NISTIR 7446

Proceedings of the NIST/USCAR Workshop on Friction Issues Related to Metal Forming

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October 2007

U.S. Department of Commerce
Carlos M. Gutierrez, Secretary

National Institute of Standards and Technology
James M. Turner, Acting Director

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Abstract

Variability in the friction behavior between the work piece and the forming die during forming is a significant obstacle impeding the widespread use of new alloys developed to increase automobile fuel economy. In response to this critical issue, the NIST Metallurgy Division and the United States Council for Automotive Research (USCAR) sponsored a workshop designed to improve the reliability of the numeric models used to predict the friction behavior during sheet metal forming. The main goals were to clearly identify the factors responsible for the variability in the friction behavior, and to establish the industrial measurement and modeling needs so that an appropriate solution may be developed. This summary of a one-day workshop, held in July 2006, features presentations by members of a working group of experts from the automotive, academic, and materials modeling and measurement communities. The major conclusions were: a) classical friction models are not adequate in sheet metal forming, b) new measurements that focus on the interaction between surfaces must be developed, and c) new surface characterization measurements and tools that relate surface morphology to the functional behavior must be developed.

Keywords: Friction behavior; Springback; Mechanical properties; Friction measurements; Numeric predictions

ACKNOWLEDGEMENT

The author would like to thank Dr. Thomas B. Stoughton of the General Motors Manufacturing Systems Research Lab, and Dr. Lyle E. Levine of the NIST Materials Performance Group for their indispensable contributions, recommendations and help with the organization of this workshop. The author would also like to acknowledge the efforts of Dr. Manish Mehta of the National Center for Manufacturing Sciences and the offices of the United States Council for Automotive Research (USCAR) for allowing us to use their facilities to hold our workshop.

DISCLAMER

This report is intended as a record of the presentations and discussions that took place at a workshop sponsored by the Metallurgy Division of the National Institute of Standards and Technology. The opinions, conclusions or recommendations that are expressed herein are those of the organizers or of the individual presenters and do not necessarily reflect the views of NIST. Any references made to commercial equipment in this report are for identification purposes only and do not constitute any endorsement or evaluation of the relative merits of such equipment by NIST.

WORKSHOP SUMMARY

The NIST Metallurgy Division recently held a workshop designed to improve the reliability of the numeric models that are used to predict the friction behavior during sheet metal forming. The principal driving force for this workshop was identifying the factors that cause the variability observed in the friction behavior between the work piece and the forming die. This variability is primarily due to the evolution of an inhomogeneous surface morphology produced by plastic strain. Inhomogeneities in the surface character are known to localize strain and promote component failure by tearing or wrinkling, alter the friction between the metal sheet and the die surfaces during metal forming, produce unexpected variations in residual stresses that affect springback, and progressively degenerate the die shape via accelerated wear. The inability to reliably model the friction behavior during sheet metal forming presents a significant obstacle that impedes the widespread use of the high strength alloys intended to increase automobile fuel economy. While the overall accuracy of the numeric predictions of friction have been improved, many of the models still heavily rely on empirical friction measurements and data.

There are many approaches for evaluating friction behavior established in the literature. However, most of these accepted measurement techniques focus primarily on friction mechanics and they generally do not account for the strong influences that dynamic loading and variations in initial metallurgical conditions (e.g., grain size, microhardness) have on the material properties during the deformation process. Clearly, a reliable friction model must correctly assess the complex force relationships that occur during forming, but that model must also accurately predict the changes that occur in the material properties. This is a considerable challenge because rapid loading and metallurgical condition have profound influences on the properties and on the evolution of deformation-induced surface roughness. Consequently, the friction values used in a finite element analysis (FEA) simulation are likely to not fully represent the true metal behavior under a particular set of loading conditions. As a result, new experimental approaches are needed to a) evaluate both the static and the dynamic properties for the materials of interest, and b) improve the understanding of the intricate relationships between loading, microstructural variations and friction behavior that affect the properties during metal forming.

The primary intent of this workshop was to establish a working group that is composed of members from the automotive, academic, materials modeling and measurement communities, and to foster a regular dialog among this working group. The objective was to clearly identify and prioritize the problem(s), with a particular emphasis on the industrial measurement need, so that an appropriate approach for a solution may be developed.

This one-day workshop was directed at two principal topics. The first was friction measurements. The extensive background information on the traditional techniques used to measure friction was elucidated through a series of presentations by experts in the field. Both the limitations associated with these measurement techniques, and the primary assumptions made regarding the material behavior, were discussed to help identify the principal gaps in understanding. Key areas where research should be focused, as well as the type of data required by both existing and new models of dynamic friction behavior from the metal forming perspective, were also discussed. An assessment of the problem revealed that historically, friction has been regarded as a “fudge factor” in most metal forming models. In addition, a great deal of effort has been dedicated to measurement of Coulomb friction; however, research has shown that Coulomb friction is not a major concern at the length scales used for metal forming. Perhaps the most central issue is that, currently, there is no consensus for an appropriate approach to solve the problem among experimentalists and modelers—

the common practice is to pass it off to the code developers. Two of the most significant findings were: a) that the current two-dimensional techniques for characterization of surface roughness are not adequate for the modeling purposes, and b) the coefficient of friction is a highly variable quantity that depends on material properties, surface roughness and true contact area, micro-hardness, surface temperature, lubrication properties, lubrication film thickness, contact pressure, and velocity.

Clearly, the next generation of friction models must accurately account for all of these influences. The findings regarding surface roughening were the most relevant in that surface roughness has an enormous influence on the friction behavior and it has the strongest dependence on the properties of the work piece material. The primary concern stems from the fact that the current two-dimensional characterization of surface roughness (i.e., profiles) and the mean-roughness parameters (i.e., R_a and R_q) simply cannot provide the depth of information needed. Accurate characterizations of surface roughness must describe the behavior in three dimensions. They should also provide some insight regarding the contact behavior as well as relate the surface structure to the functional behavior (e.g., lubricity) in some form. Solving a problem of this magnitude will require a substantial collaborative effort on the part of the measurement and modeling communities. Since the significance of the friction issue varies with the particular situation, research has to produce both long-term and short-term solutions. While there are a number of tests available to measure friction, there is no "one size fits all" test and the type of test selected can have a considerable influence on the friction behavior reflected in the data. That is, one may accurately measure friction, but if the data were produced through an inappropriate test, the numeric model that is base on that data will not accurately predict the true friction behavior for a particular situation in the forming process; regardless of how precisely the test may have been performed in the laboratory.

The second topic was pathways to develop better predictive models of the friction behavior during forming. The main finding from this session was that modelers may prefer to use a single friction value, but there are many friction values and each is highly sensitive to the changing surface conditions. Thus, a realistic model must track several variables and conditions, and this will substantially increase the complexity of the model. It is, therefore, possible that a single model will not be appropriate for the task. Thus, an adequate model, or set of models, will take time to develop and validate.

The best approach appears to be improving our understanding of how surfaces interact and relating that improved understanding in an appropriate format for the modelers to use. Recent research indicates that the average behavior/interaction is not the factor that limits performance. Rather, it is the "hot spots", or areas of unusually high stress/strain. Problem areas usually have multiple contact points, or "hot spots", which are exacerbated by the additional constraints imposed by localized changes in the lubricant properties and surface coatings. As noted earlier, the accuracy of the model strongly depends on the accuracy of the input data, so given the substantial complexity of the problem; it may be more practical to improve the measurements and understanding of the functional properties of the materials in question. That is, current statistical measures of roughness do not effectively describe the functional role that changes in surface character have on the local surface chemistry and, ultimately, on the friction behavior. The current models also do not adequately account for the "penalty factors" imposed by lubricant effects (e.g., variability in lubricity due to temperature changes, pressure, film break down). The next generation of friction models should track these penalty factors. An additional issue is the proper terms in which to express the friction data. Most experiments report the friction data as a function of test time. However, in a model, time may not always be a consistent variable. If the data are expressed as a function of time, and time is not constant within the frame of the model, the data will not be accurate. One possible solution is to express friction data as a function of sliding distance. Length is constant within the framework of the model, so the data will be properly interpreted. In addition, if it is needed by the model, velocity can be computed directly by the model if the sliding distance in known.

In summary, consensus was achieved in three key areas: a) classical friction models are not adequate in sheet metal forming, b) new measurements that focus on the interaction between surfaces must be developed, and c) new surface characterization tools that relate surface morphology to the functional behavior must be developed. It was also determined that additional workshops should be held at regular intervals. Another workshop is tentatively planned for 2008.

WORKSHOP AGENDA

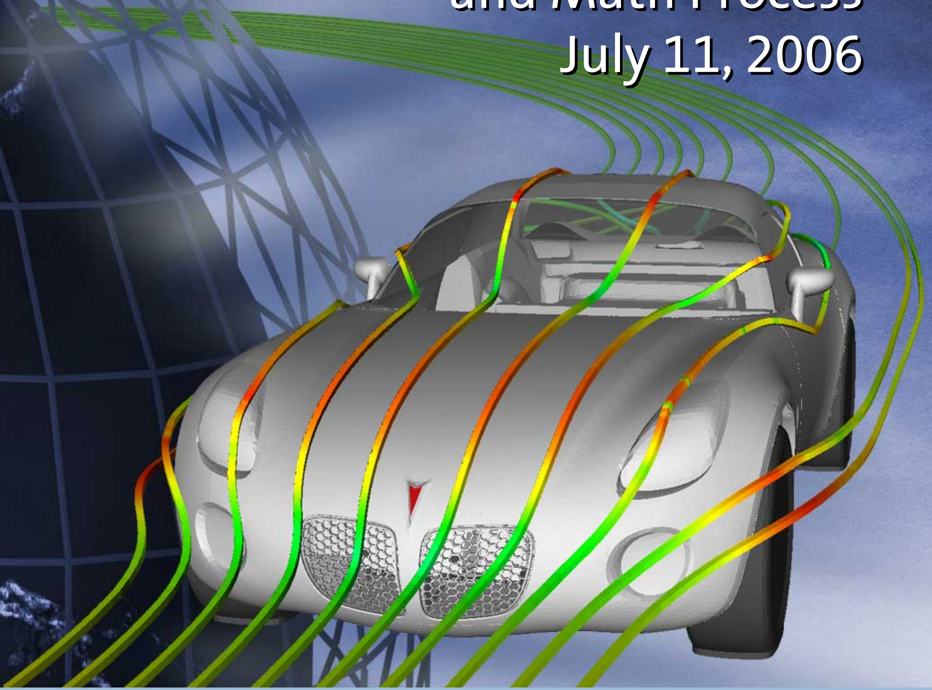
Tuesday, July 11, 2006
United States Council for Automotive Research Facilities
1000 Town Center Building
Suite 300
Southfield, MI

8:00 AM	Arrival / Coffee /	
8:15	Welcome, Opening Remarks and Introductions	M. R. Stoudt
	Issues Pertaining to Measurement During Metal Forming	
8:30	Friction in Sheet Metal Forming – An Overview	C. Y. Sa
9:30		J. Reid
10:00	Effects of coating and forming conditions on friction	H. C. Shih
10:30	The Role of Friction in Product and Process Design: Which Friction Measurement Should You Use?	G. Dalton
11:00		R. Wagoner
11:30		M. R. Stoudt
12:00	Lunch and Roundtable Discussion	Stoudt (Moderator)
	Overview	T. B. Stoughton
	Issues Related to Friction Modeling	
1:30	Experimental and Numerical Investigations of Friction and Lubrication in Metal Forming Applications	T. Altan
2:00		T. B. Stoughton
2:30	Roundtable Discussion	Stoughton (Moderator)
4:00 PM	**Wrap Up**	Stoudt/Levine/Stoughton
6:00 PM	**Social Session / Dinner**	All participants

SLIDES FROM INDIVIDUAL PRESENTATIONS

Friction in Sheet Metal Forming

Dr. Chung-Yeh Sa
Technical Manager
Global CAE Development
and Math Process
July 11, 2006



SYNOPSIS

- Background
- The Impact of Friction in Sheet/Tube Metal Forming
- Friction Overview
- Friction Characterization, Test & Measurement
- Numerical Modeling of Friction
- Current & Future Partnership

Impact of Friction on Sheet Metal Forming

MYTH

- Friction doesn’t matter in metal forming ?
  - What is the easiest common trick used in T/O?
- Friction has little effect in metal forming simulations ?
- Friction is a fudge factor in metal forming simulations ?
  - Aren’t they contradicting to each other?
- Friction a.k.a. Coulomb Friction a.k.a. Coefficient of Friction are totally wrong in metal forming simulations ?
  - Are they? Do we have a common ground?
- Code developers should have a better model ?
  - They implement good models developed by “tribologists”

Friction Overview - Definition

- Tribology
  - the science and technology of **friction, lubrication, and wear**.
- Friction
  - the force that opposes the relative motion or tendency of such motion of two surfaces in contact.
- Coulomb Friction
  - the classical approximation of the friction (force).
- Coefficient of Friction
  - a scalar value which describes the ratio of the friction force and the normal force between two bodies in contact

$$\mathbf{F}_f = \mu N$$

Coulomb Friction – Assumptions

- Independent of contact area but the actual contact is a small fraction;
- Independent of speed when two objects are moving relative to each other;
- The force of friction is always against movement (for kinetic friction) or potential movement (for static friction) between the two surfaces;
- Coefficient of friction, μ, is constant. It depends on the materials (e.g., type, hardness, roughness, …) in contact.

Coulomb Friction – Limitations

- No interference of some fundamental forces such as electromagnetic force
- No chemical reaction induced property changes.
- No thermal reaction induced property changes.
- No significant physical property changes such as roughness change due to many factors
  - Flattening
  - Micro-hardness
  - (stretching or compression induced) Deformation

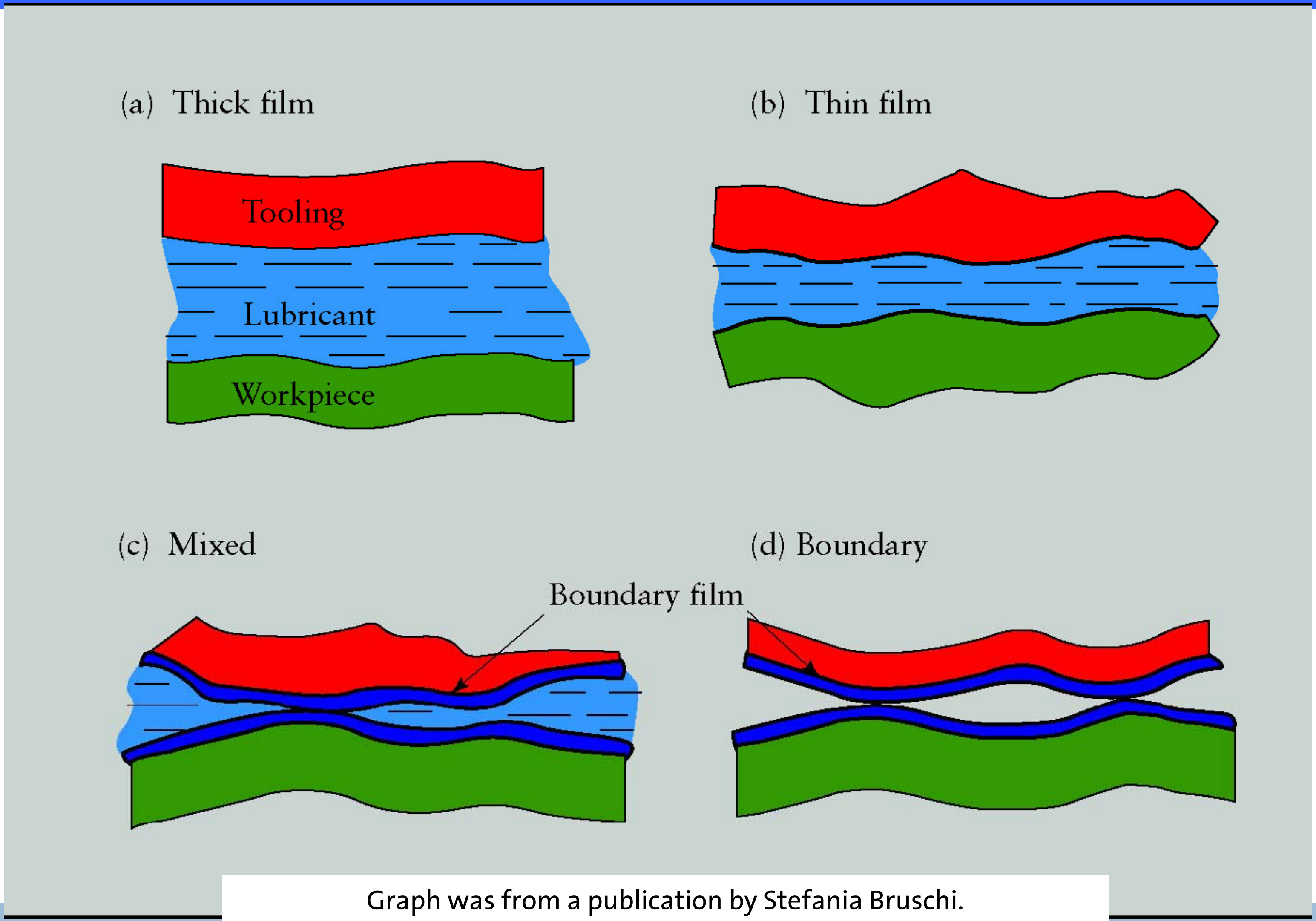
Coefficient of Friction in Metal Forming

- Frictional coefficient, **μ**, always exists but
  - it's NOT constant
  - It's NOT uniform
  - It's NOT a simple property of the material (sheet metal)
  - It's NOT a simple property of the lubricant
  - It's an "interface property" of the contacting bodies and the lubricant used (if any).

Coefficient of Friction in Metal Forming

- The real questions are
  - What factors will change μ?
  - How do they influence and interact?
  - How do we model it?
  - Should we look at a totally different friction model?
    - Friction factor?
    - Friction stress/force?
    - …

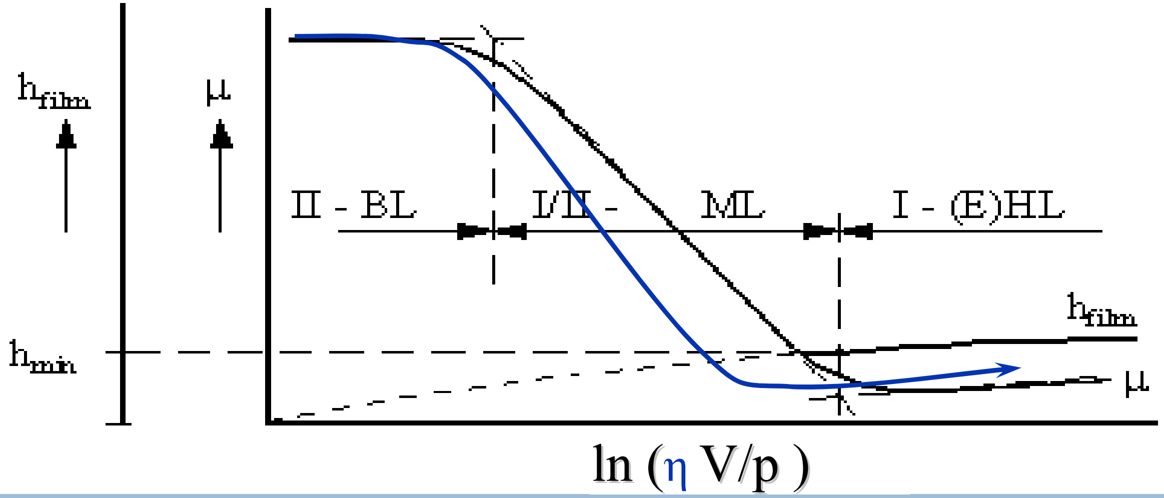
Friction Characterization - Regimes of Lubrication



Graph was from a publication by Stefania Bruschi.
The concept has been published by Prof. WRD Wilson and his students.

Friction Characterization - Stribeck Curve

- Boundary
  - Supported by asperities; lack of hydrodynamic effect
- Mixed
  - Supported by both asperities and hydrodynamic pressure
- Elasto-Hydrodynamic (EHD)
  - Supported by hydrodynamic pressure w/o asperities



Friction Tests

- Pin-On-Disk
- Twist Compression
- Strip Draw Flat Die
- LDH
- Draw Bead Simulator (DBS)
- RPI & NWU Friction Simulator (Strip Pulling over a Roller)
- GM Stretch Form (Friction) Simulator
- OSU Friction Tester
- Strip Draw Die w/ Bead
- …

Do the tests provide needed information for friction modeling?

Friction Characterization and Measurements

- Roughness & Asperity
  - R_a, R_q, …
  - 3D characterization
  - Contact ratio
  - hardness
- Lubricant behavior
  - Lubricity/viscosity
  - Velocity effect
  - Temperature effect
- …

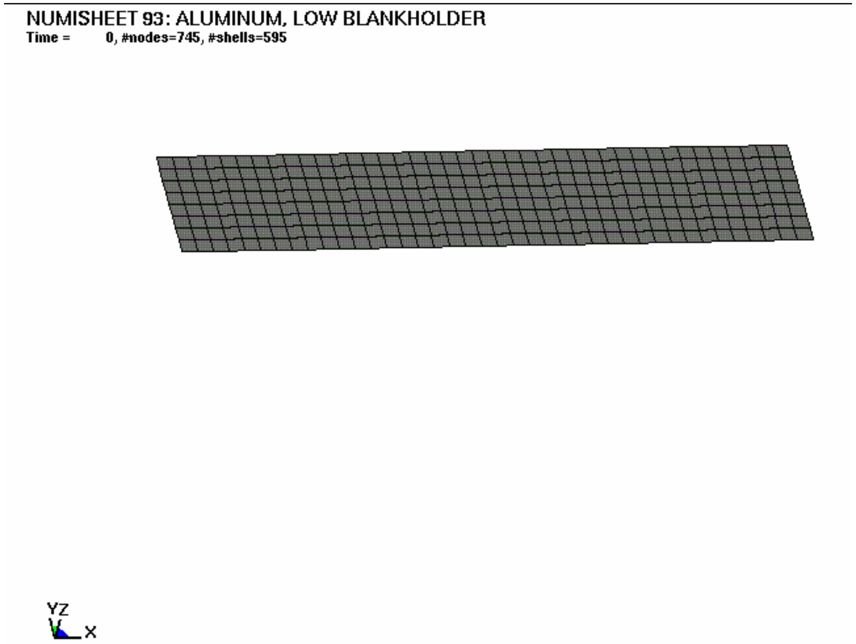
Need collaborative efforts for both short term and long term solutions

Friction Modeling in Forming Simulations Factors

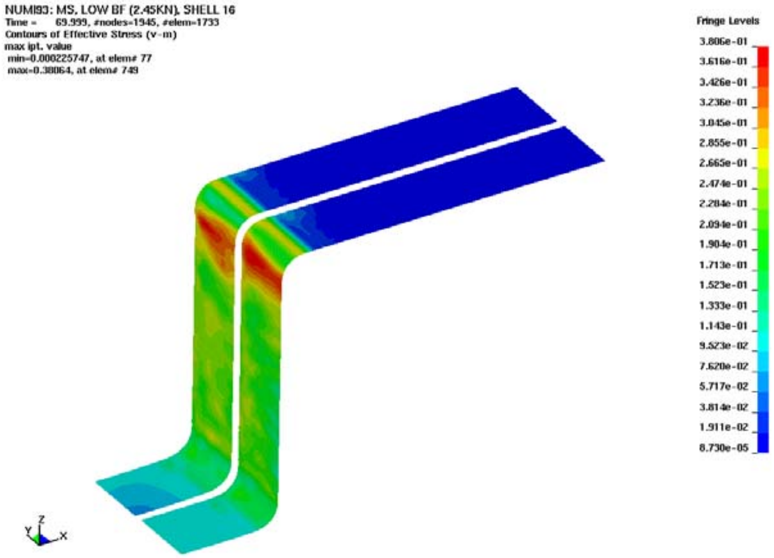
- Physical Properties
- Surface Roughness & Actual Contact Area
- Micro-Hardness
- Surface Temperature
- Lubricant Properties (e.g., viscosity)
- Film Thickness
- Contact Pressure
- Sliding Velocity
- …

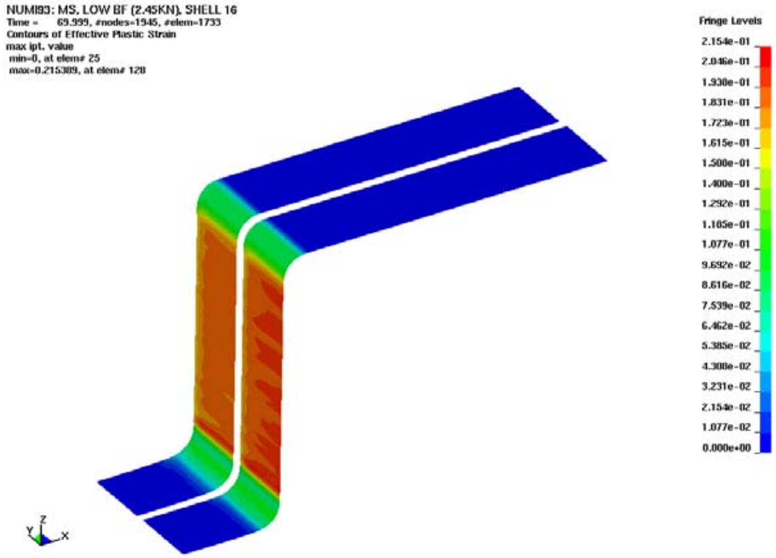
Friction Modeling in Forming Simulations Example – U-channel

