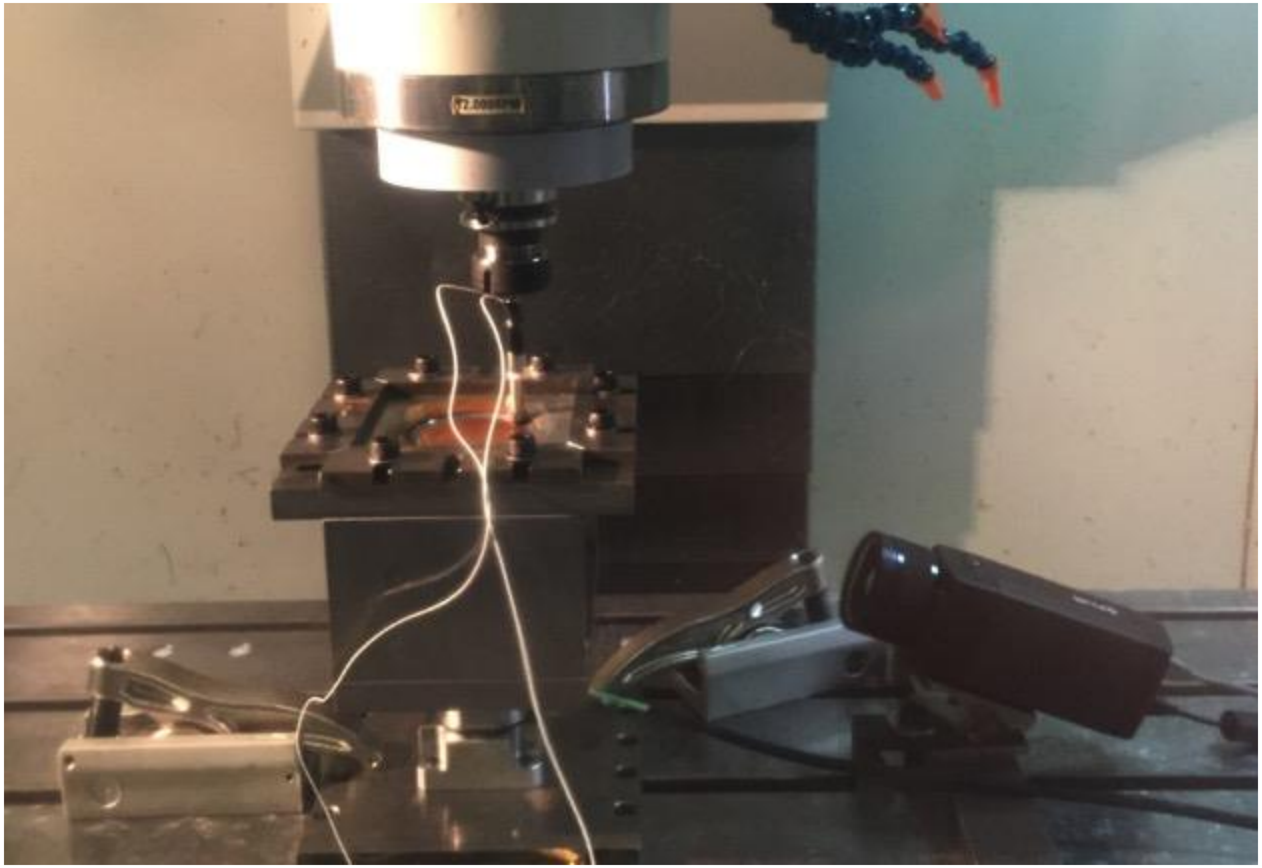
- Incremental passes of a round tipped tool over a work piece.
    - Controlled by CNC
    - No need for a forming die
    - Reduces cost for low production runs
- But how much can you press each run
- Role of lubrication under different forming conditions





Tool Instrumentation





Test No	Feed rate (mm/min)	Lubricant	Forming Angle (degree)
1	1000	Grease	60
2	1000	Grease	30
3	2000	Grease	30
4	1000	oil	30