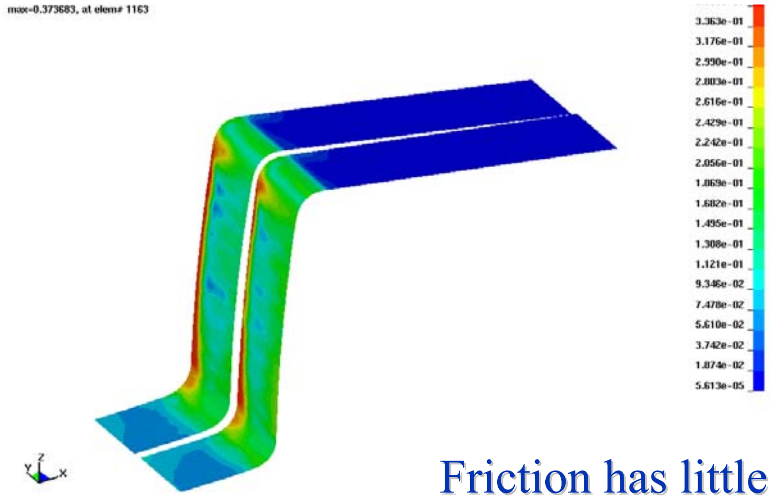
- Friction influences the following
  - draw-in & material flow
  - Restraining force in the binder, through the draw bead and over radii
  - Temperature (hence lubrication effectiveness)
- Results in premature failure
- Change the springback (stress state in the sheet metal part could be different)
- …

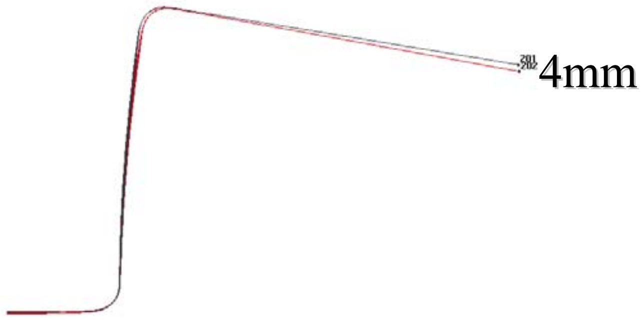


Impact of Friction on Sheet Metal Forming – Example



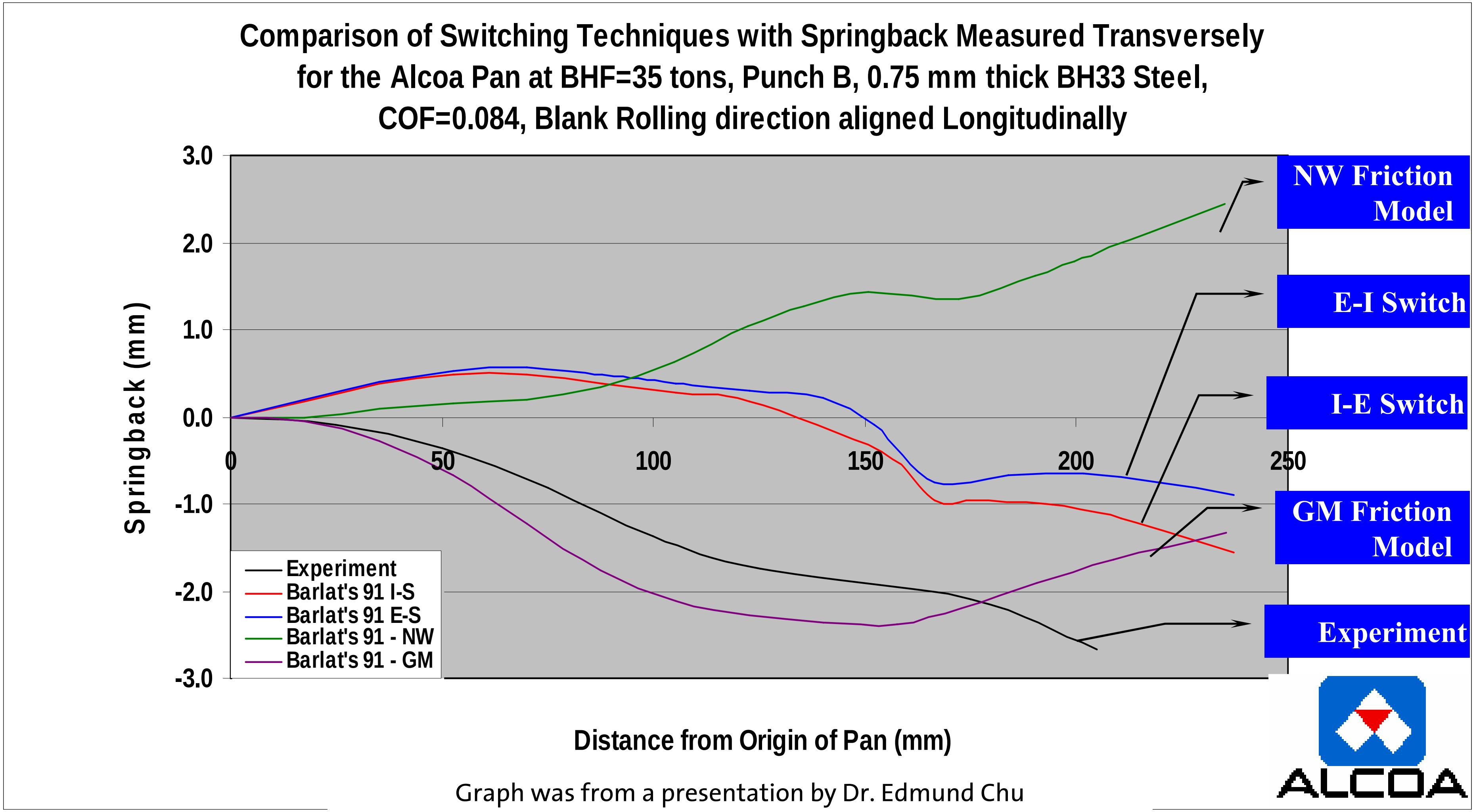






Friction has little impact in this case

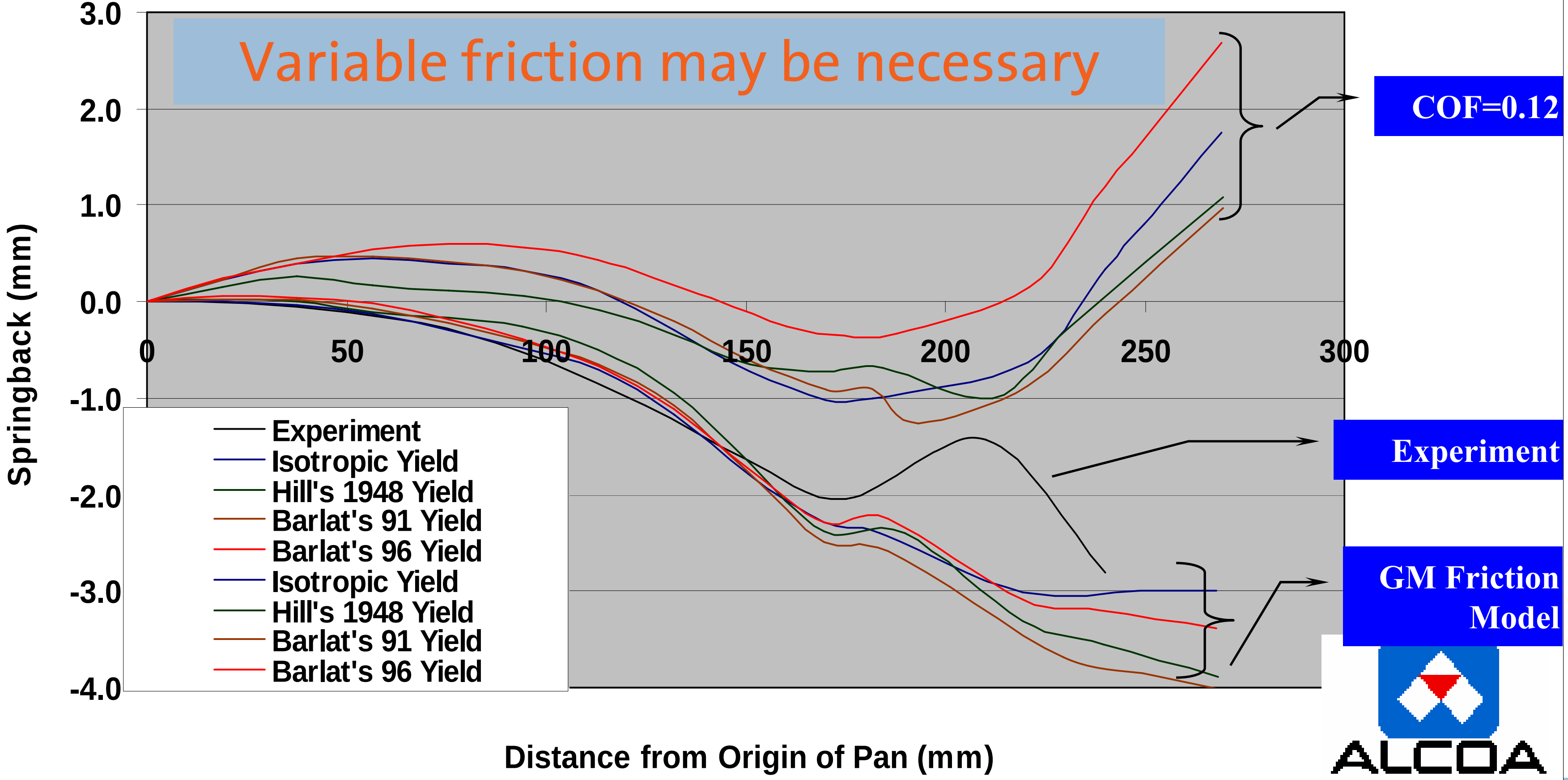
Friction Modeling in Forming Simulations Example – Alcoa Pan



Graph was from a presentation by Dr. Edmund Chu
as part of the progress report for the NIST/ATP sponsored SPP

Friction Modeling in Forming Simulations Example – Alcoa Pan

Comparison of FEM Predictions with Springback Measured Longitudinally for the Alcoa Pan at BHF=25 tons, Punch B, 0.9 mm thick 6022-T4, COF=0.12 vs. GM Friction Equation, Blank Rolling direction aligned Longitudinally



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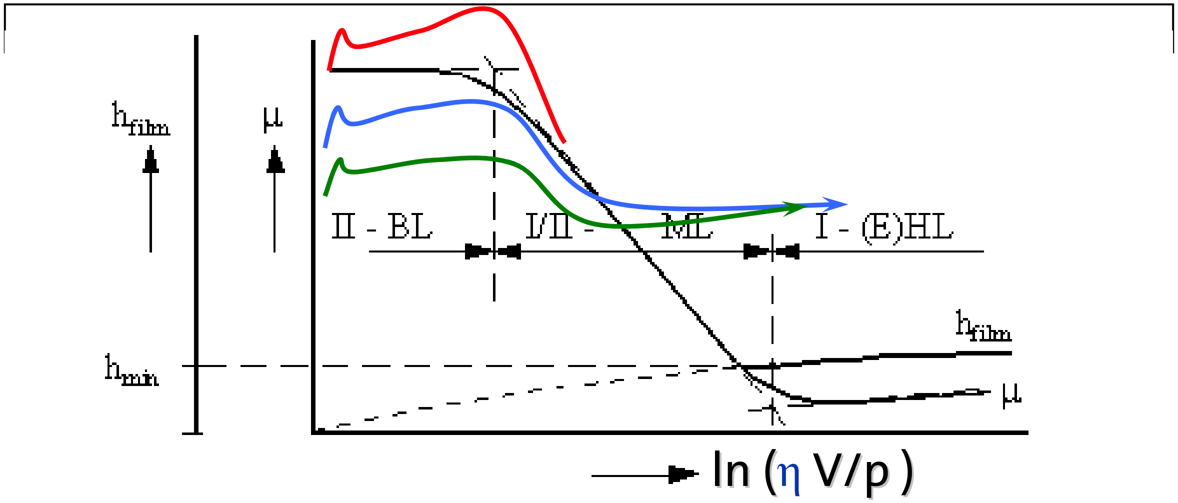
Friction Modeling in Forming Simulations
Possible Direction



$F_f = \mu_0 N f($		
	p,	contact pressure
	ε,	plastic strain
	V,	sliding velocity
	a_1, a_2,	*roughness*
	η (η_0 , t, p),	viscosity
	HK_1, HK_2,	hardness
	h (h_0 , p, …),	film thickness
	…	)

f can be viewed as a penalty function that may vary the friction in the process.

Friction Modeling in Forming Simulations Math

- Detect/enable regime change
- Detect/enable metal thickness and roughness change
- Consider viscosity and velocity change
- Accurate contact and pressure calculation
- Not too calculation-intensive
- …

Friction in Sheet Metal Forming - Summary

- Establish standard “friction” testing procedures for various forming processes w/various lubrication
  - stamping, sheet/tube hydroforming, SPF, …
  - liquid (oil, emulsion) & solid/dry lubricants
- Establish standard friction characterization;
- Develop long term plan in developing friction modeling (from simple to complex);
- Establish collaboration network.

Collaborations
Direct and indirect activities involving everyone

- NIST (National Institute of Standards and Technology)
- USCAR (United States Council for Automotive Research)
- ASP (Auto Steel Partnership)
- NSF (National Science Foundation)
- Other Consortia w/Universities and National Labs
- Industries
  - Automotive, materials, lubricants, …
- Software Vendors
- …

Thank You!

Workshop Objectives

A) Clearly identify the problems with a particular emphasis on the industrial perspective.

B) Develop an appropriate approach for a solution to these problems.

C) Open and foster a dialog among the participants.

D) Establish a working group consisting of members from the automotive, academia, materials modeling and measurement communities.

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Friction in Metalforming Applications

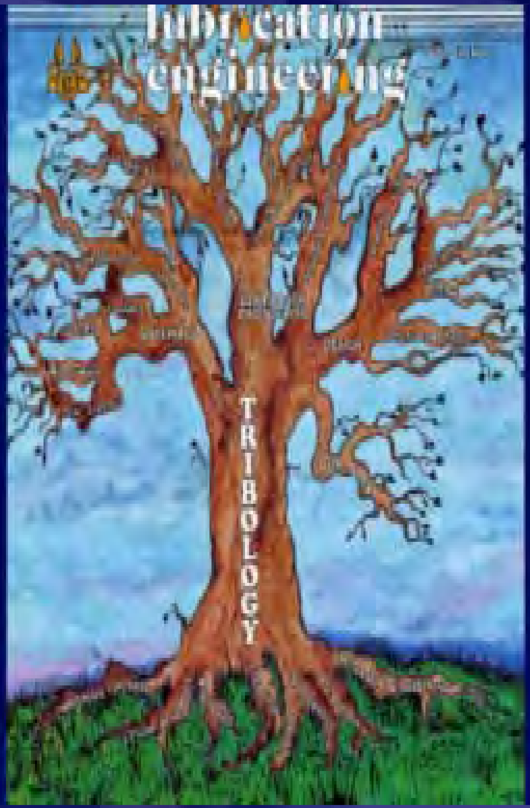
Friction Workshop
July 11, 2006
Southfield, MI

Jean V. Reid, PhD, P.Eng

reid@irdi.com; 705.526.2163 ext-235

Outline

- What determines friction?
- Importance of friction
- Process examples
  - Tribological tests
  - Challenges



Control of Friction?

Skidding is the action where friction is the fraction of the vertical reaction that does not result in traction. G. Cowie

Importance of Friction

- Driving Factors
  - Cost and quality
- How
  - Understand the process
  - Identify lubrication regime
  - Experimental testing & modeling for optimization

Friction Models

- Coulomb's friction $\tau = \mu\rho_i$

$$\mu = \frac{F_f}{P} = \frac{\tau A}{p_i A} = \frac{\tau}{p_i}$$

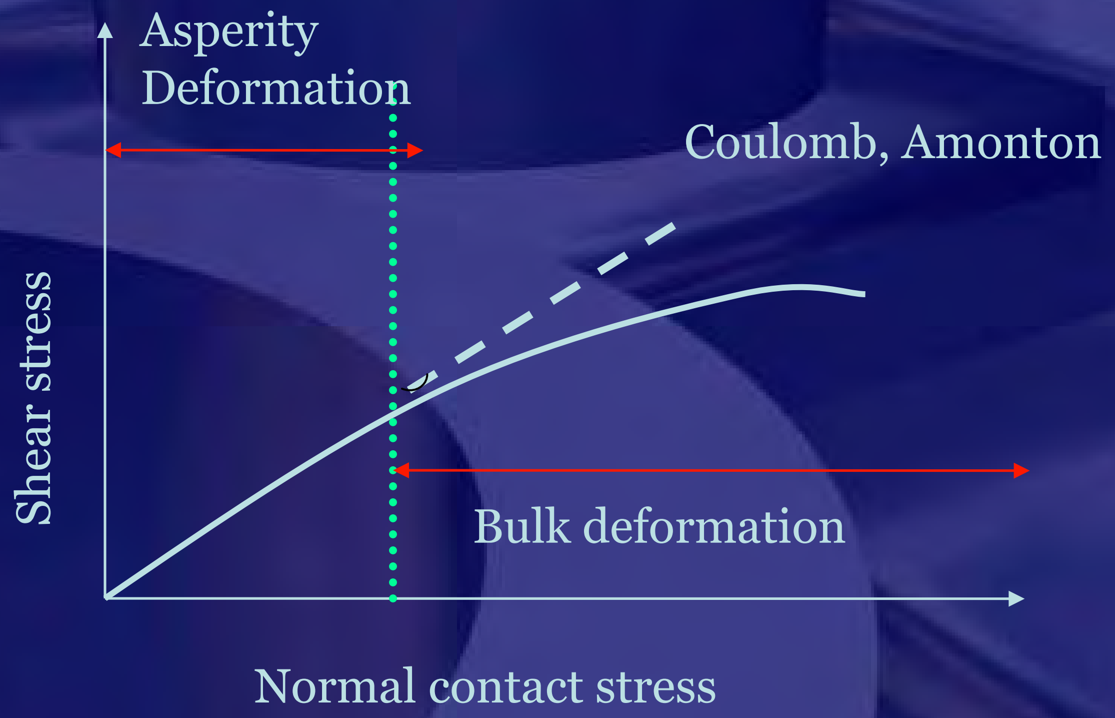
- Constant friction model $\tau = mk$

$$\tau = f\sigma = m\frac{\sigma}{\sqrt{3}} mk; 0 \leq m \leq 1$$

- General friction model $\tau = f\alpha k$

- Empirical friction model $\tau = \beta\rho^b$

Friction vs. Normal Pressure



Bulk Deformation

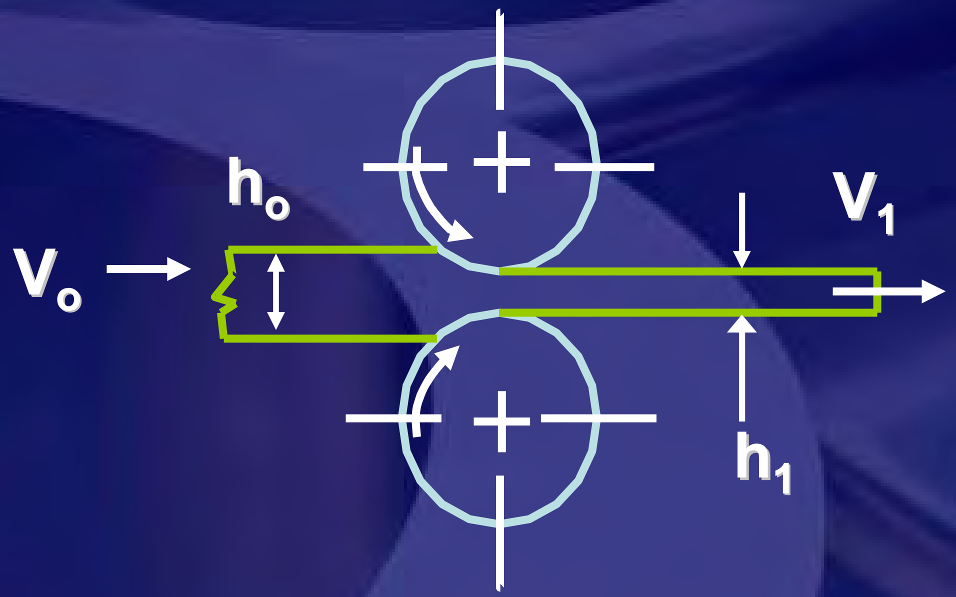
Rolling

- The Process
  - Uniform thickness
  - Flat and uniform surface
  - Reproducible physical properties
- Lubrication Regime
  - Plastohydrodynamic lubrication
  - Mixed Film lubrication
- Applicable Tests
  - 4-Ball
  - Pin & V-block
  - Laboratory rolling mill

Pictures courtesy of: Blair and Andritz

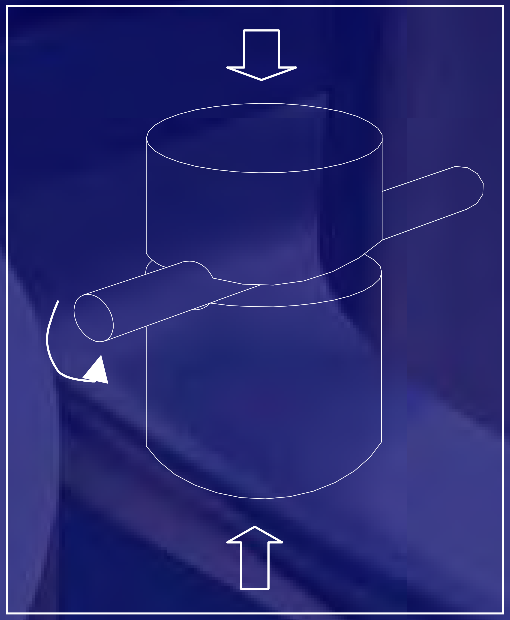
Rolling

- Sheet or strip reduced from thickness h_o to h_1 using rolls of radius R
- Workpiece drawn into roll gap by friction



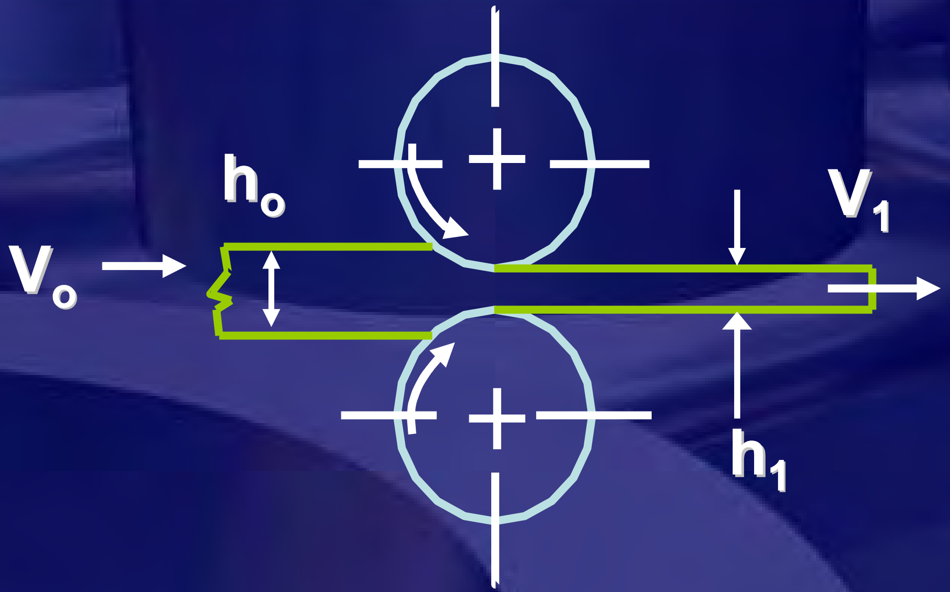
Rolling - Bench Test

Shell four-ball wear tester



Falex lubrication test machine

Rolling – Laboratory Rolling Mill

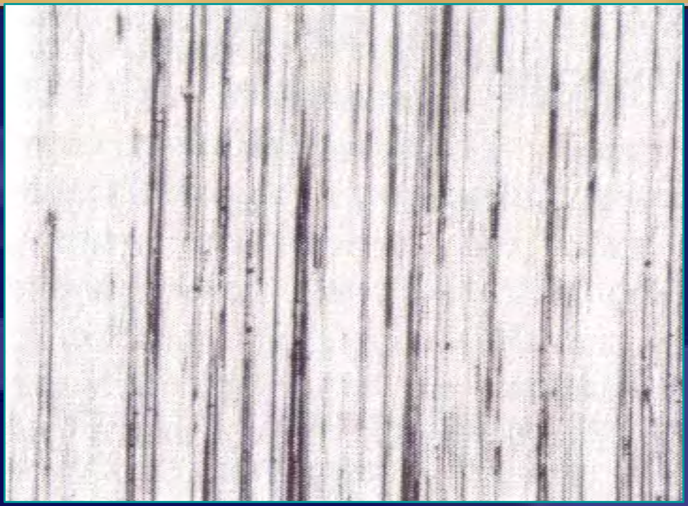


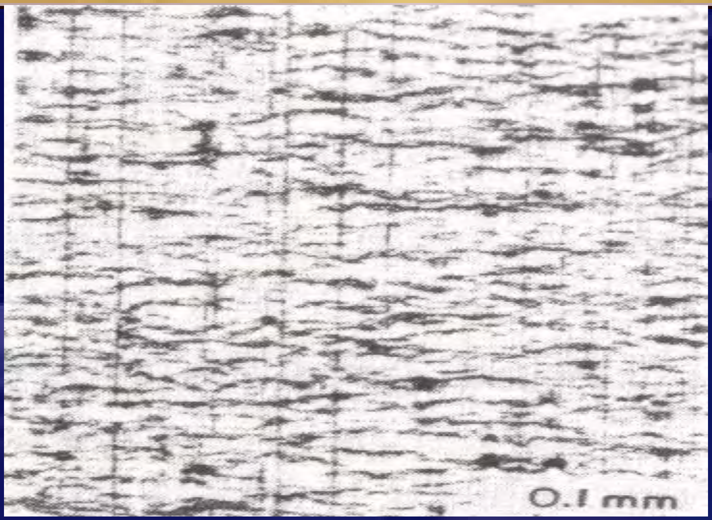
$$s_f = \frac{v_1 - v}{v}$$

$$s_f = \frac{1}{2}\phi^2\left[\frac{2R'}{h_1} - 1\right]$$

$$\phi = \left[\frac{h_o - h_1}{4R}\right] - \frac{1}{\mu}\left[\frac{h_o - h_1}{4R}\right]$$

Rolling – Mixed Film Lubrication





- Boundary lubrication
- In sliding contact
  - – roll surface finish is reproduced but modified

- Hydrodynamic effects
  - Exit strip roughness determined by
    - •Initial strip roughness
    - •Lubricant

Friction in Rolling

- In mixed-film lubrication regime, a decrease in friction (positive forward slip) occurs with:
  - an increase in velocity
  - an increase in viscosity
  - an increase in roll diameter
  - a decrease in front tension
  - a decrease in reduction

Sheet Metal

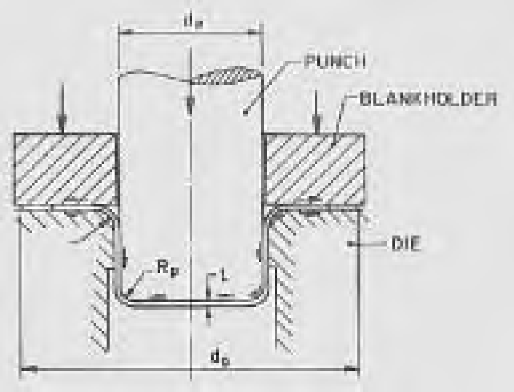
Stamping

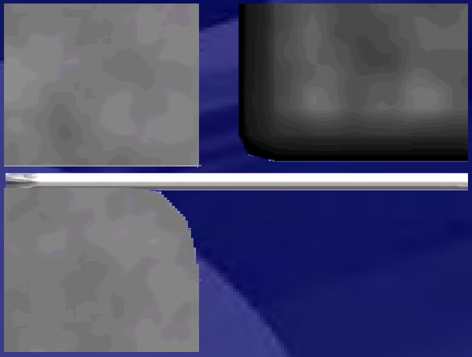
- The Process
  - Uniform thinning
  - Without tears or folds
- Lubrication Regime
  - Boundary lubrication
- Applicable Tests
  - FLD (Dome or Marciniak)
  - LDH
  - TC

Sheet Metal

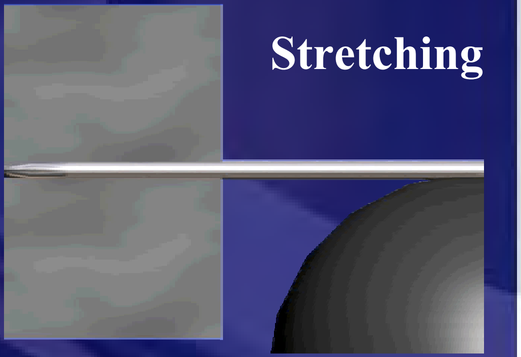
Drawing

- Lubrication Regime
  - Mixed film
  - Boundary lubrication
- Applicable Tests
  - FLD
  - DBS
  - Drawing Press

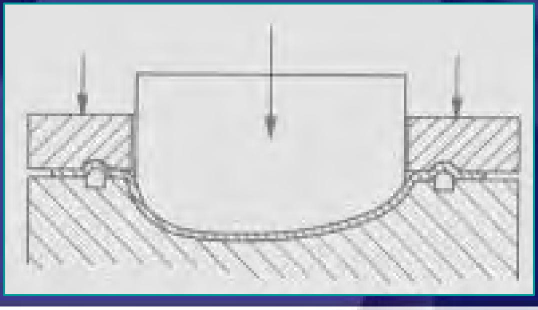




Deep Drawing

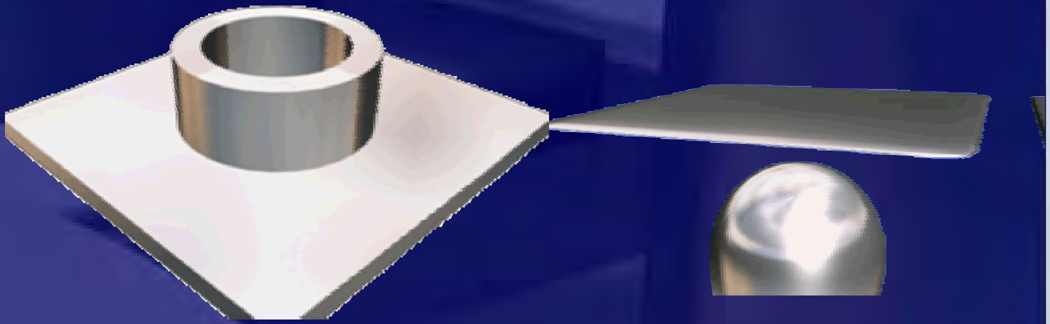


Stretching

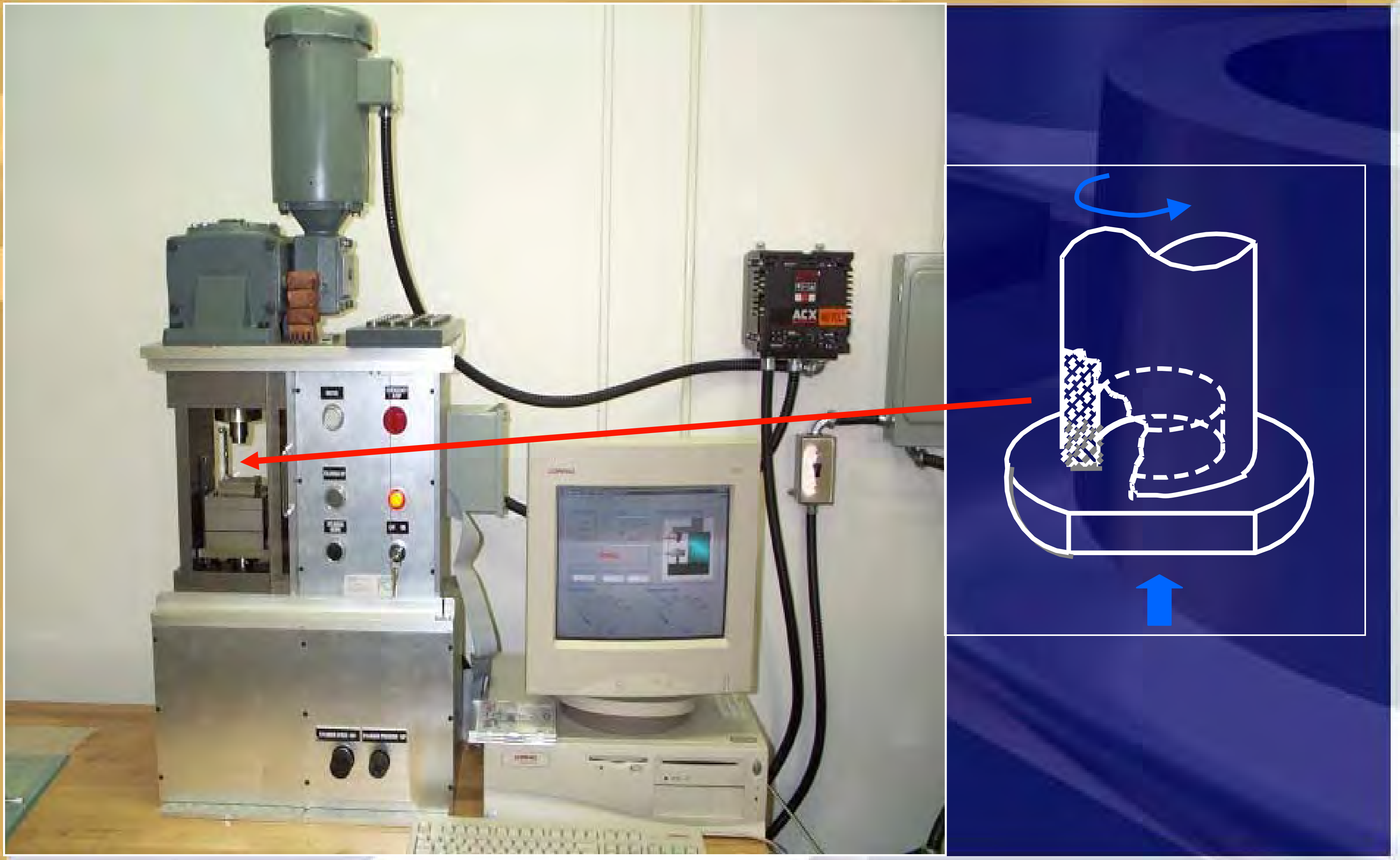


Tribological Testing

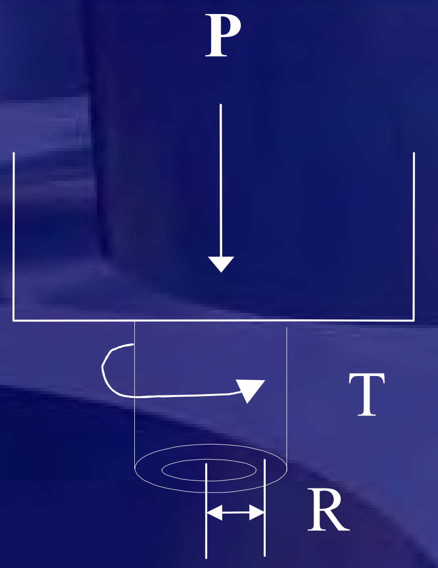
- Types
  - Bench
  - Simulation
- Testing Produces
  - Evaluation
  - Comparison/Ranking
- Examples
  - LDH, TC, DBS, draw press, etc

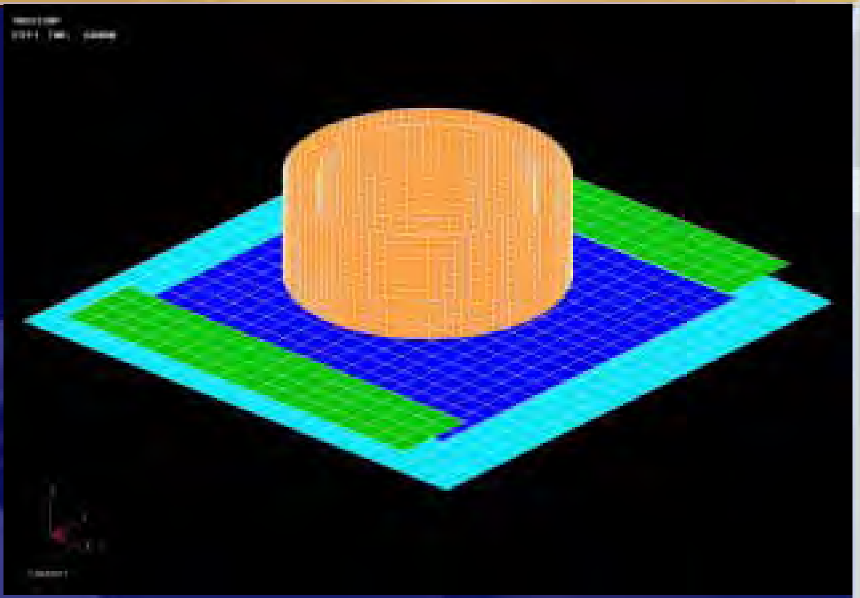


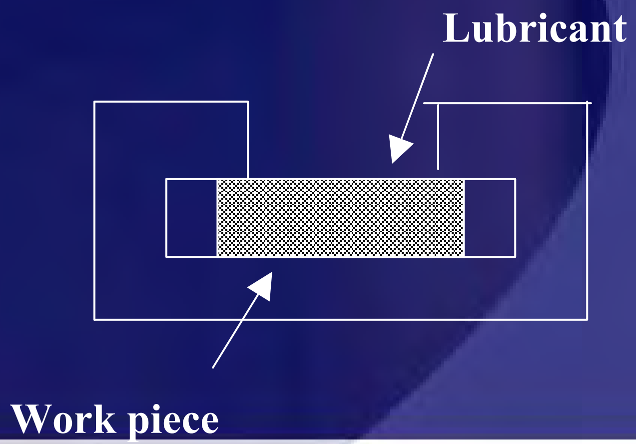
Twist Compression



Twist Compression

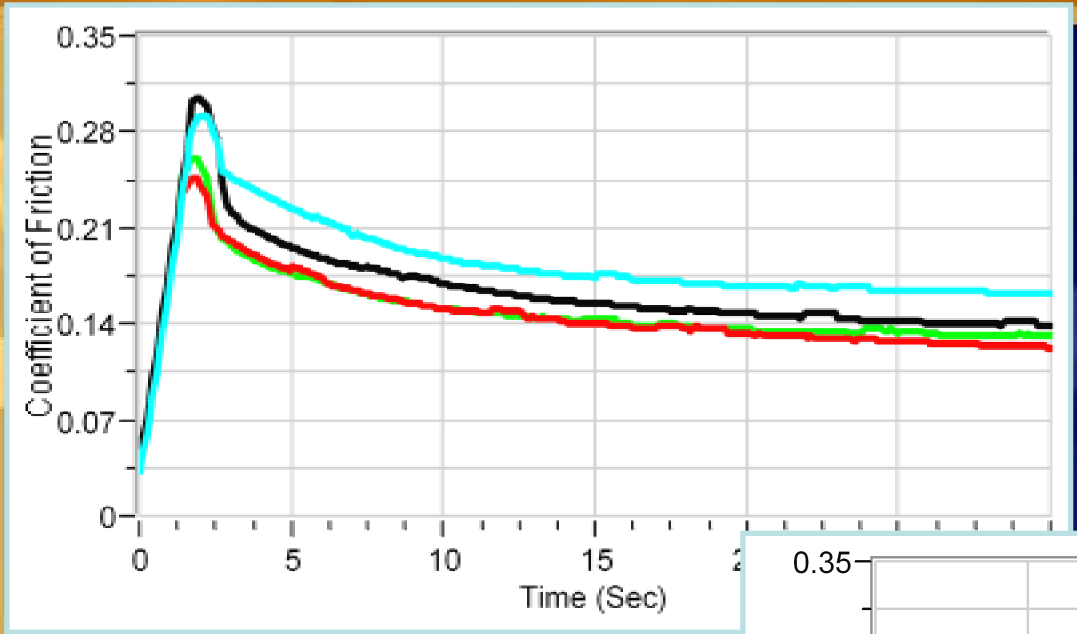






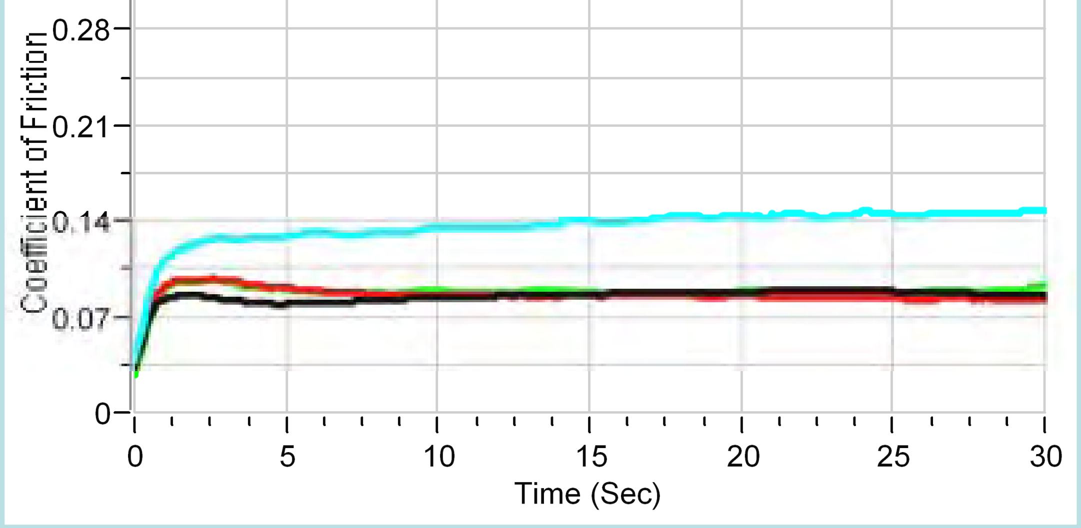
$$\mu = \frac{\tau}{p_i} = \frac{\frac{F}{A}}{\frac{P}{A}} = \frac{T}{RP}$$