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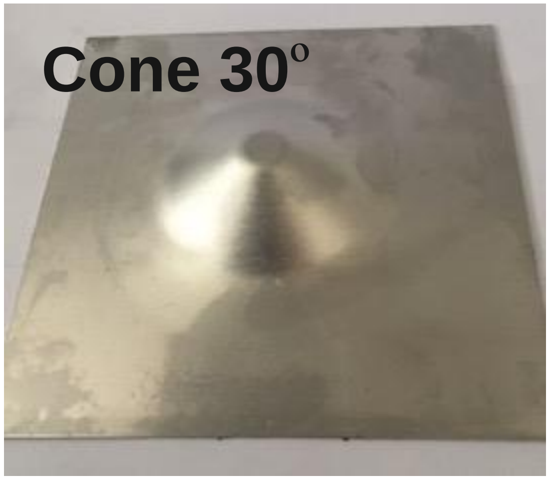
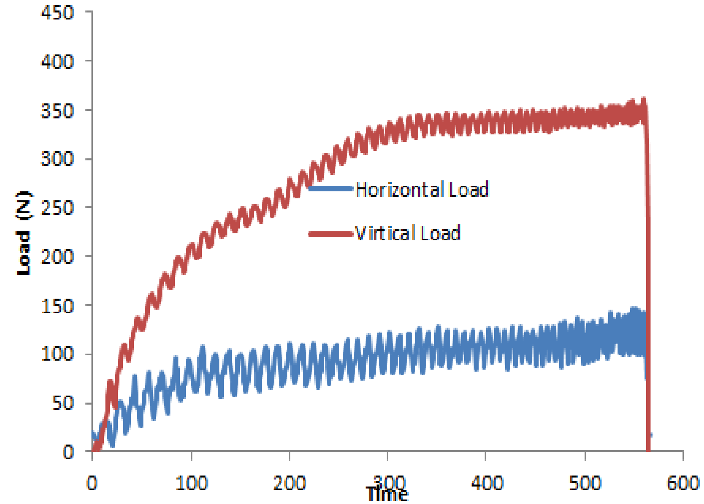
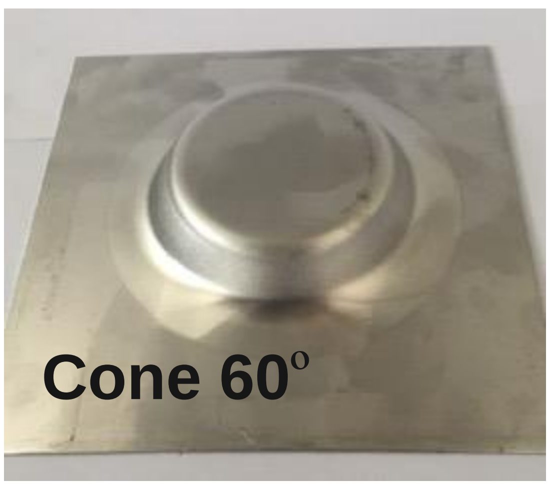
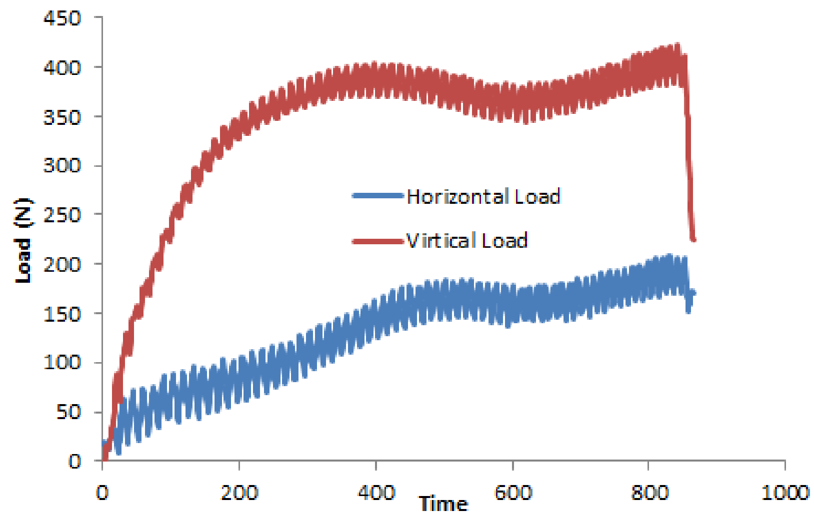