Static or Dynamic

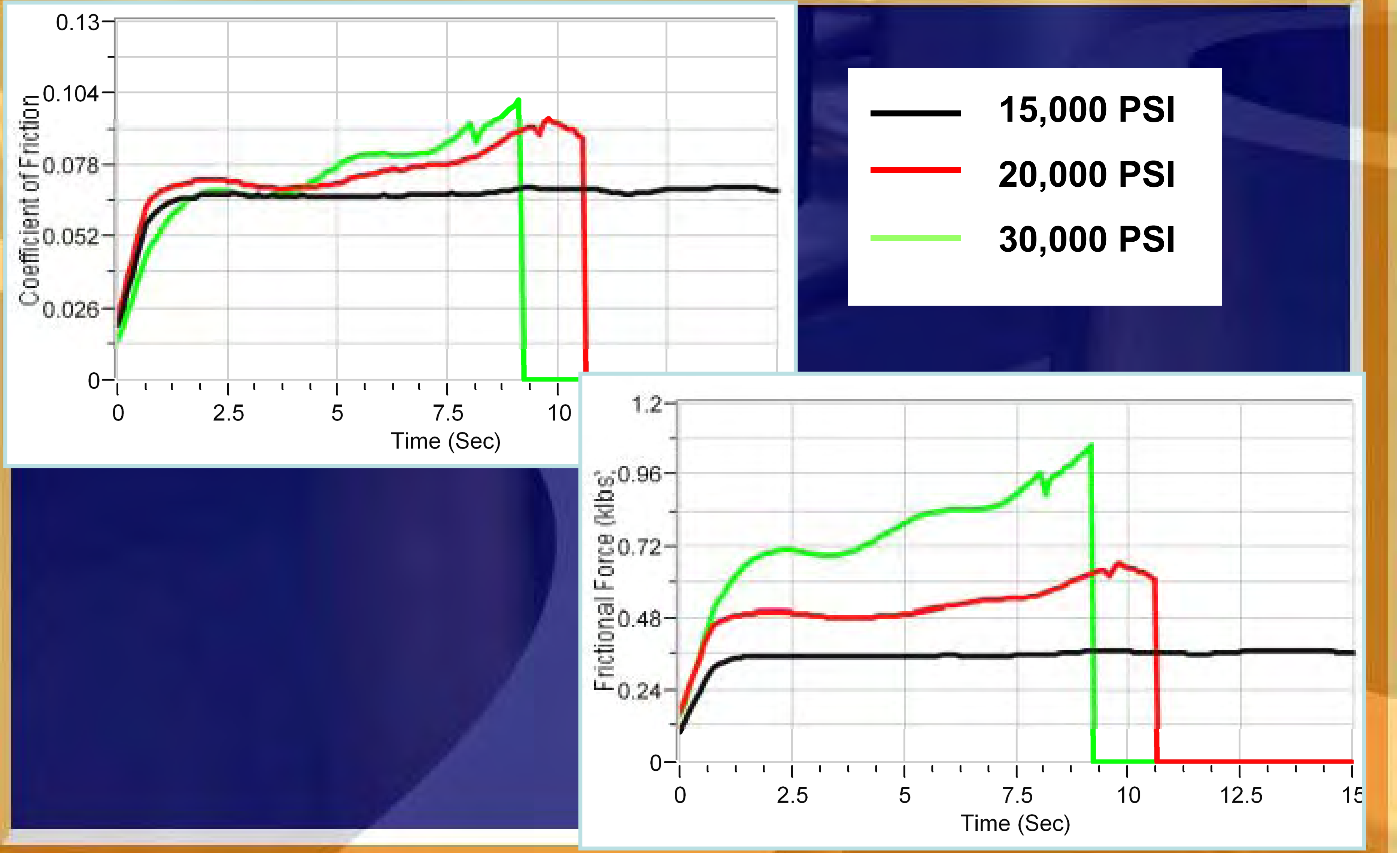


Static

Dynamic



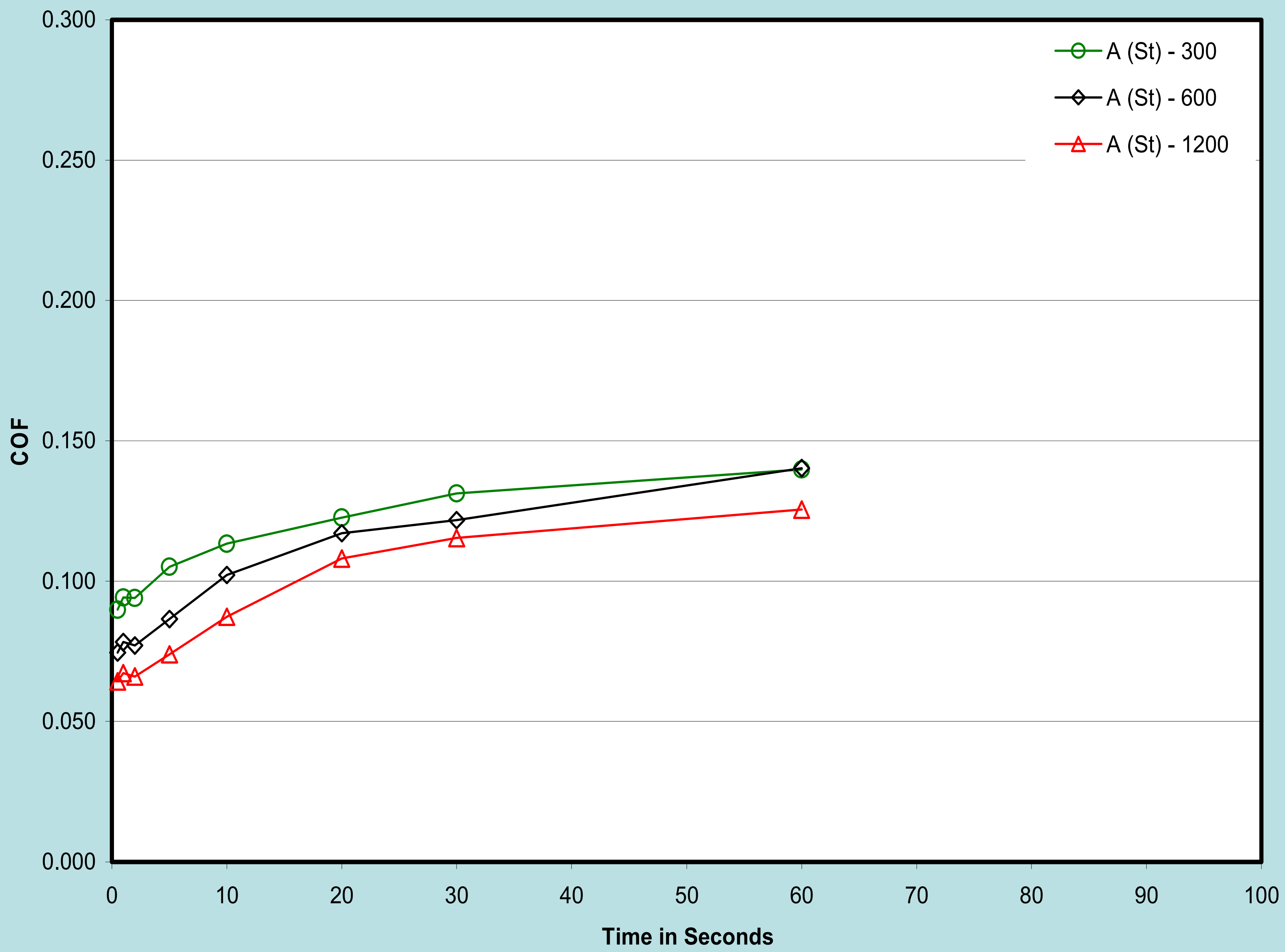
Frictional Force

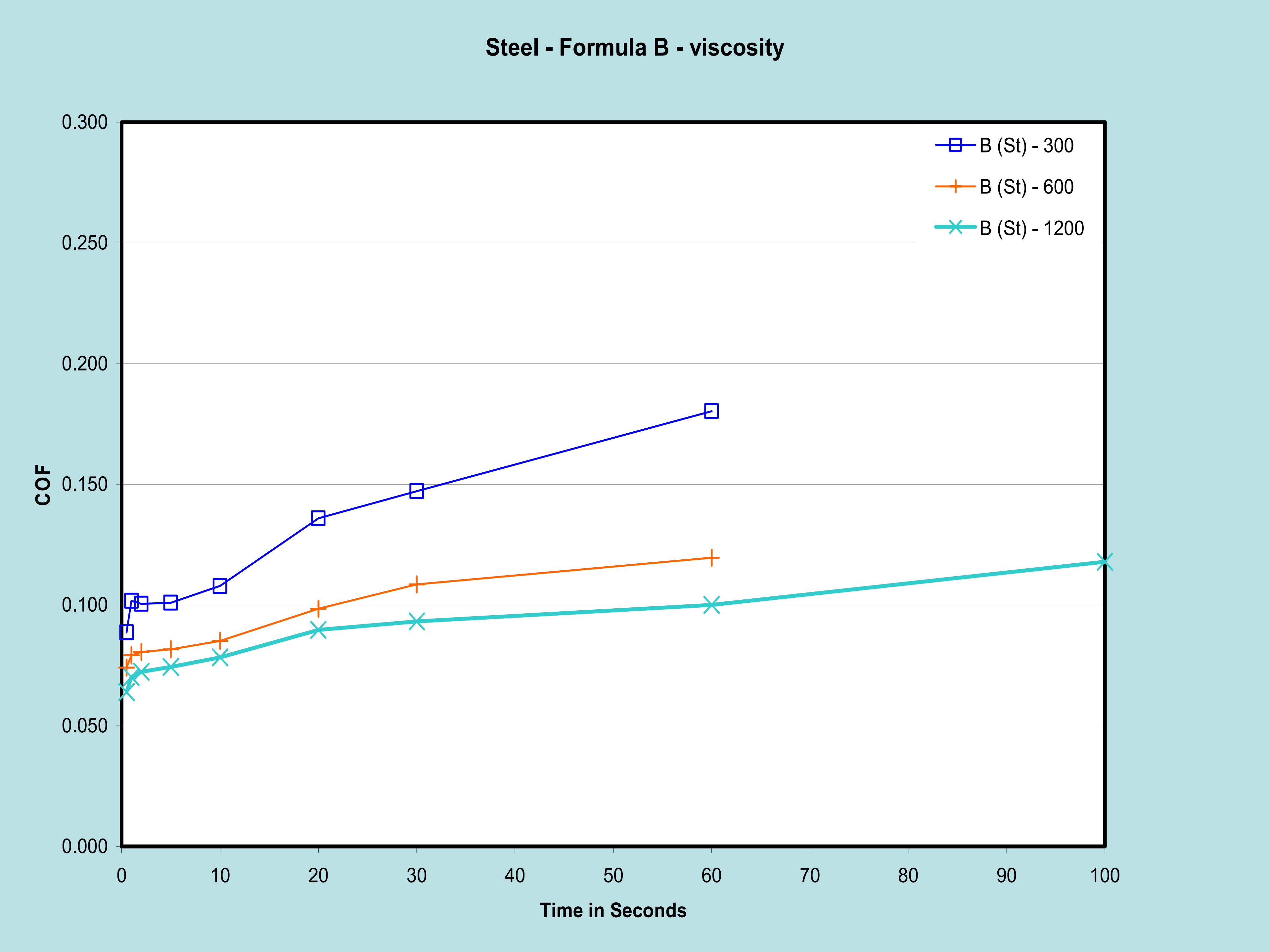


ASTM Round Robin

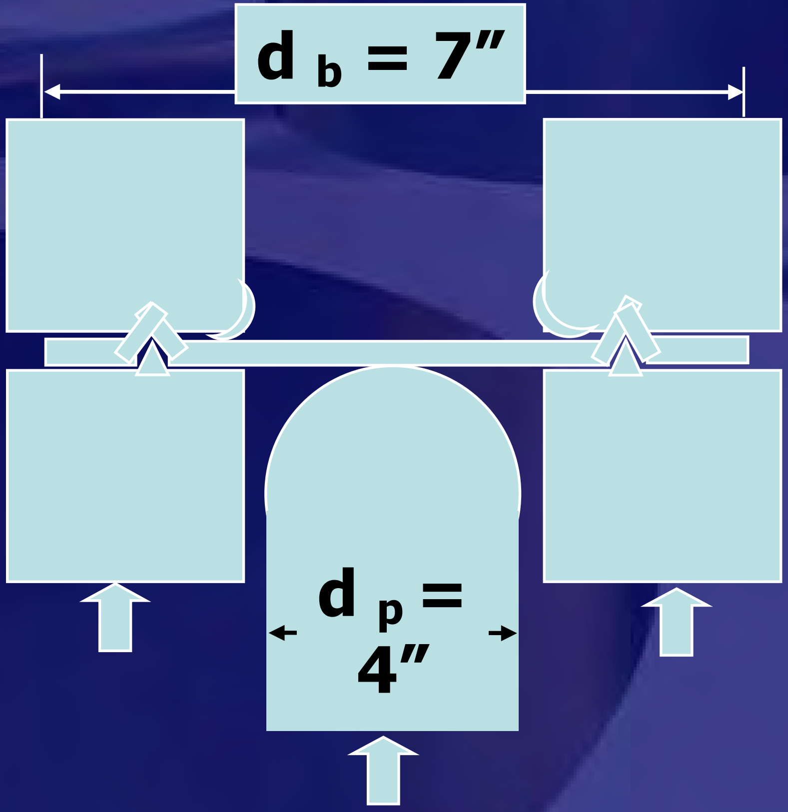
- 6 labs
  - 5 participated
- Materials
  - 2 metals (steel & Al)
  - 6 lubricants
    - Formula A (300, 600, 1200 SUS)
      - Boundary-lubricity additives in mineral oil
      - 1200 SUS – commercial product
    - Formula B (300, 600, 1200 SUS)
      - EP chemistry (sulfur, chlorine, phosphorus)
      - 600 SUS – commercial product

Steel - Formula A - viscosity



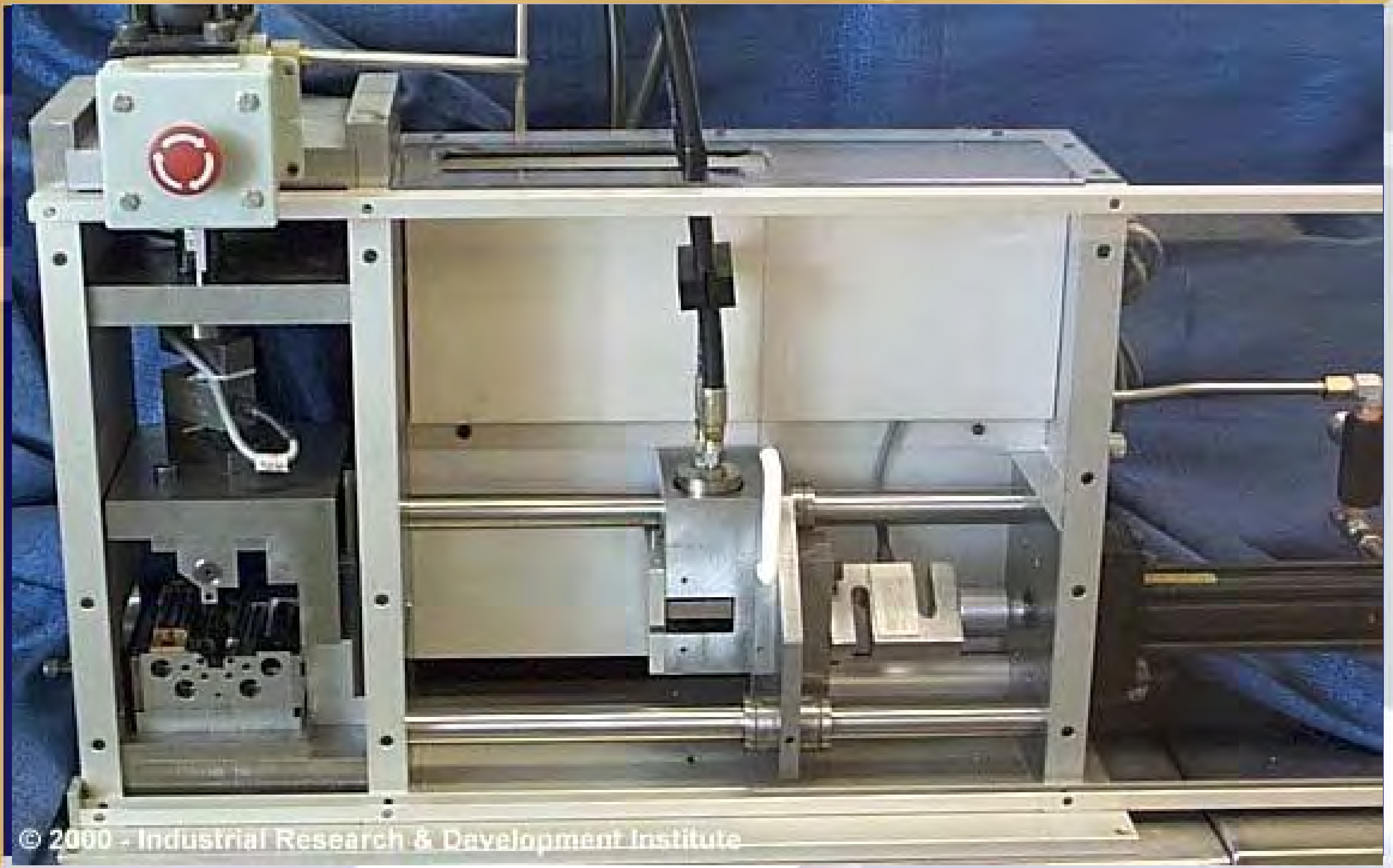

Steel - Formula B - viscosity
COF
0.300
0.250
0.200
0.150
0.100
0.050
0.000
0
10
20
30
40
50
60
70
80
90
100
Time in Seconds
B (St) - 300
B (St) - 600
B (St) - 1200

Limiting Dome Height

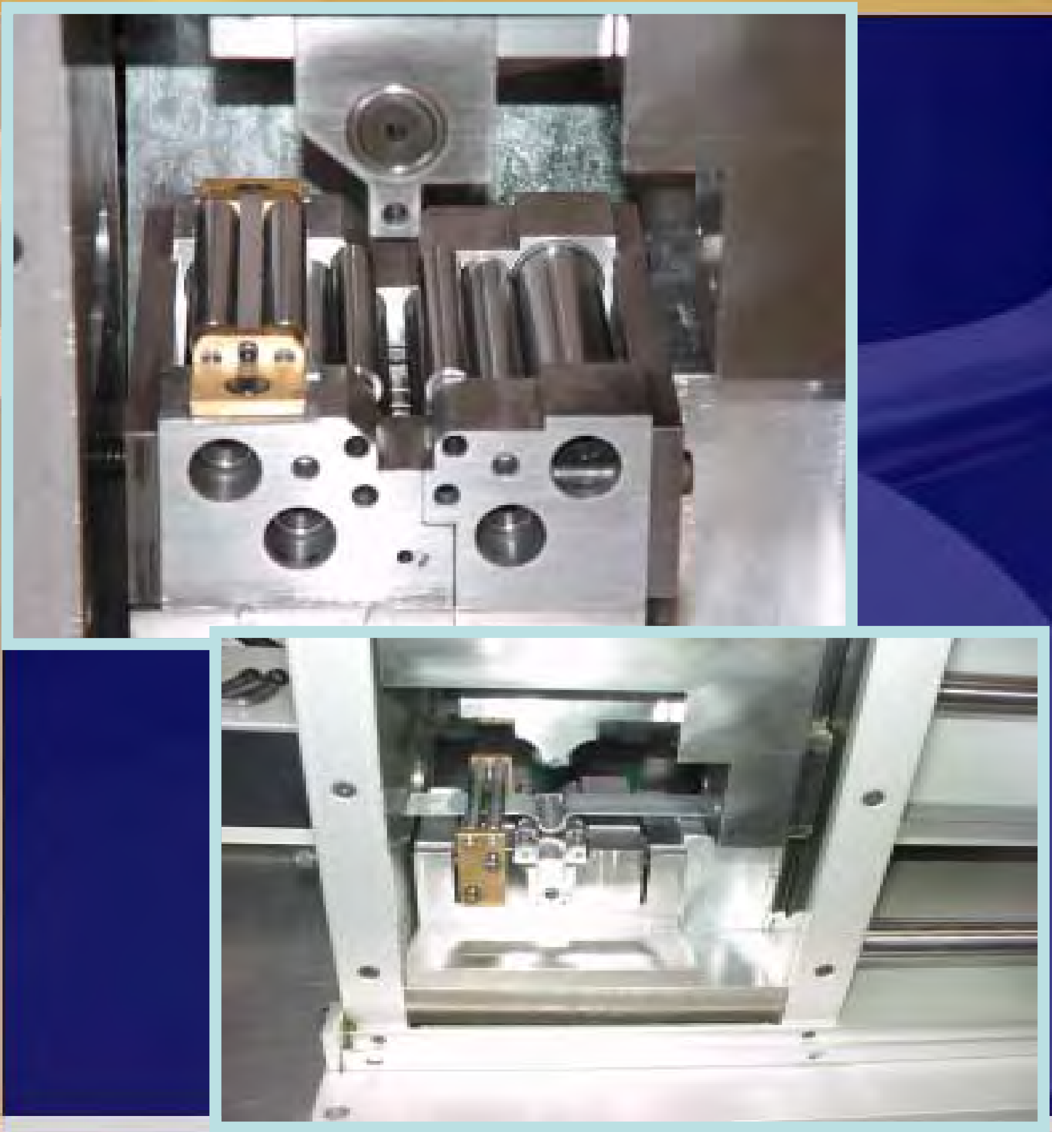


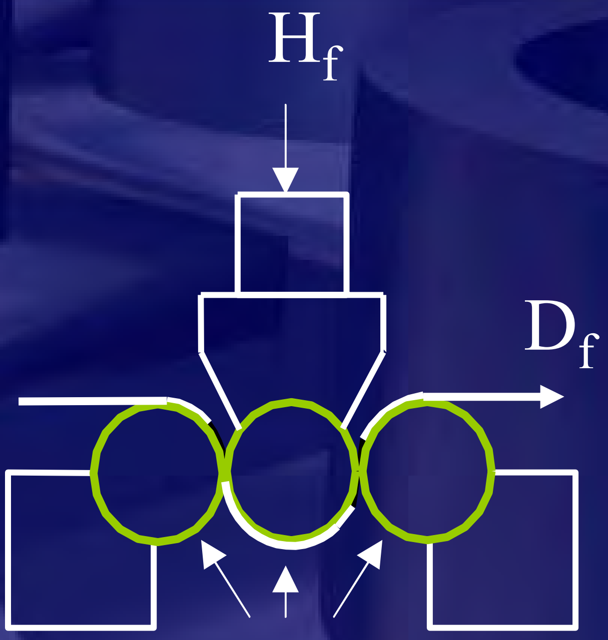
- Stretching
  - LDH
  - shape developed by sheet thinning
  - necking & fracture determined by friction and material properties

Draw Bead Simulator



DBS





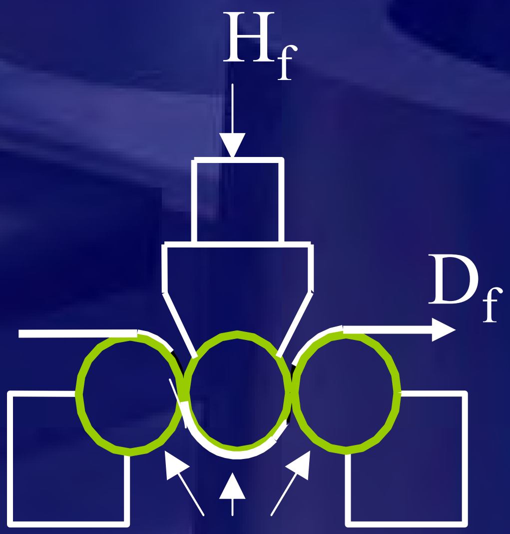
H_f

D_f

Draw beads

DBS - Friction

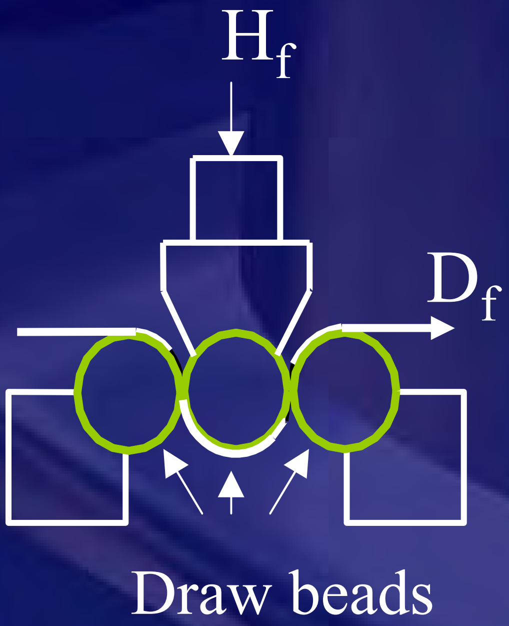
- Unlubricated with roller dies
  - obtain roller force (R_f) (deformation component of drawforce (D_f))
- Lubricated with fixed dies
  - deformation and friction conditions
  - Draw force (D_f)
  - Head force (H_f); hold-down force



Draw beads

DBS - Friction

$$\mu = \frac{\left(D_f - R_f\right)}{\pi\left(H_f\right)}$$



DBS Procedures

- NADDRG standard
- Procedure on A/SP website

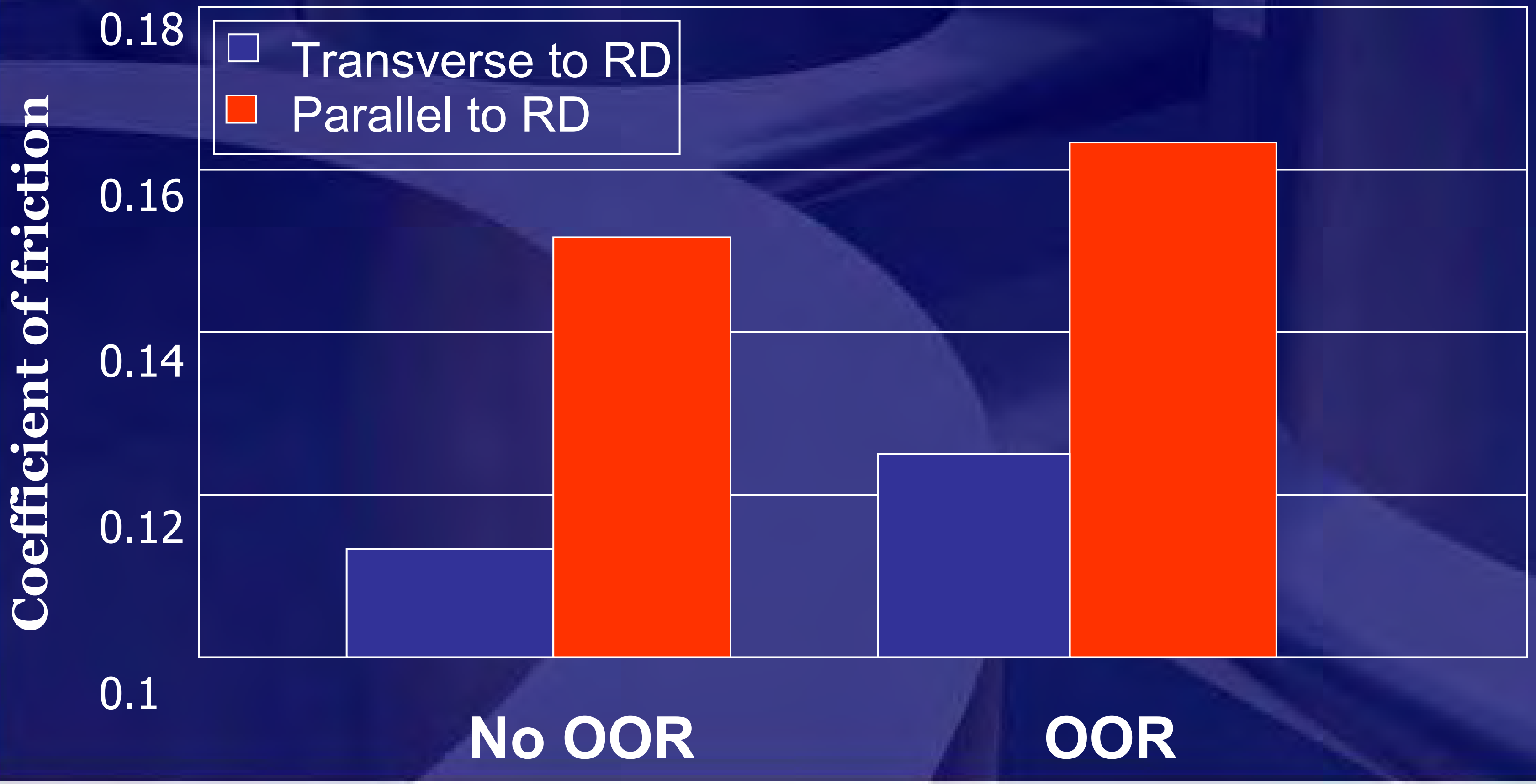
- Major difference
  - Cutting pattern within coil

DBS Evaluation of Can Stock

- Al 3104 H-19
- Five production lots
  - 2 “no OOR”
  - 3 “OOR”
- Post-lub. & cupping lub. used
- Test speed: 140 mm/s

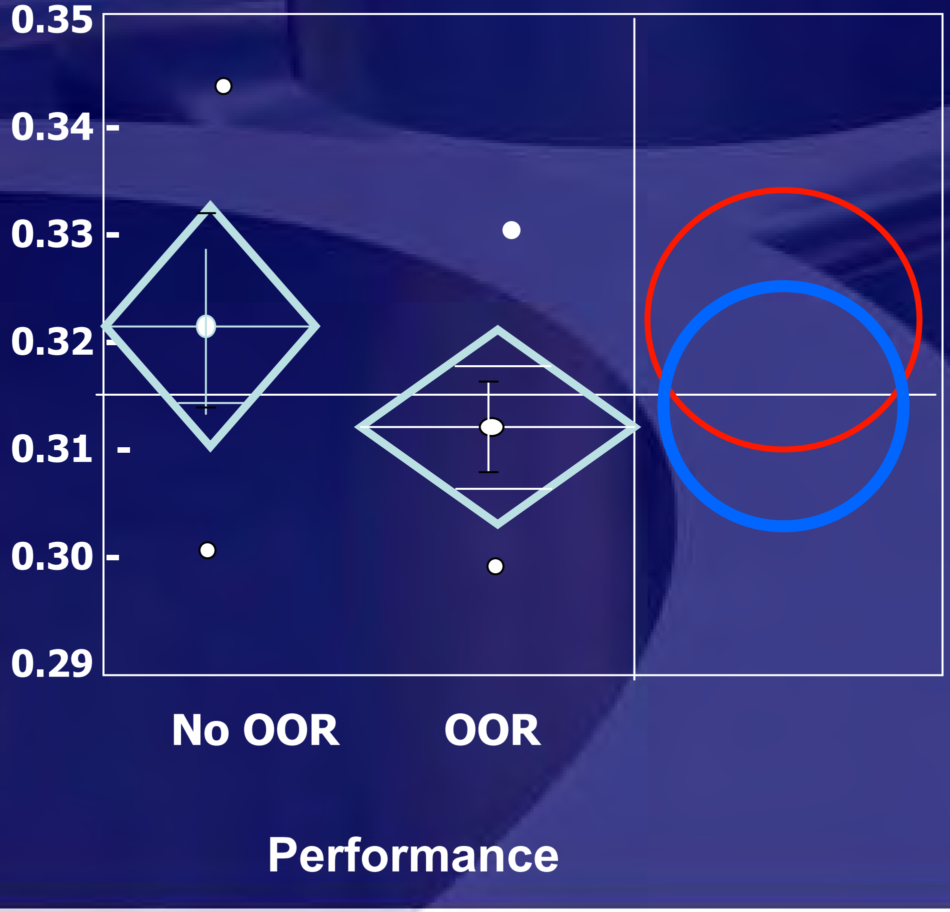
DBS Evaluation of Can Stock

Comparison of average coefficient of friction values for "OOR" and "No OOR" lots



DBS – Can Stock Study

R_a by performance



Means Comparisons

Dif= Mean(i)-Mean(j)	No OOR	OOR
No OOR	0.000000	0.009167
OOR	-0.00917	0.000000

Alpha= 0.05

Comparisons for all pairs using Tukey-Kramer HSD.