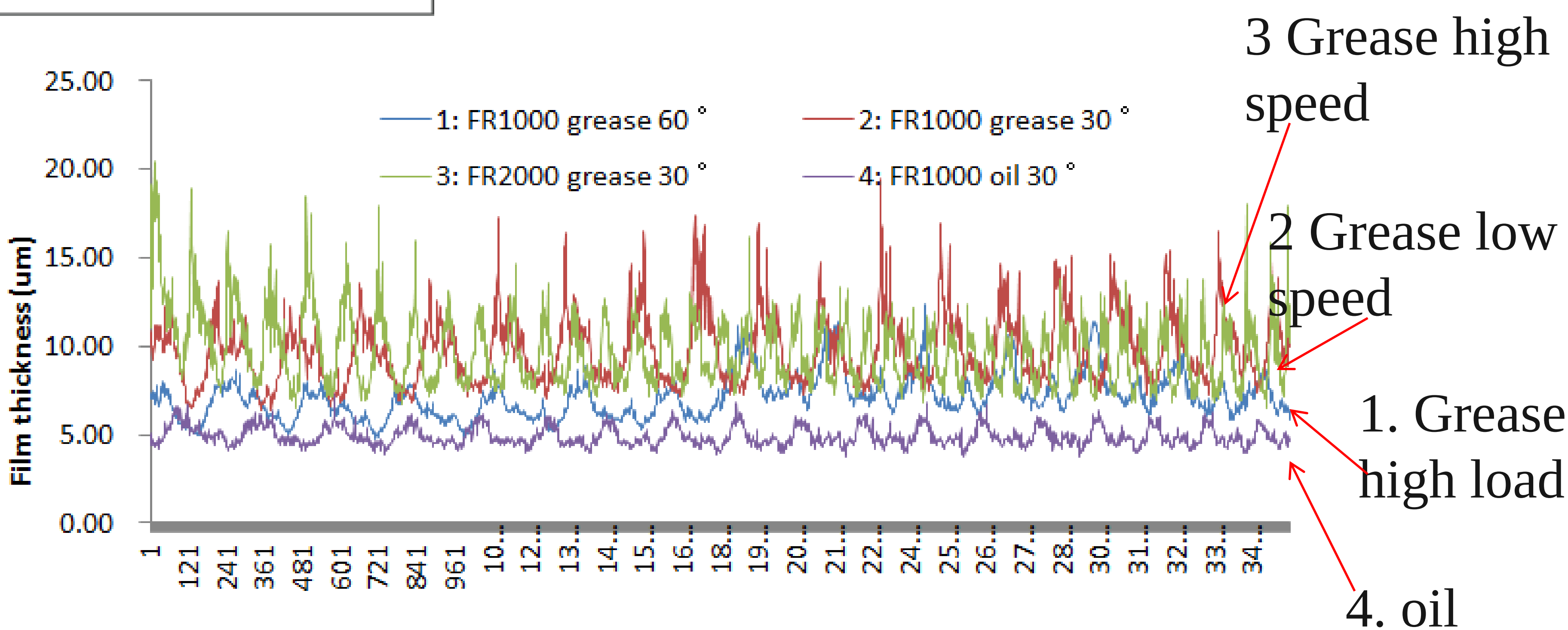




The forming load from cone 60° is slightly higher than 30°

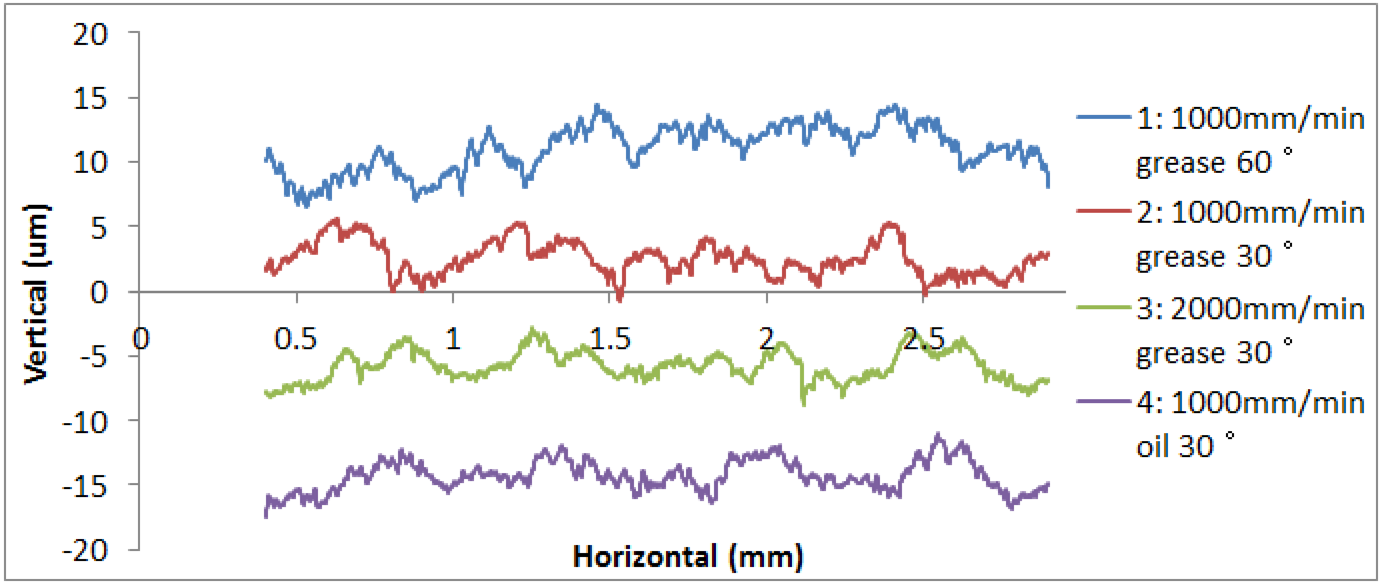
The University Of Sheffield.

Measured Oil Film

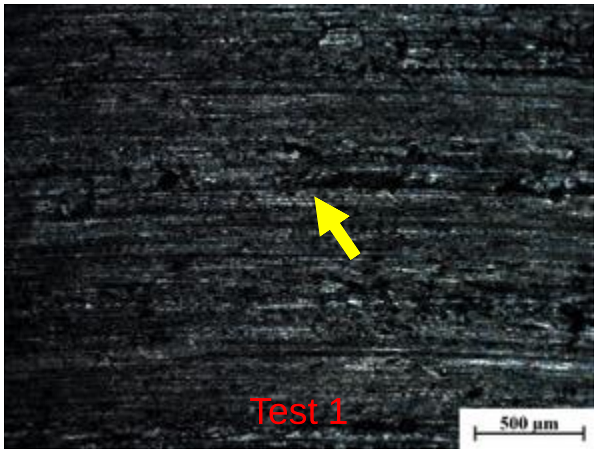


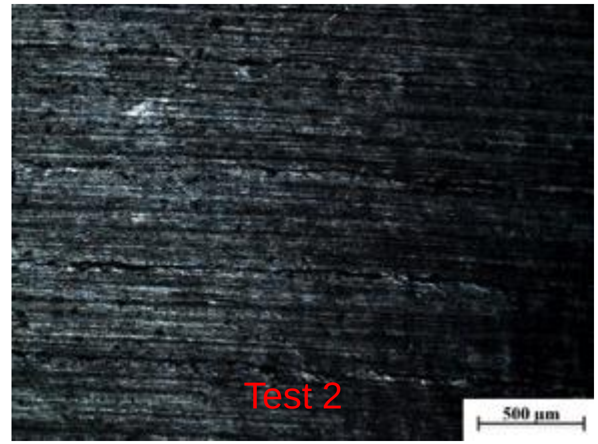
- Fluctuation around the circumference
- The oil film is thinner than the grease film
- For grease
  - The higher loaded case has lowest film
  - Speed made little difference
- 3 > 2 > 1 > 4

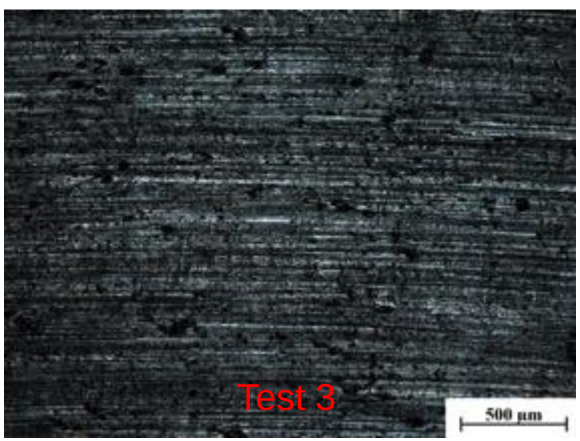
- Sample 1 has largest RA value
- No obvious difference can be seem in surface profiles
- 3 < 2 < 4 < 1

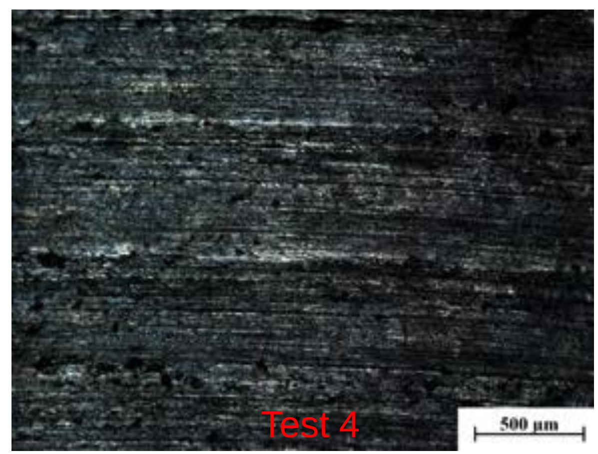


Sample	RA, um
1	2.017
2	1.132
3	0.883
4	1.134


Test 1
500 µm


Test 2
500 µm


Test 3
500 µm


Test 4
500 µm

Conclusions

- The cutting/forming interface is critical in manufacturing
- Ultrasound can be a non-destructive way of measuring that interface
- The problem is that interface is often small and inaccessible
- If we have nice big contacts
  - Direct measurement of oil film, geometry and contact stress
- Often the interface is small
  - smallest sensor size 1 – 2mm square
  - We can only observe 'empirical' correlations
- Challenge – using the measurements to change the process

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  - Dlair Obaid (machining)
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