q
2.10092

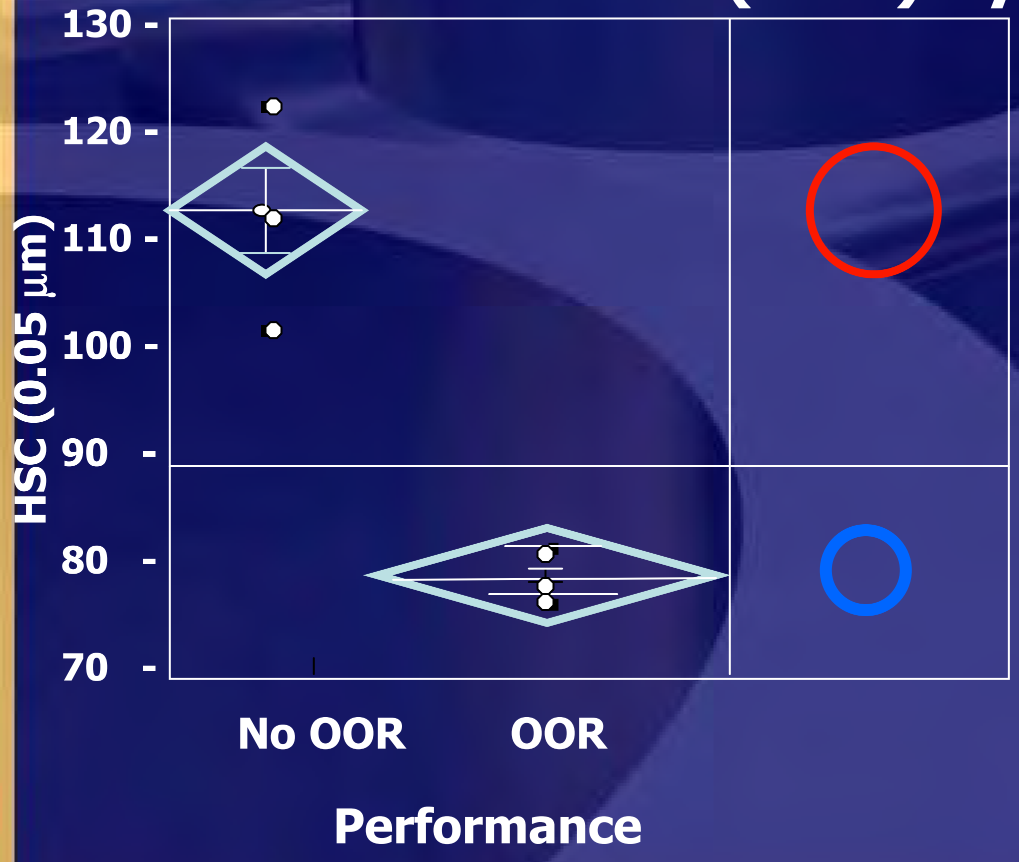
Abs(Dif)-(LSD)	No OOR	OOR
No OOR	-0.01905	-0.0082
OOR	-0.00822	-0.01555

Positive values show pairs of means that are significantly different.

ALL Pairs Tukey - Kramer 0.05

DBS – Can Stock Study

HSC (0.05) by Performance



Means Comparisons

Dif= Mean(i)-Mean(j)	No OOR	OOR
No OOR	0.0000	29.1667
OOR	-29.1667	0.0000

Alpha= 0.05

Comparisons for all pairs using Tukey-Kramer HSD.

q

2.10092

Abs(Dif)-(LSD)	No OOR	OOR No
OOR	-7.7536	22.0886
OOR	22.0886	-6.3308

Positive values show pairs of means that are significantly different.

ALL Pairs

Tukey - Kramer 0.05

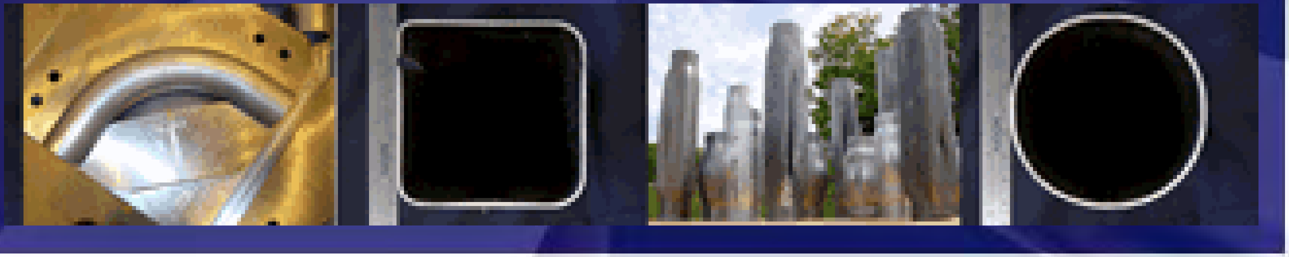
Can Stock Study Results

- OOR lots
- Higher friction
- Lower HSC, P_c, Δ_q

Hydro Forming

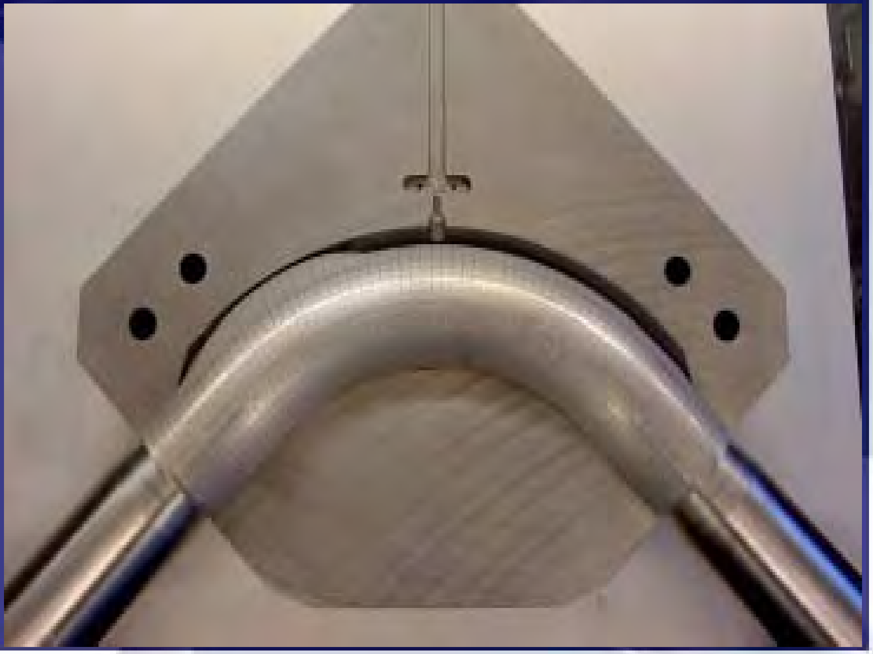
Tube Hydro Forming

- The Process
  - Growth industry
  - Uniform thinning
- Lubrication Regime
  - Boundary
- Applicable Tests
  - Free Expansion
  - TC
  - Corner Fill
  - OSU tests

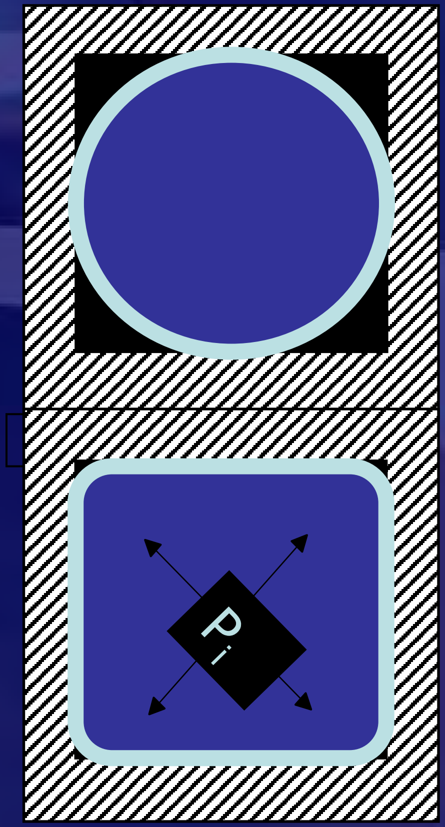


Hydroforming

- Guiding Zone
- Transition Zone
- Expansion



Corner Fill Test



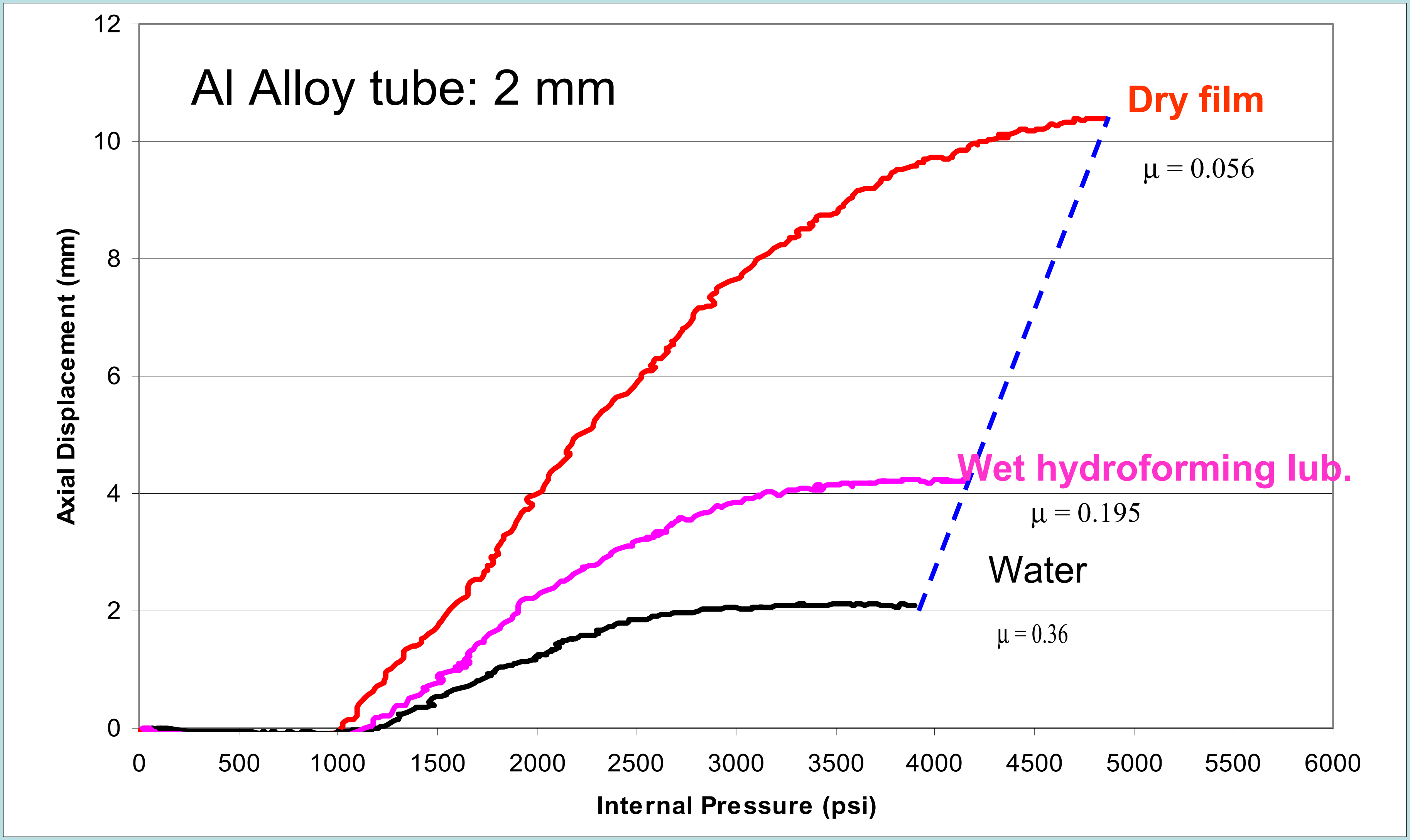
Corner Fill Test

Dry film

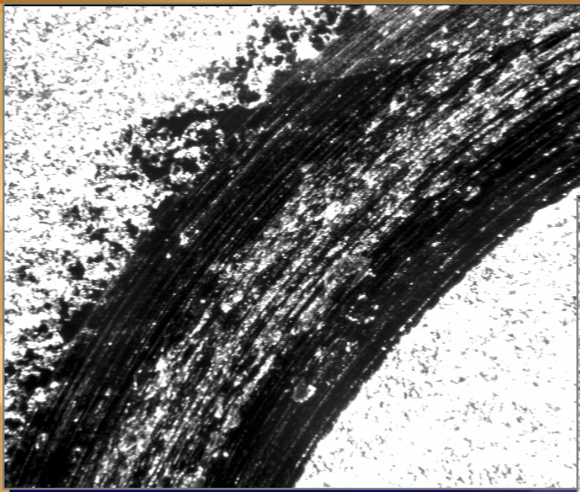
Mill oil

No end feeding

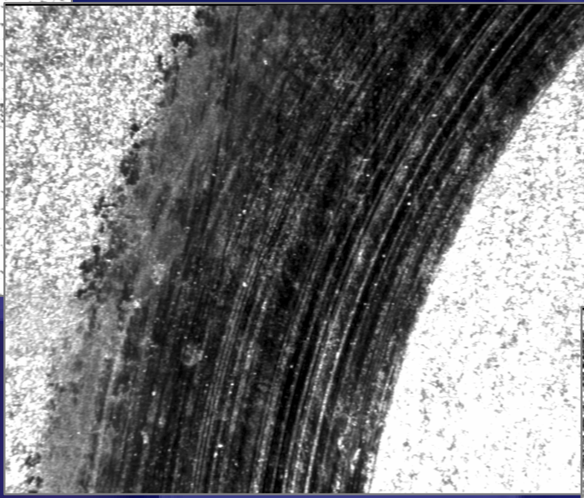
Axial Displacement vs. Internal Pressure



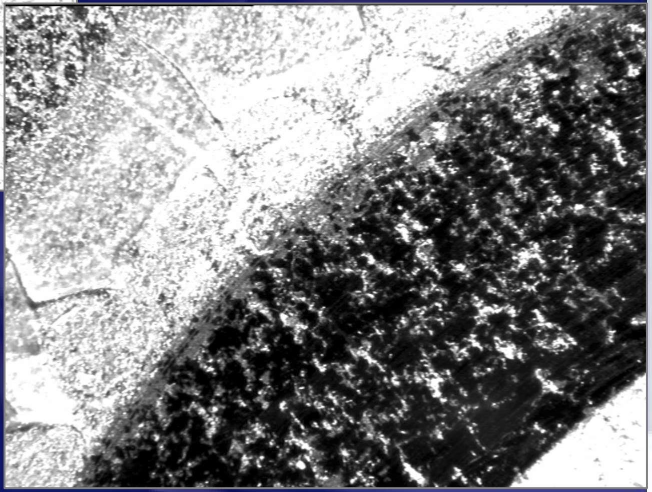
Comparison of Workpiece



Mill Oil



Wet Lube



Dry Lube

Choosing Friction Test

- Outline conditions of sliding in application
    - Temperature
    - Load
    - Velocity
    - Contact Area
    - Geometry
    - Material Properties
    - Surface Finish
    - Vibration
    - Type of lubrication

Interpreting Friction Results

- Major factors that can affect interpretation of results
  - Lubrication mechanism
  - Load -- same unit loading will result in higher temp.
  - Temperature -- capacity of material and lubricant
  - Shape -- geometry determines time in and out-of-contact

Words of Wisdom

…."All things and everything whatsoever thin it be which is interposed in the middle between objects that rub together lighten the difficulty of this friction".

Leondardo da Vinci

(Forster Bequest Manuscript II 132)

United States Steel

Effects of Coating and Forming Condition on Friction

Hua-Chu (Michael) Shih

NIST friction workshop
July 11, 2006

Outline

- Background
- Experimental work
    - Results and discussions
- Summary

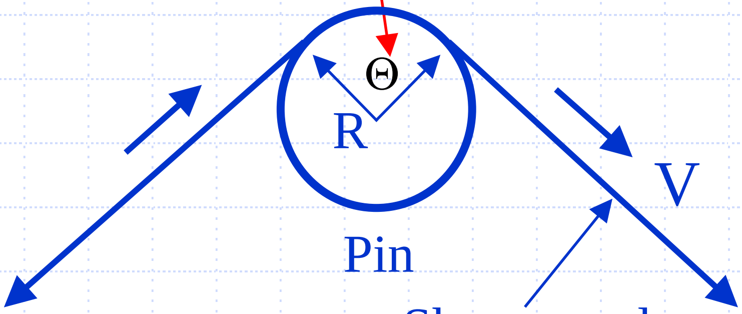
Background

- Various zinc-based sheet steel coatings have been used in automotive components
- Friction varies due to different coatings and forming processes
- Problems encounter in stamping AHSS, which is related to friction
  - Splitting around draw bead
  - High temperature of the panel and die surface
  - Coating adhesion and die surface build-up
  - Die wear

Experimental Work

- Bending Under Tension (BUT)
- Materials: DDS (EG, EGA, HDGI, HDGA, HDGA+phosphate)
  DP600 HDGA
- Friction measurements
  - Effects of coatings, sliding speeds and contact pressures : DDS
  - Effects of die materials, temperatures & back tension force : DP600
  - Effects of climate temperatures (Winter, Summer) : DP600
- Die wear vs. coating adhesion
  - Water cool draw bead system
  - Cyclic bend test
  - Field validation

Bending Under Tension (BUT) Test



90 degree wrap angle

Sheet metal

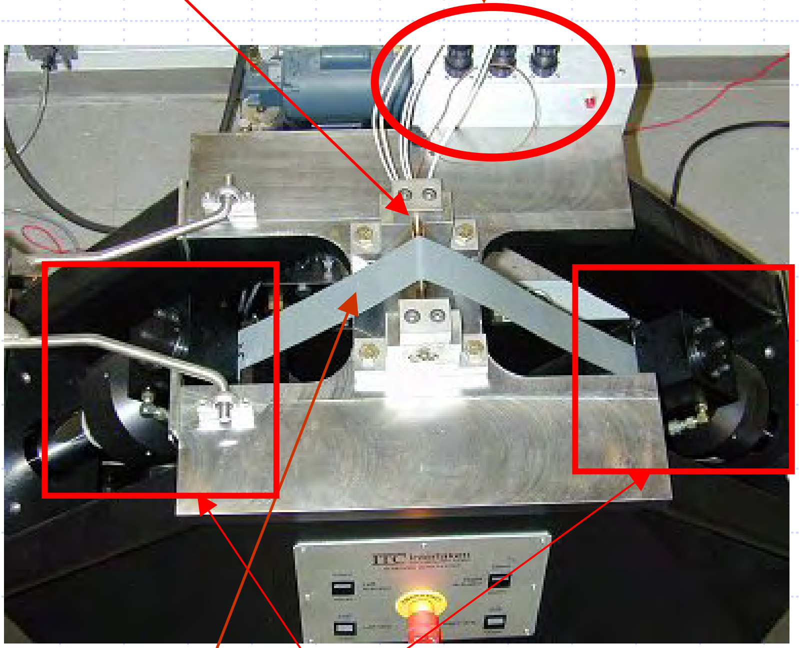
Back tension force F1

F2

(friction model, Wilson et al. 1991)

$$\bar{\mu} = 2\left(F_2 - F_1 - \boxed{F_b}\right)/\Theta\left(F_1 + F_2\right)$$

$$F_b = \frac{\sigma_y t^2 w}{2R}$$ (Swift 1948)



Pin die

Heater

Specimen

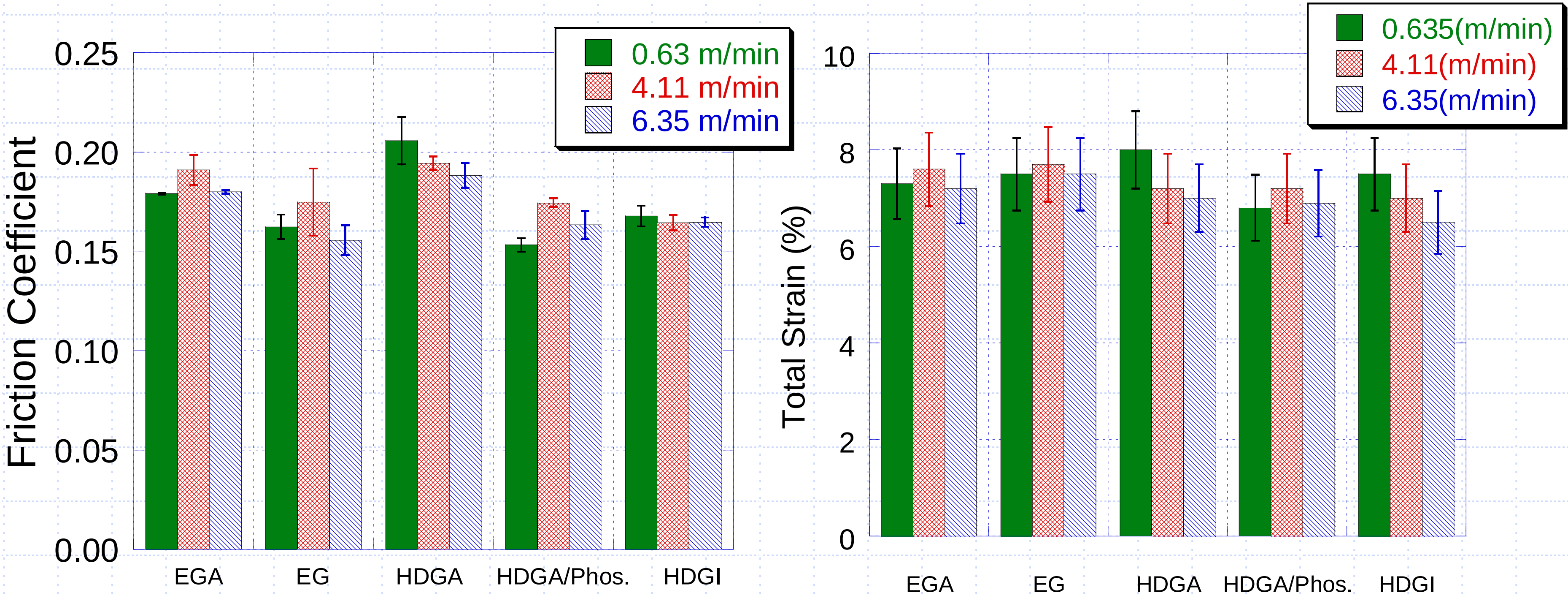
Grips and actuators

- Materials - DDS(substrate)
  - EG (electrogalvanized)
  - EGA (electrogalvanized Zn-Fe alloy)
  - HDGA (hot dip galvanneal)
  - HDGA /Phosphate (HDGA coated with a prephosphate)
  - HDGI (hot dip galvanized)

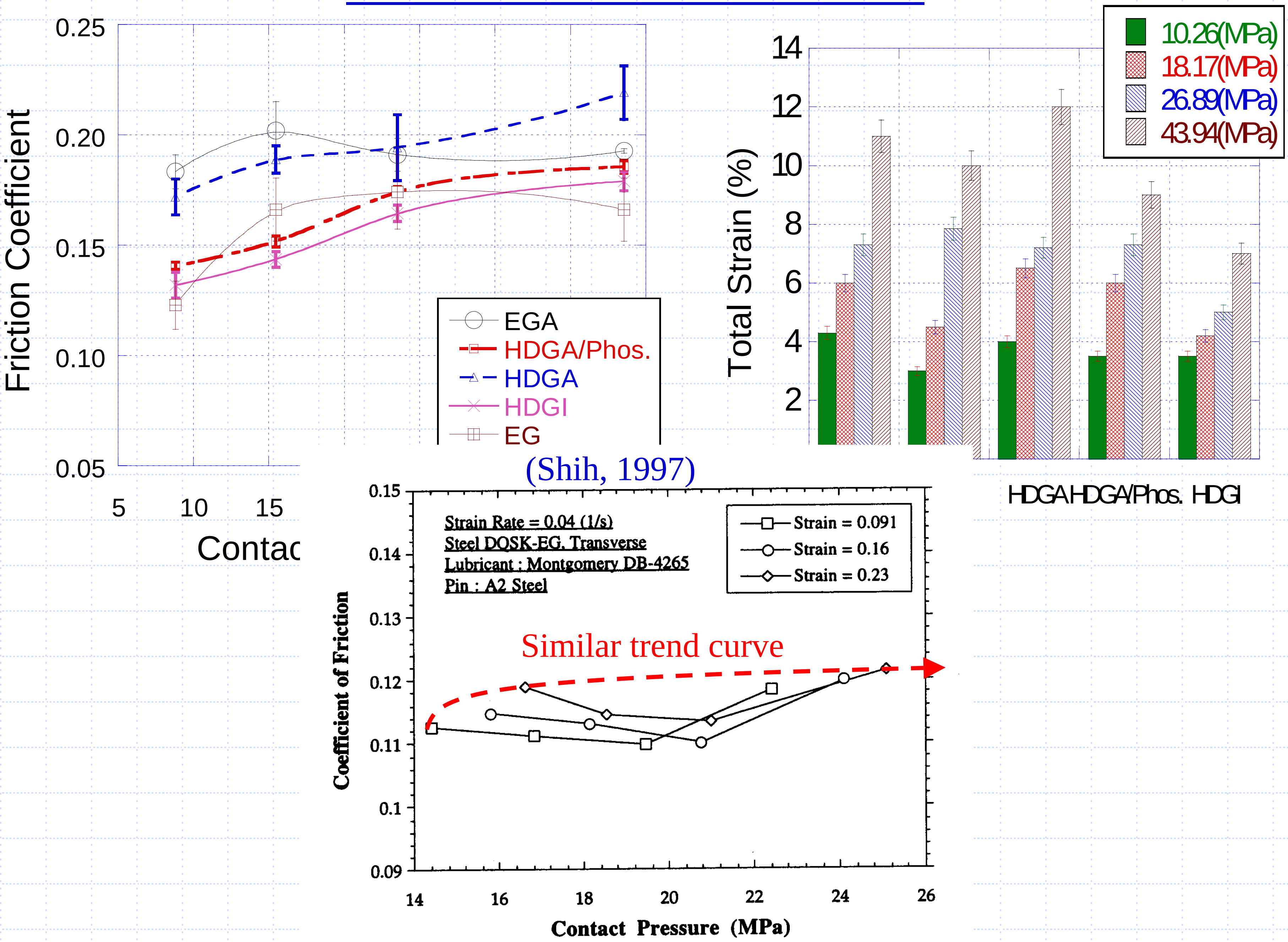
As received Surface Roughness and Mechanical Properties

Material	Gauge (mm)	Coating weight (g/m^2)	Ra (µm)	Yield Strength (MPa)
EGA	0.81	45	1.014	176
HDGA/Phos.	0.81	45	1.265	151
HDGA	0.81	45	1.207	152
HDGI	0.78	70	0.437	143
EG	0.78	70	1.053	138

Effects of sliding speed



Effects of Contact Pressure

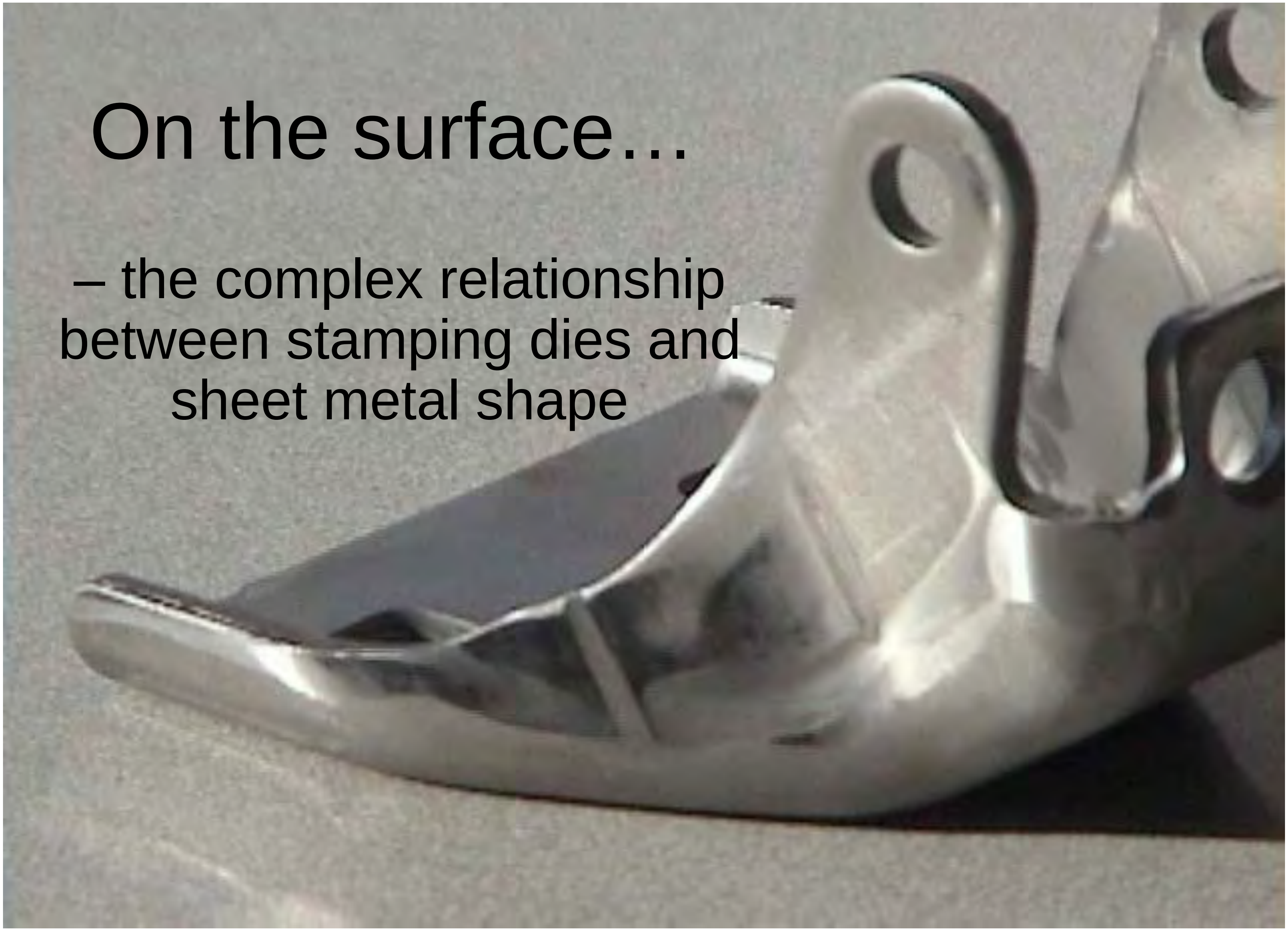


(Shih, 1997)

Similar trend curve

Summary

- With increasing sliding speed, the friction coefficient decreases for the HDGA and EG coatings. For the EGA and HDGA/Phosphate coatings, the friction coefficient increases with increasing speed at low speeds while at high speeds the friction coefficient decreases with increasing speed
- For the EG and EGA coatings, the friction coefficient increases with increasing pressure (strain) at low levels, which is associated with the asperity flattening. At high levels, the friction coefficient tends to decrease with pressures (strain), which is associated with the surface roughening. For the HDGA, HDGA/Phosphate and HDGI coatings, the friction coefficient increases with increasing pressure (strain), which is associated with asperity flattening.

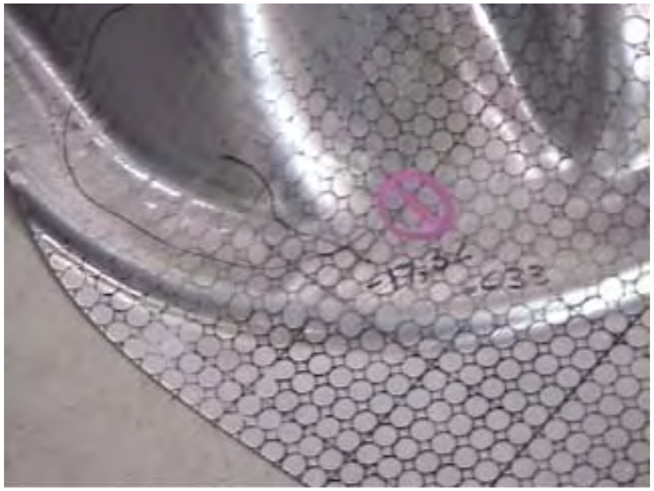


On the surface…

– the complex relationship between stamping dies and sheet metal shape

Outline

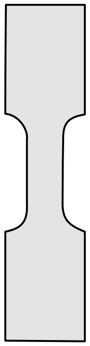
- Background
- The Role of Surface
- Impact on Design and Production
- Meeting the challenge



Gregory Dalton, July 11, 2006

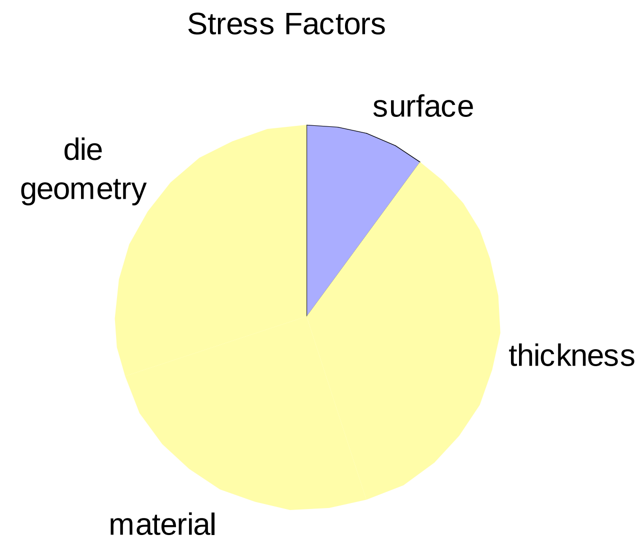
The Art of Sheet Metalforming

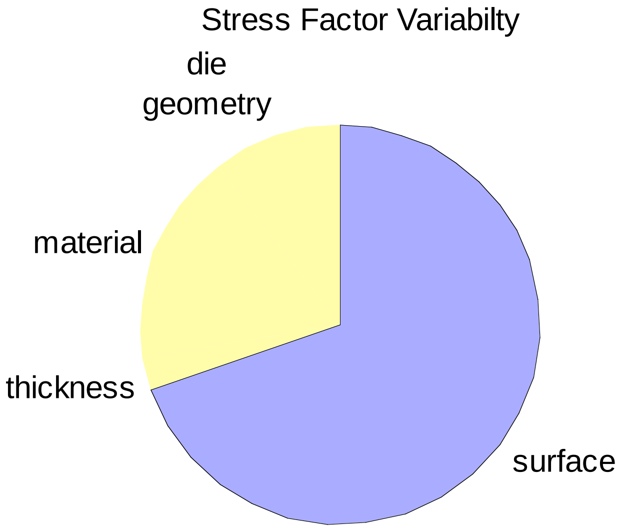
- Elastic/plastic behaviour not just metallurgical in Sheet metalforming (much more complex than tensile test)
  - Much more important for AHSS
  - Thickness and property differences are important variables.
- Relationship between stress and strain



The Role of the Surface

- Surface effects are secondary to material properties and geometrical (t, r) factors
- Surface factor variability is many times higher than the "major" factors





Surface conditions are transient for one part for many.

- Contact changes in space and in time
- Events are not predictable or gradual
- Complex function of surface properties (bulk and local) and surface morphology

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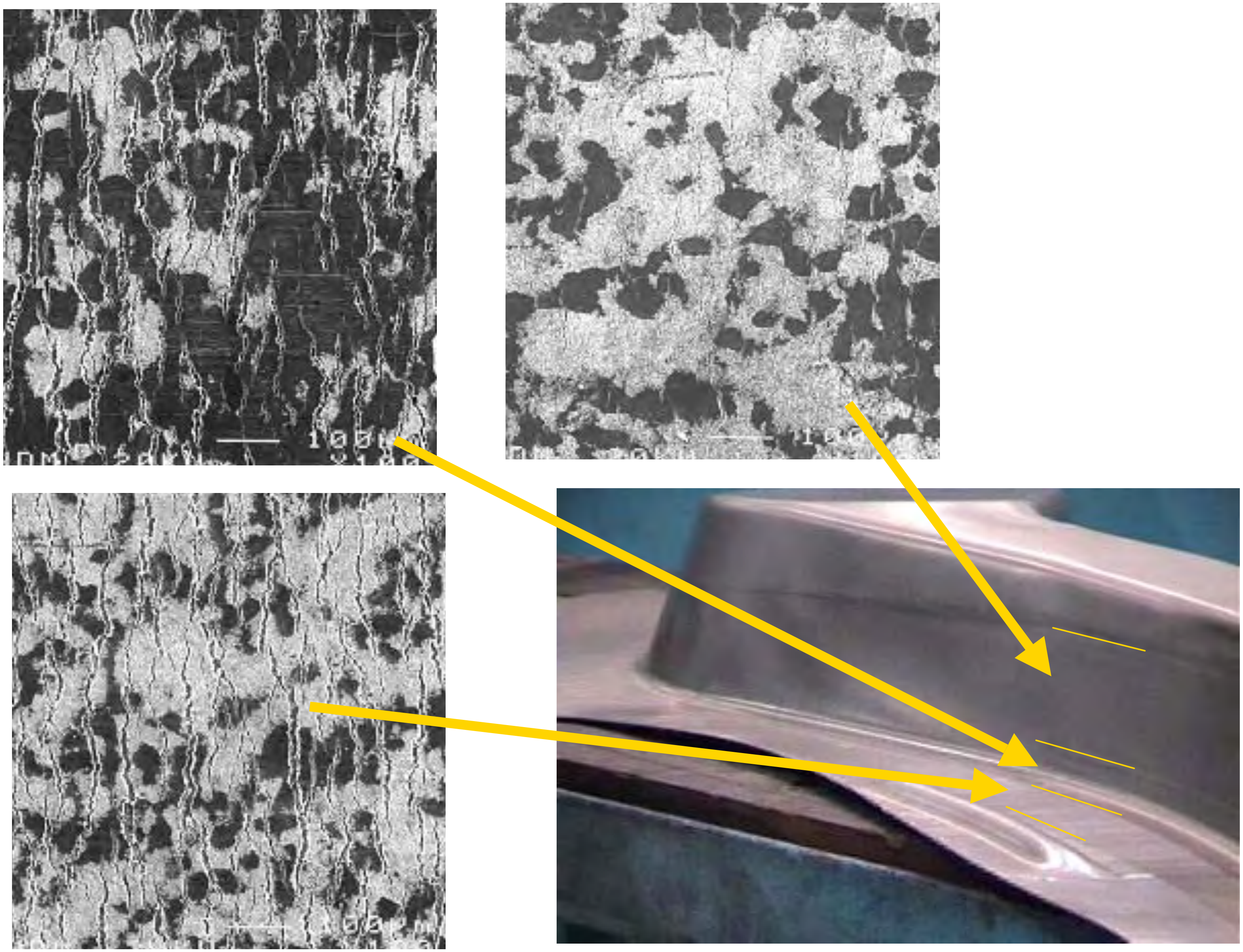


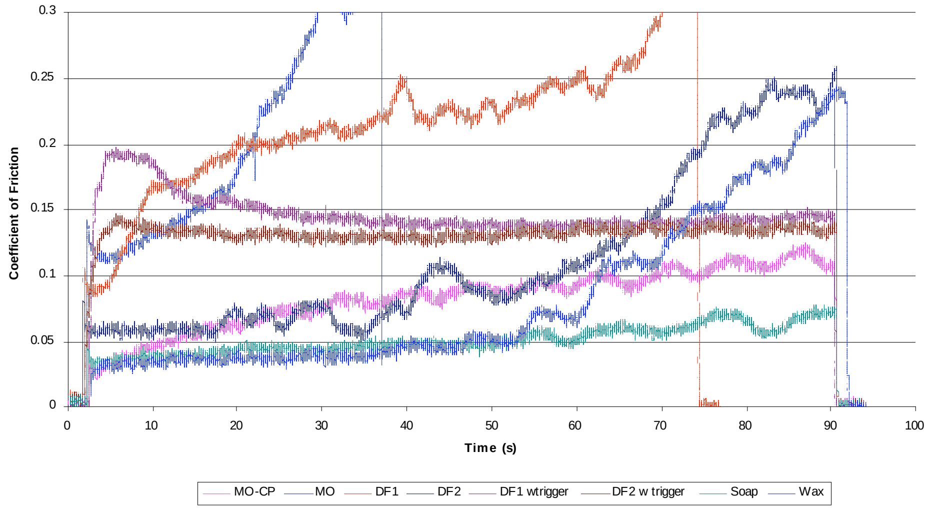
Gregory Dalton, July 11, 2006

The Reality of Data

- What they want…

Lube	A	B	C	D
COF	0.10	0.12	0.14	0.20

- What you've got…



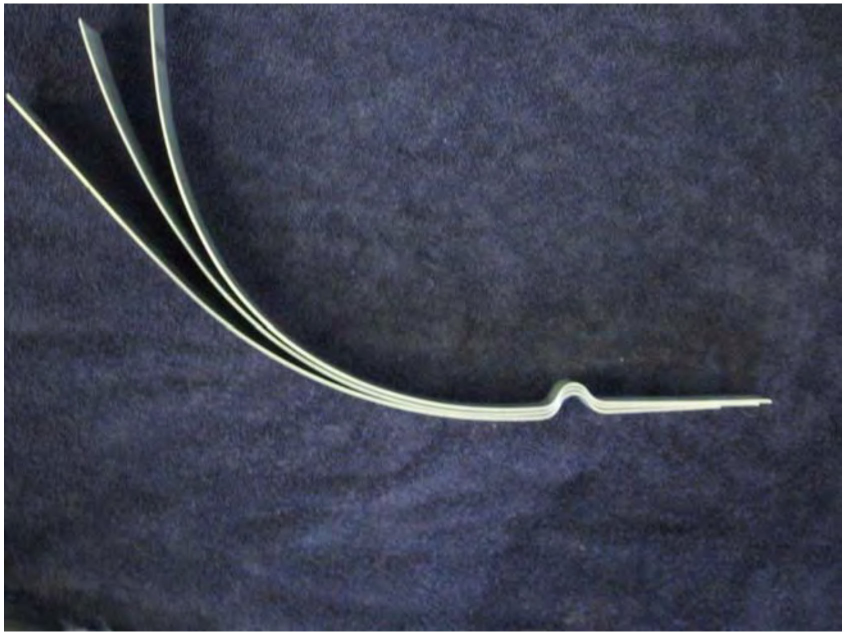
Surfaces are most important for drawn parts

Some stampings are more surface sensitive…

- Long sliding distances
- Deep and complex draws
- Sharp die features
- Restrikes

How does this affect:

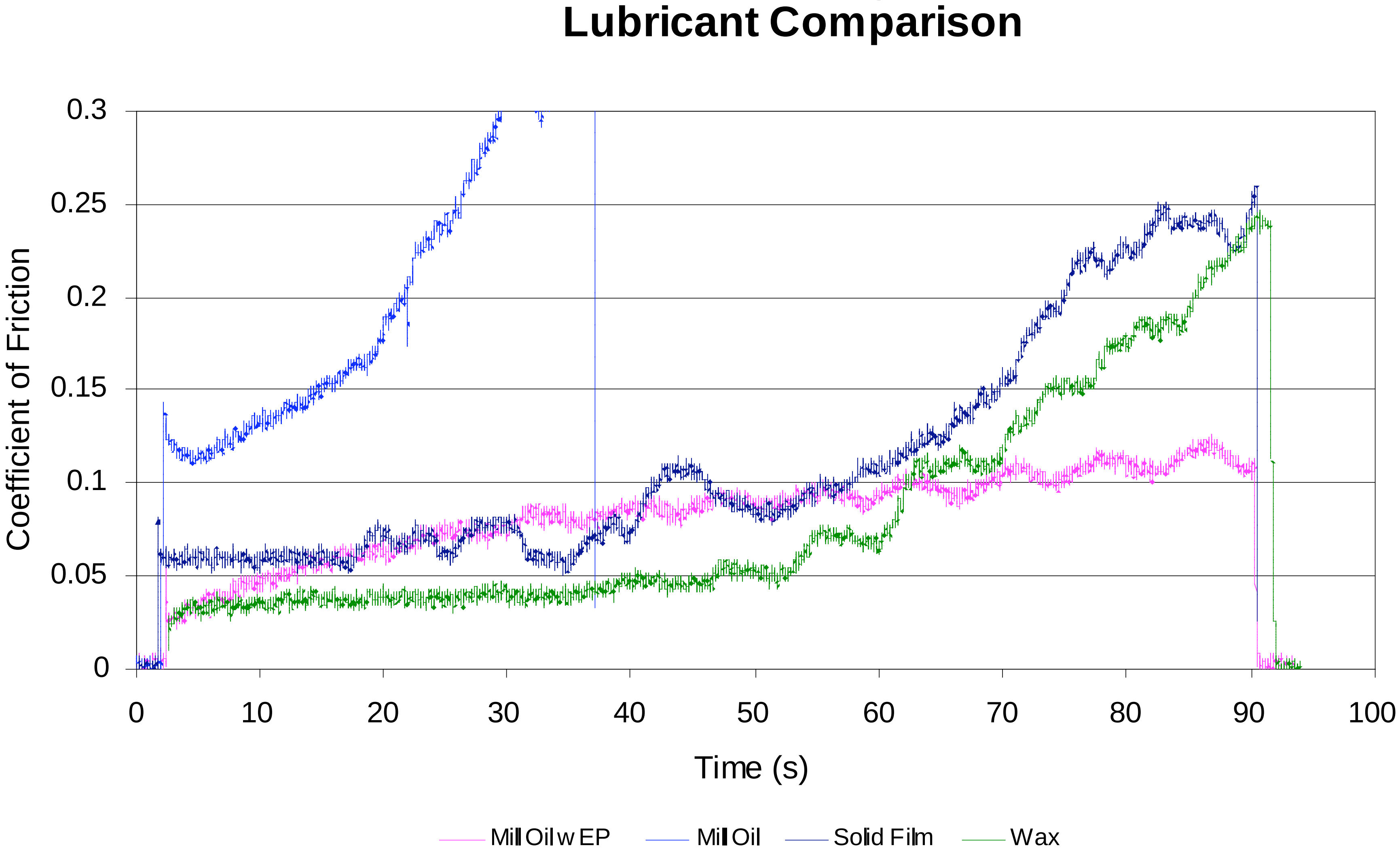
- The design process
  - Selection of materials and surface data
- Die tryout and buyoff
  - Representative surfaces
- Process capability
  - Surfaces changing in time



Designing for Robust Surfaces

- Materials (die surface, sheet coatings, and lubricants) that are insensitive to inherent process variability
- Defining multiple processes within a single process with settings linked to measurable characteristics.
- Identifying surface sensitivities on die designs (geometric rules)

Lubricants: the magic bullet?



Gregory Dalton, July 11, 2006

CAMMAC Friction Tests

Presentation to NIST Workshop, July 11, 2006

Robert H. Wagoner, Smith Chair
Director, CAMMAC
Professor, Mat. Sci. & Eng.
Professor, Mech. Eng.

THE OHIO STATE UNIVERSITY

Center for
Advanced
Materials and
Manufacturing of
Automotive
Components

CAMMAC Background

Mission:

Advance knowledge and technology at the intersection of advanced materials and manufacturing processes for ground-based transportation.

Improve the reliability, quality, cost, performance, mass, and environmental impact of such vehicles.

CAMMAC PI'S and ADMIN

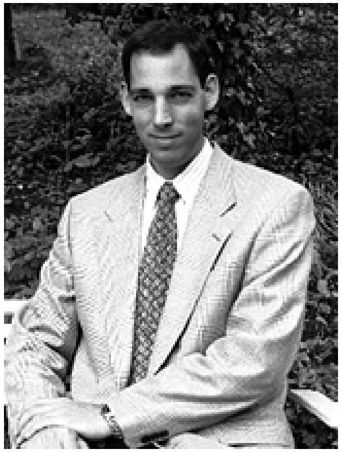
William A. Baeslack III
Dean (CoE)

Robert H. Wagoner
Director (MSE)

Glenn S. Daehn
(MSE)

Hamish L. Fraser
(MSE)

June K. Lee
(Mech. E)



Mark E. Walter
(Mech. E.)

Gary L. Kinzel
(Mech. E.)

Somnath Ghosh
(Mech. E.)

S. Bechtel
(Mech. E.)

C. E. Albright
(I.W.S.E.)

CAMMAC Friction History

Approach:

Practical / accurate friction testing applicable to forming over a die or punch radius.

Purpose: forming and springback simulation.

Tests Developed:

OSU Friction Test (1992-96). EMTEC, ERC/NSM.

Lubricant Ranking Test (1993-94). John Deere.

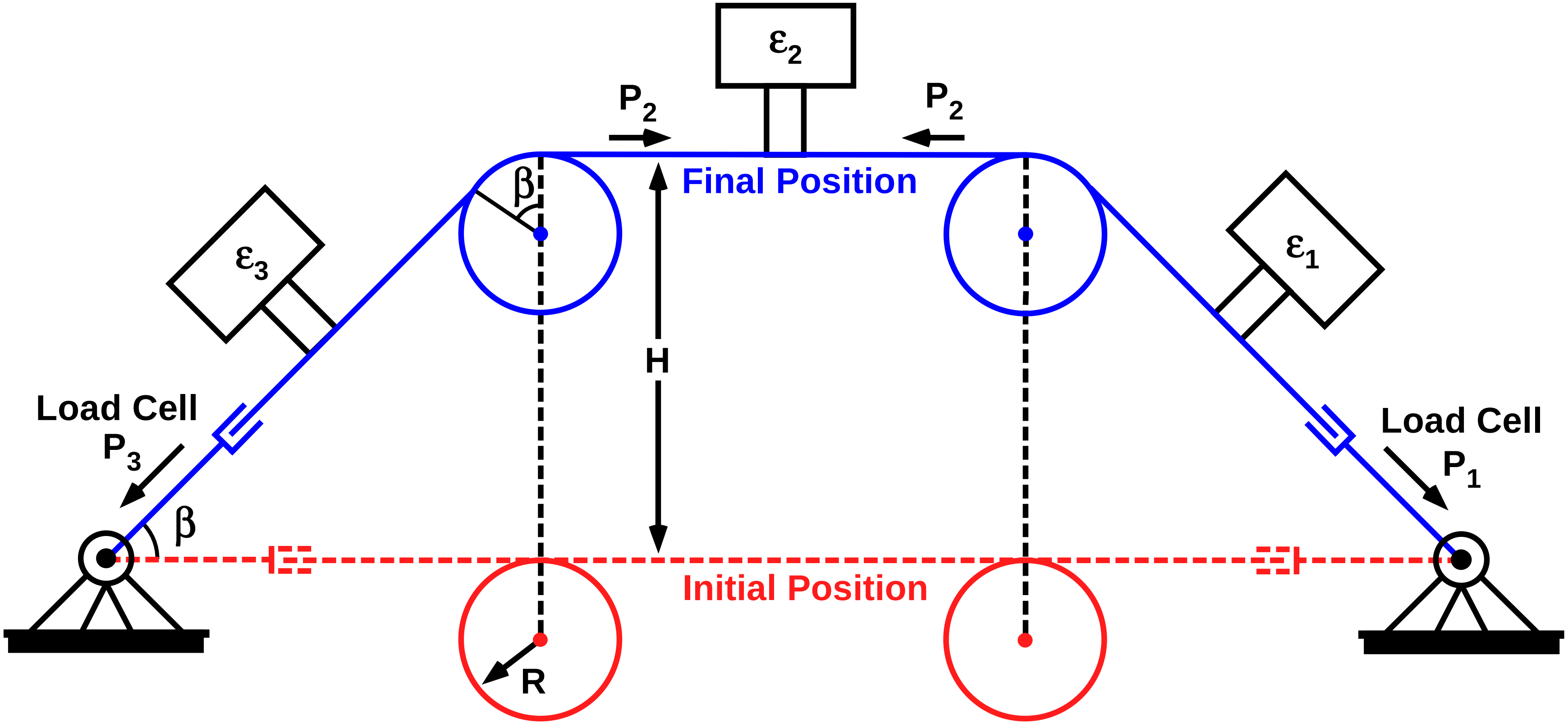
Draw-Bend Springback Test (1996-2005). USCAR / NIST.

OSU Friction Test

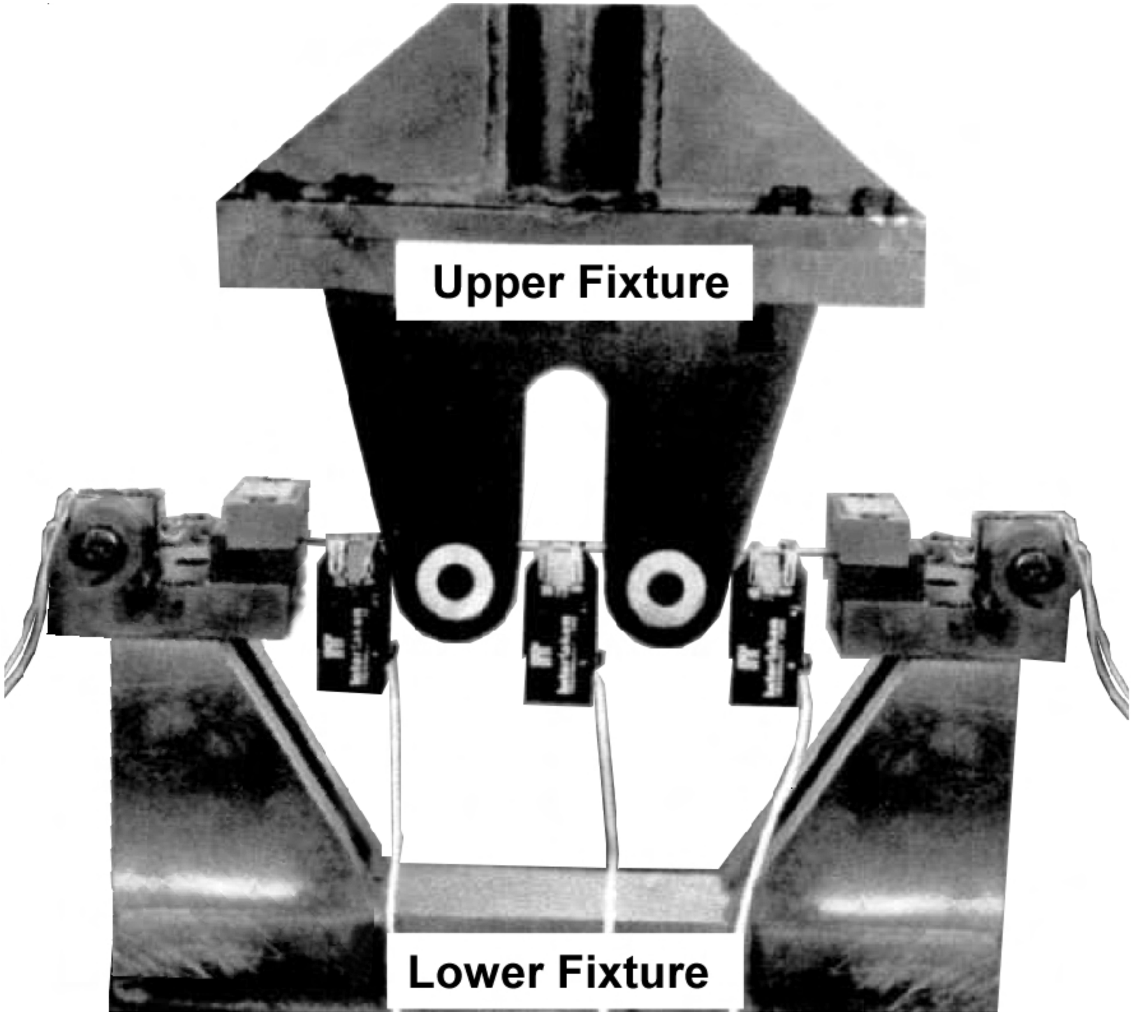
W. Wang, R. H. Wagoner: SAE # 930807, 1993.

W. Wang, R. H. Wagoner, X.-J. Wang: Metall. Mat. Trans. A, 1996, vol. 27A, pp. 3971-3981.

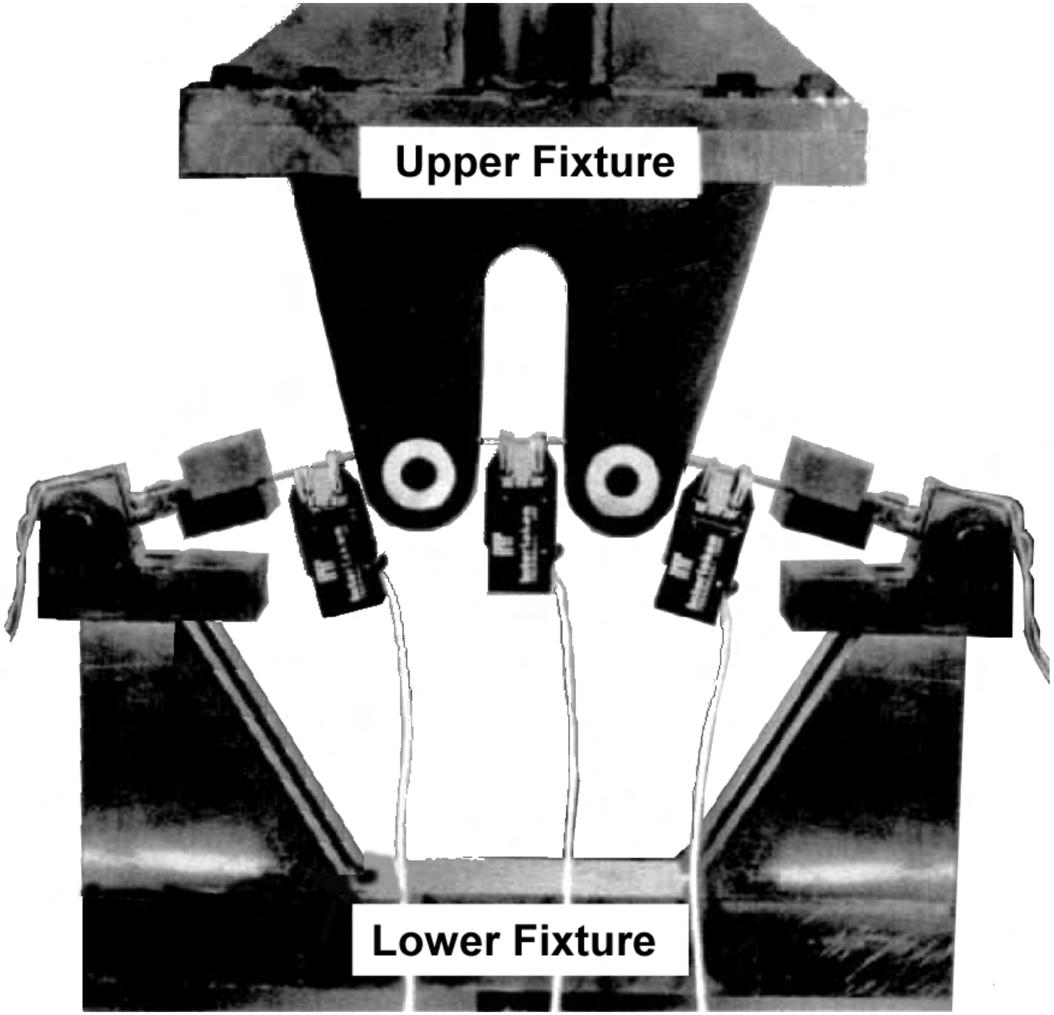
Schematic: OSU Friction Test



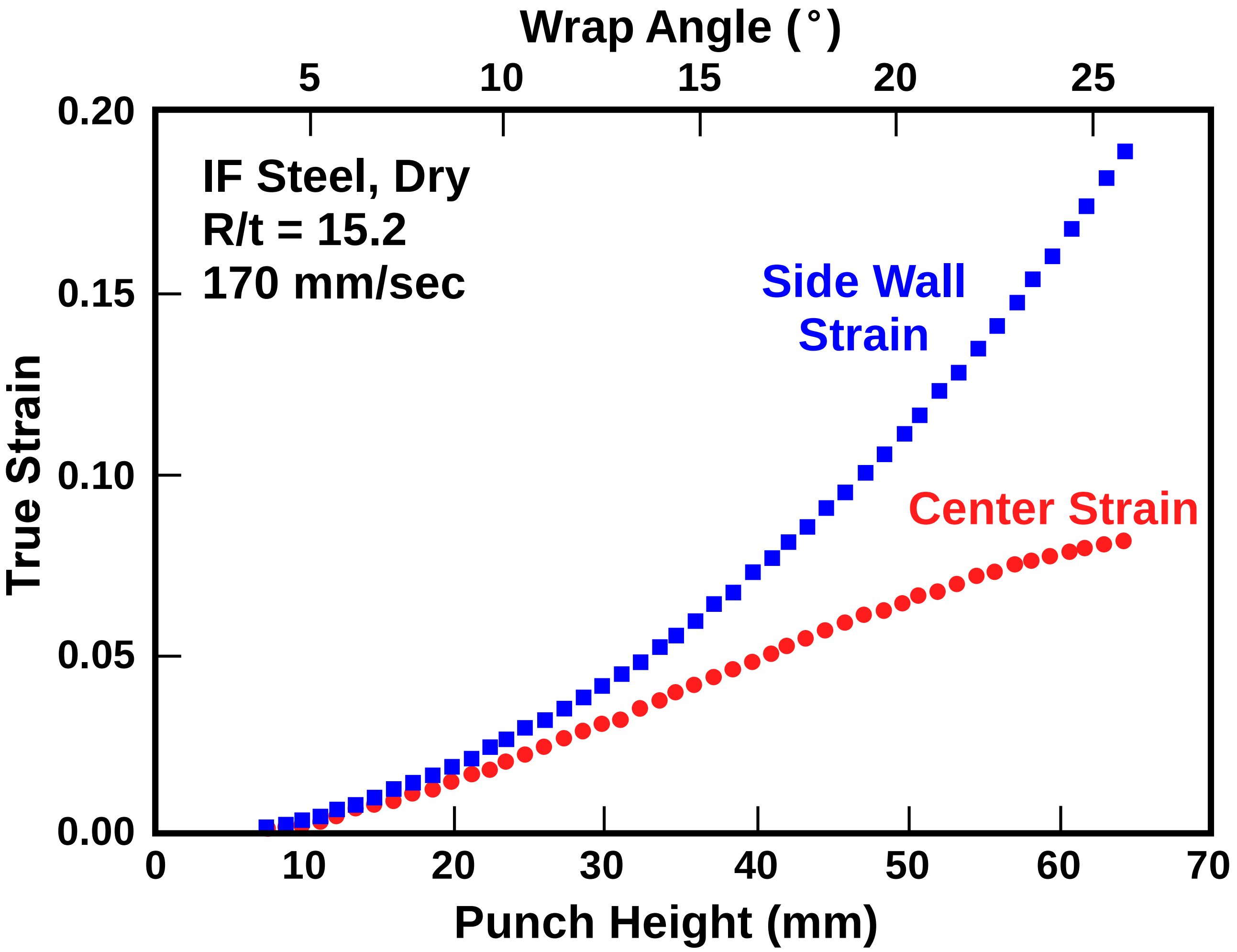
Fixtures: OSU Friction Test (initial)



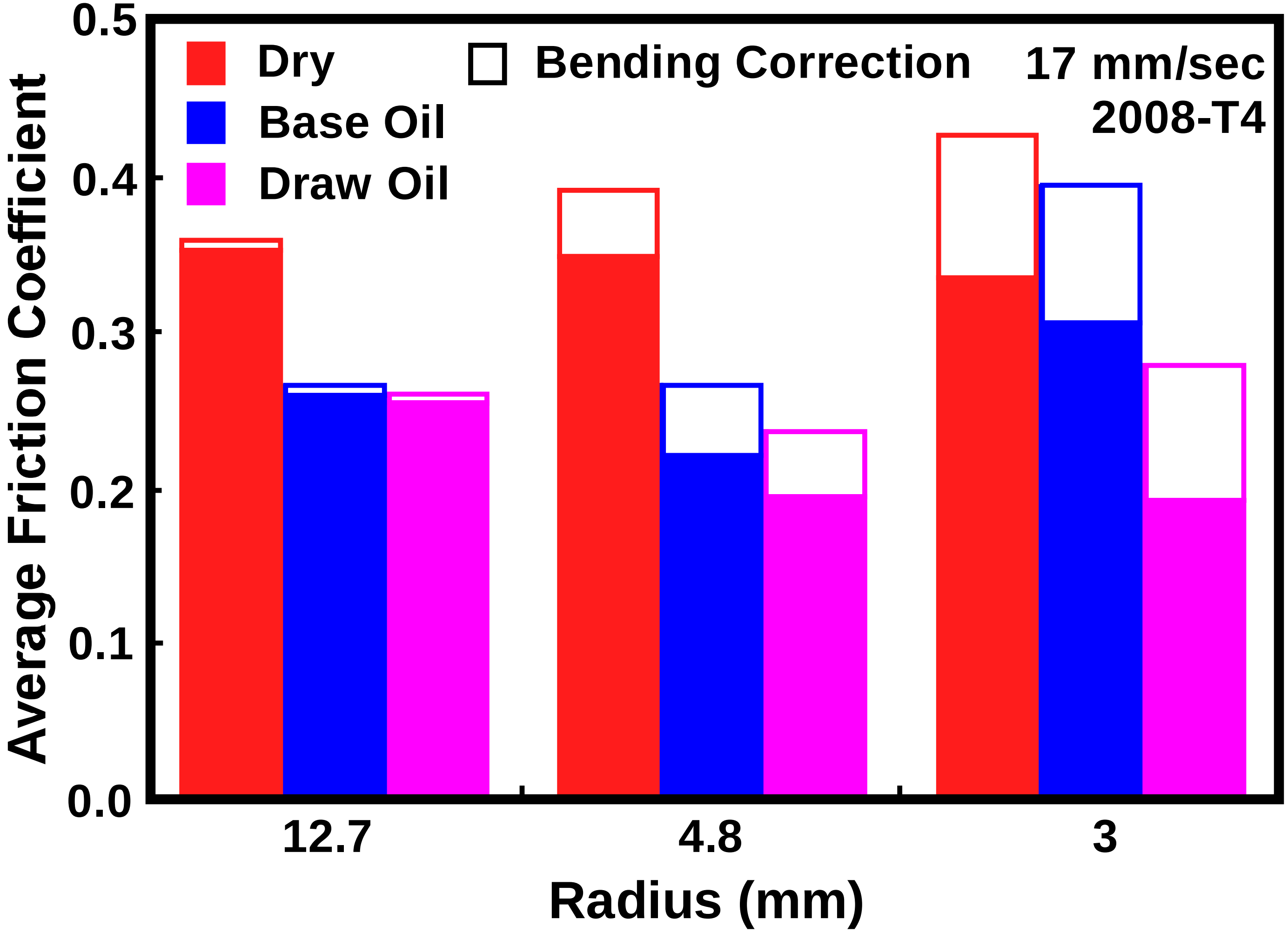
Fixtures: OSU Friction Test (mid-test)



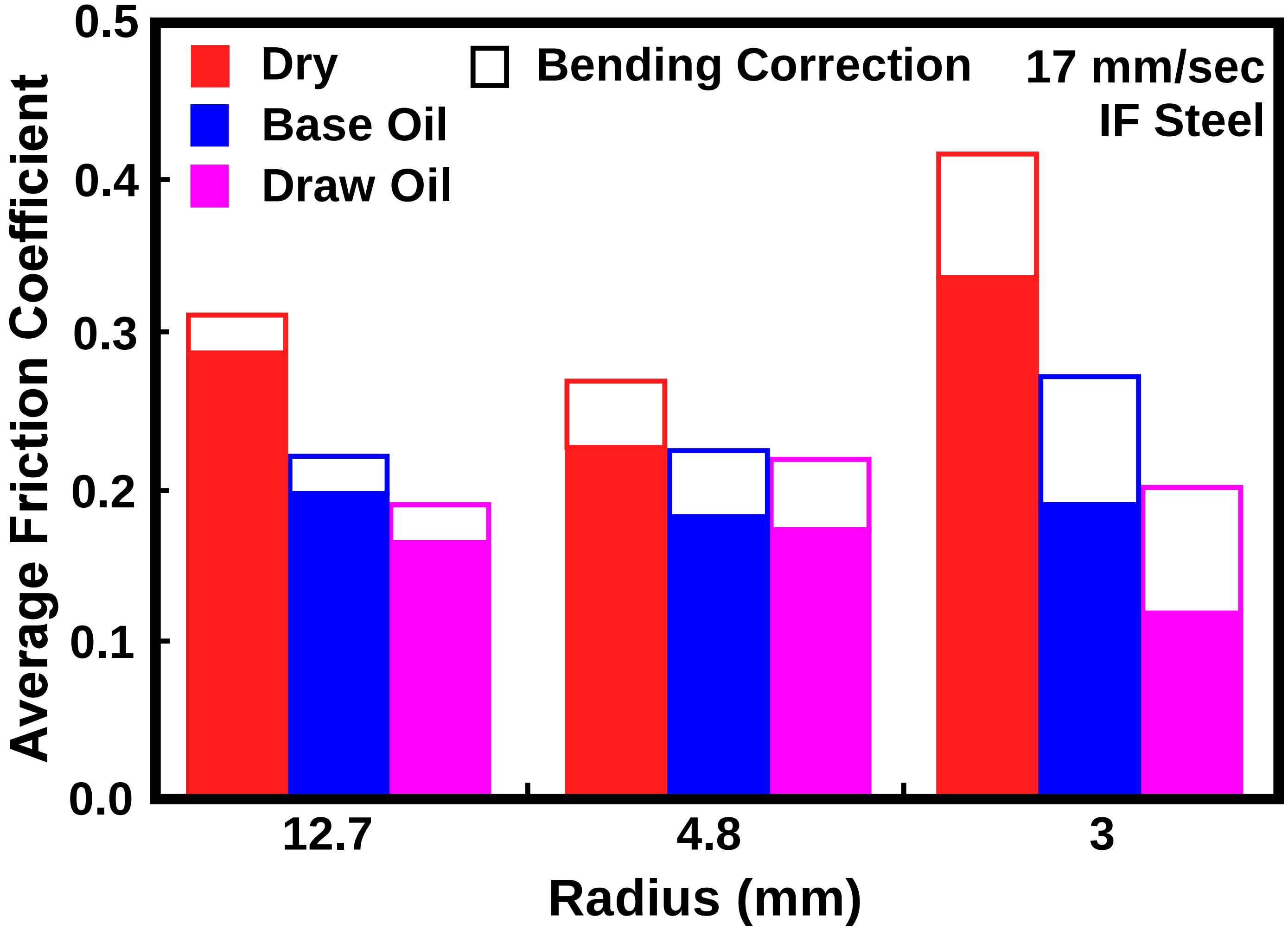
Strain-Time Trajectories



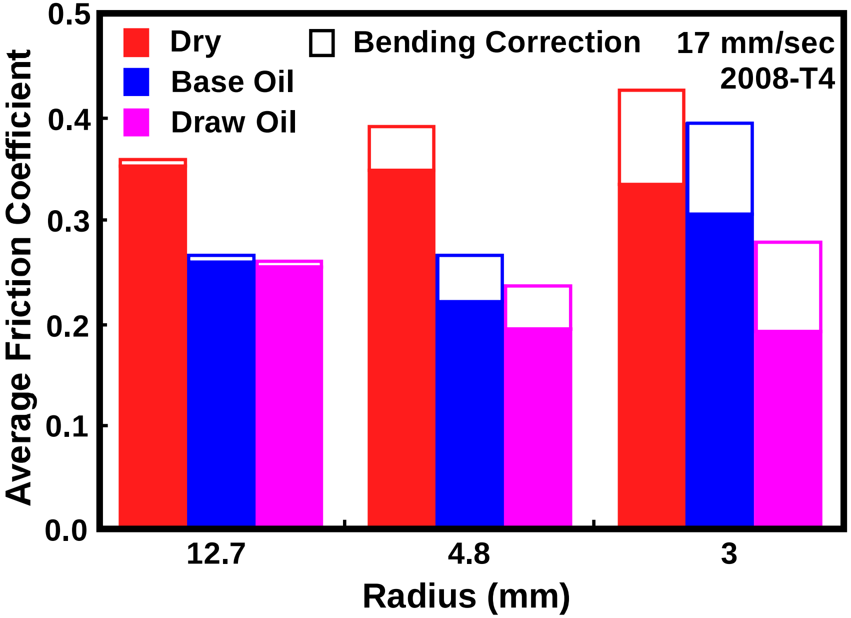
Results: OSU Friction Test

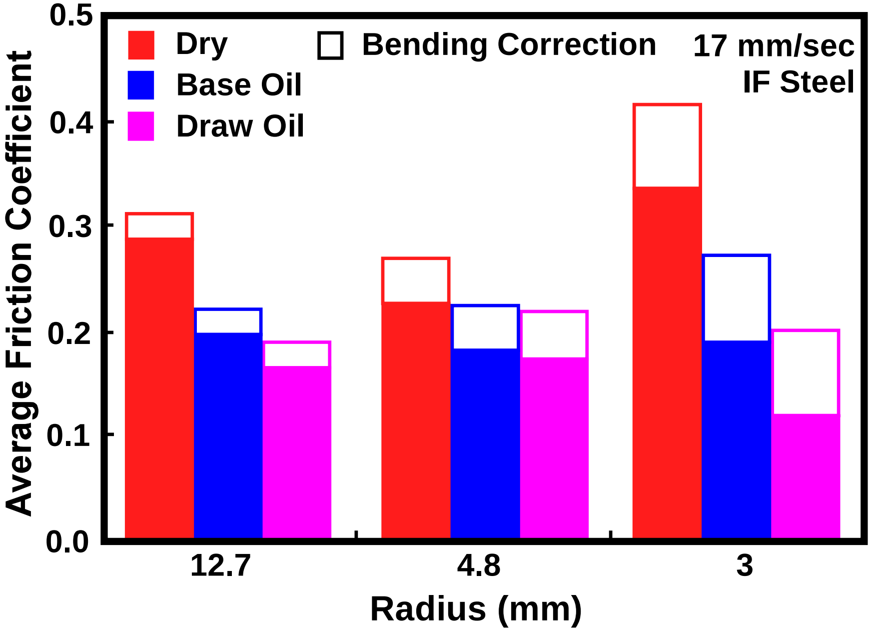


Results: OSU Friction Test

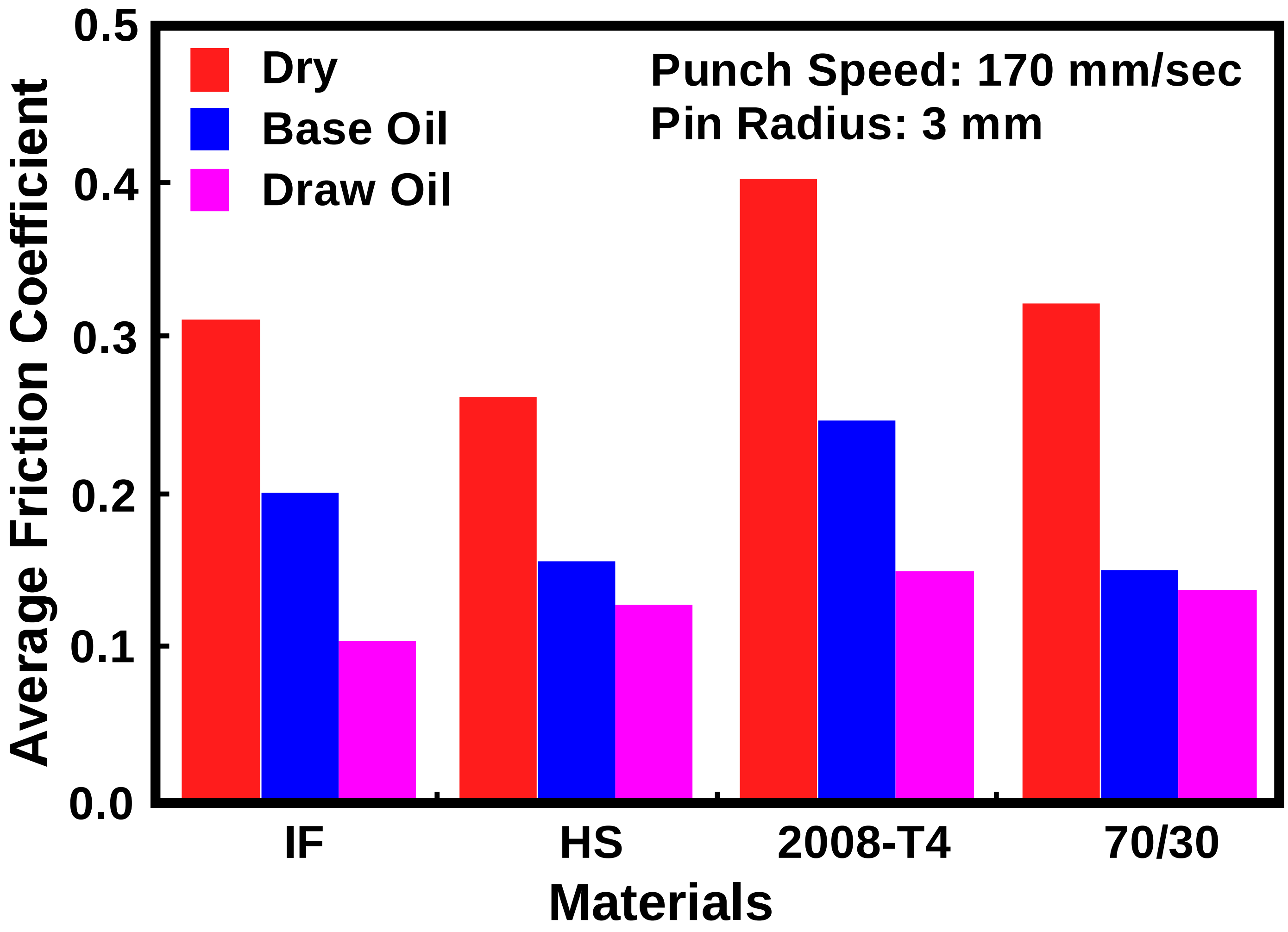


Results: OSU Friction Test





Results: OSU Friction Test



OSUFT CONCLUSIONS

Friction coefficient measurement under sheet-forming conditions requires accounting for bending.

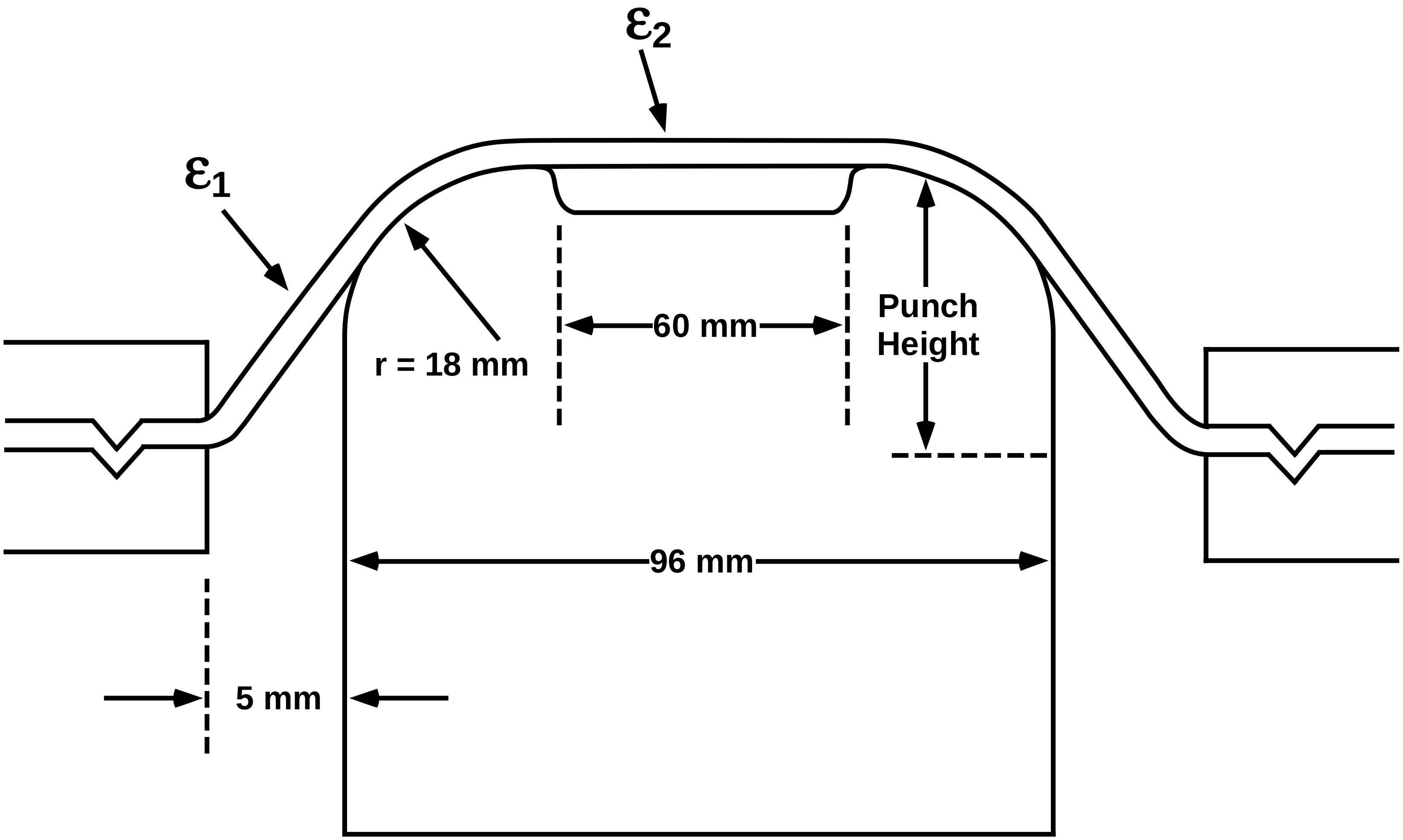
Forming friction depends on material/lubricant, r/t.

No independent control of r/t, pressure, draw distance.

Lubricant Ranking Test

R. M. Harycki, K. E. Gasper, R. J. Smola, F. I. Saunders, J. M. Garrett, and R. H. Wagoner:, <u>MetalForming</u>, 1994, vol. 28, pp. 39-47.

Schematic of Lubricant Ranking Test



Lubricant Ranking Formulas

Effective Friction Coefficient:

$$\mu_{eff} = \frac{1}{\beta}\ln\left(\frac{F_2}{F_1}\right) = \frac{1}{\beta}\ln\left(\frac{A\sigma(\varepsilon_2)}{A\sigma(\varepsilon_1)}\right)$$

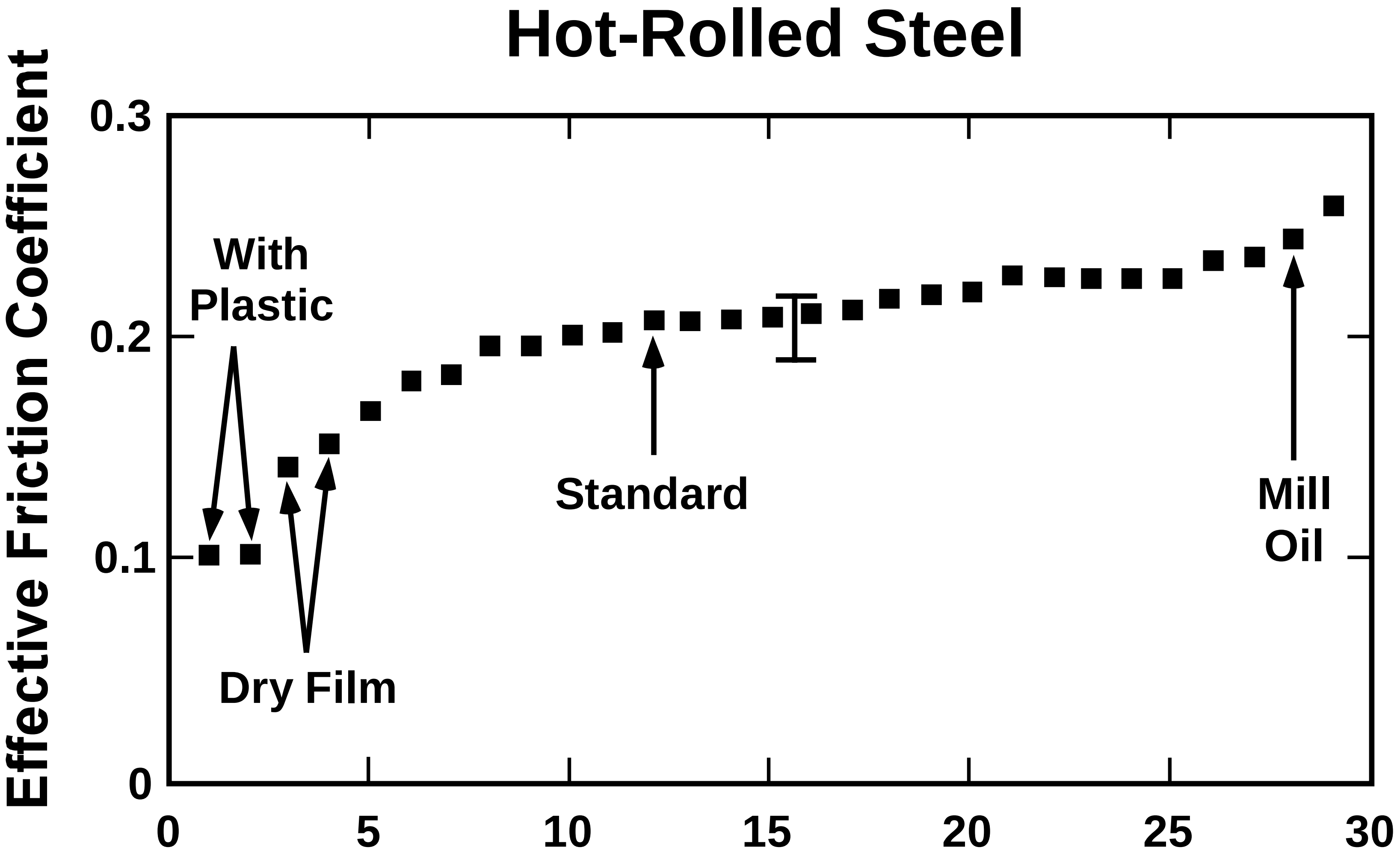
where β = angle of wrap

Simpler Measures:

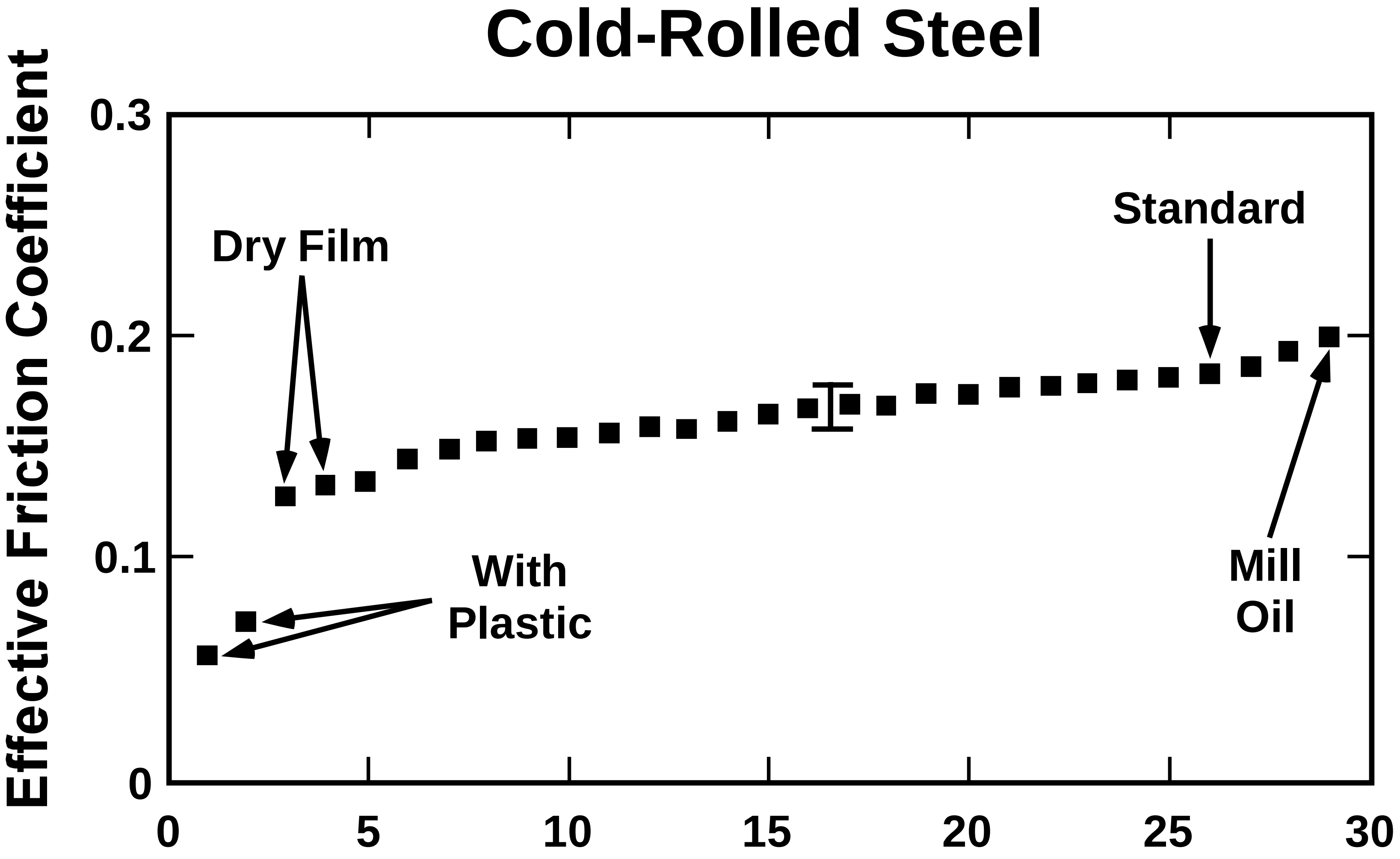
$$\frac{\varepsilon_2}{\varepsilon_1} \text{ at fixed } \beta$$

$$\varepsilon_1 \text{ for } \varepsilon_2 = \varepsilon_{uniform}$$

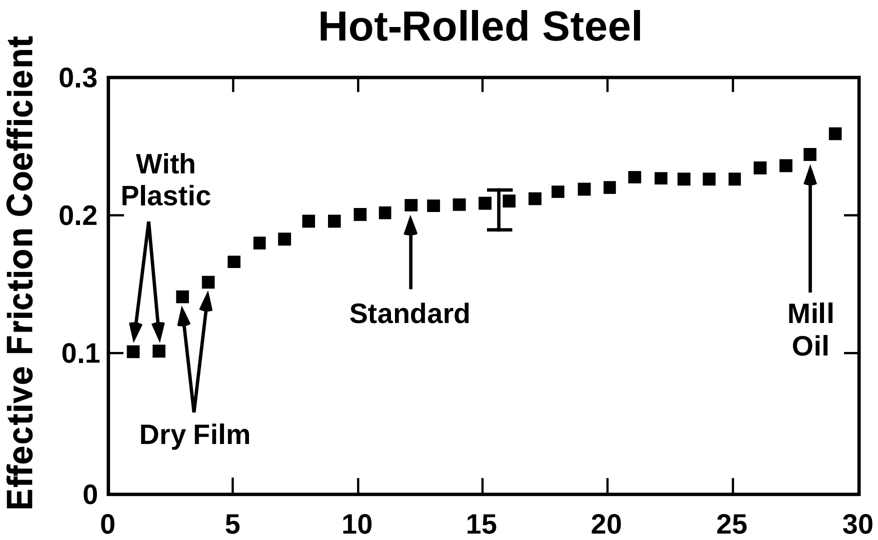
Ranking of 29 John Deere Lubricants

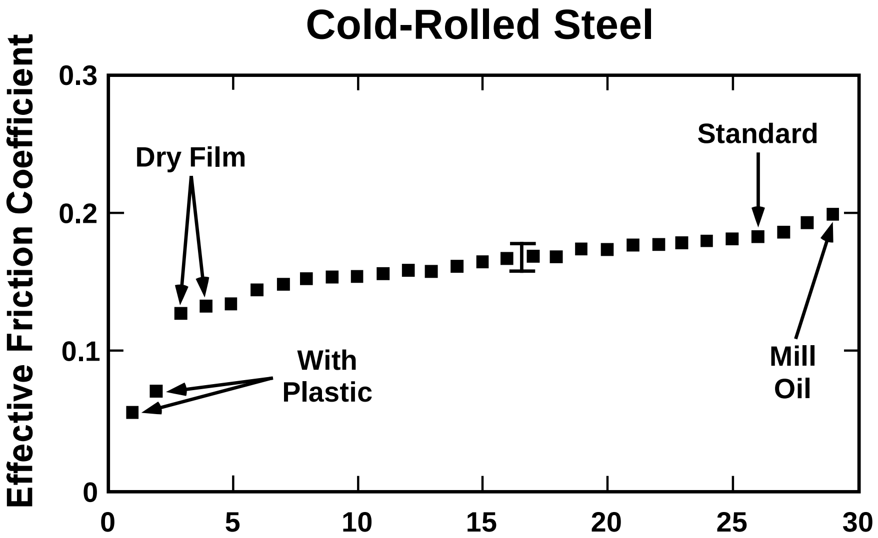


Ranking of 29 John Deere Lubricants



Ranking of 29 John Deere Lubricants





Lubricant Ranking Correlation

Correlation of John Deere and Ohio State Evaluation of Round III Lubricants

John Deere Ranking	Ohio State (μ)	Performance in Pocket Die	
1	0.131	100 pts	No Necking in Pocket
2	0.160	70 pts	Onset of Necking in Pocket
3	0.168	40 pts	Definite Necking in Pocket
4	0.189	40 pts	Definite Necking in Pocket
5	0.190	20 pts	Severe Necking in Pocket

LRT CONCLUSIONS

Very sensitive variations of lubricity can be detected, if not translated readily into friction coefficients.

Lubricant ranking by the OSU Lubricant Ranking Test correlate one-for-one with press shop experience.

Draw-Bend Springback

R. H. Wagoner, W. D. Carden, W. P. Carden, D. K. Matlock: Proc. IPMM '97, 1997, vol. 1

W. D. Carden, L. M. Geng, D. K. Matlock R. H. Wagoner: Int. J. Mech. Sci., 2002, 44(1), p. 79.

K.P. Li , W.P. Carden, R.H. Wagoner: Int. J. Mech. Sci., 2002, 44(1), p. 103.

L. Geng, R. H. Wagoner: Int. J. Mech. Sci., 2002, 44(1), p. 123.

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Materials and
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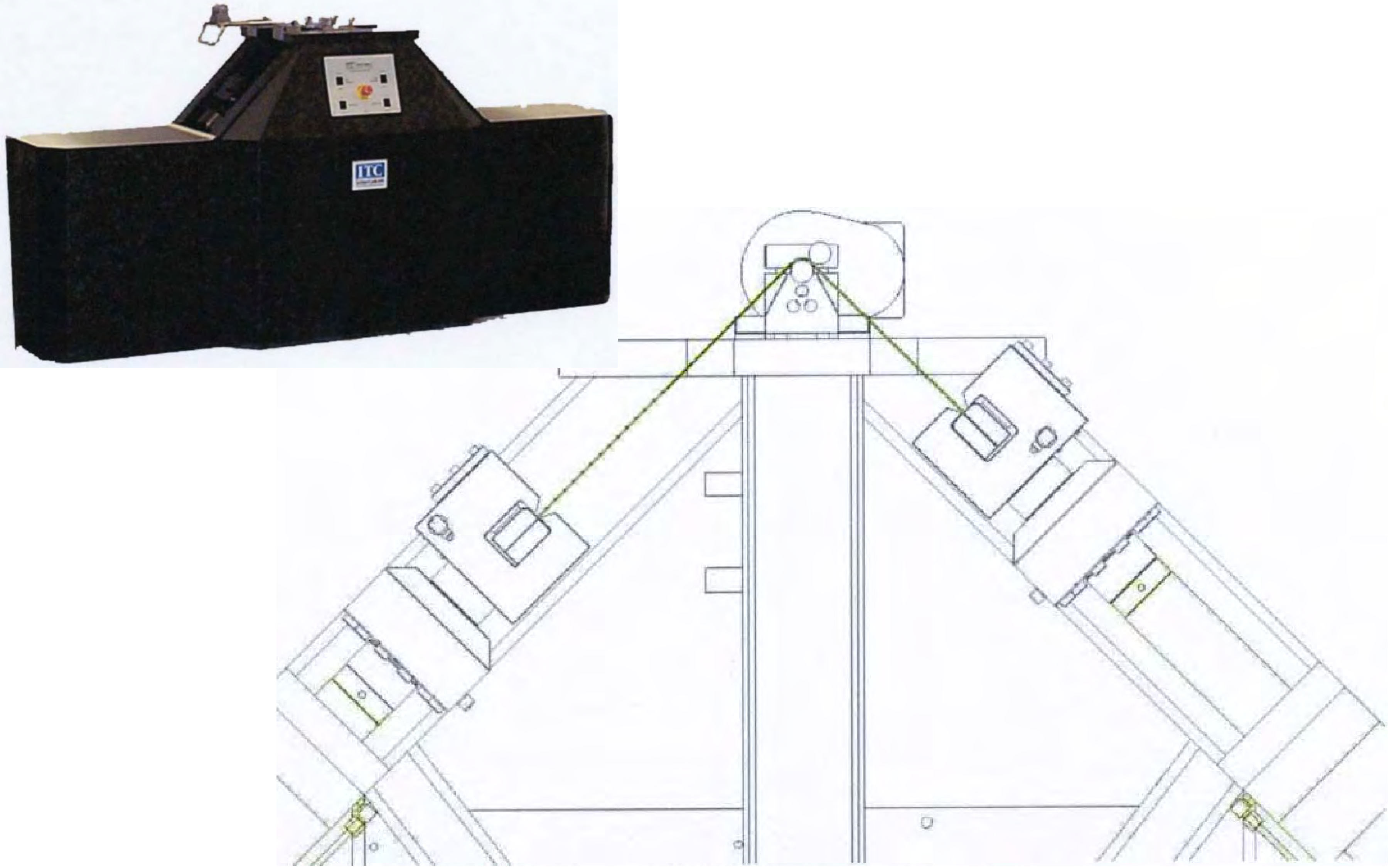
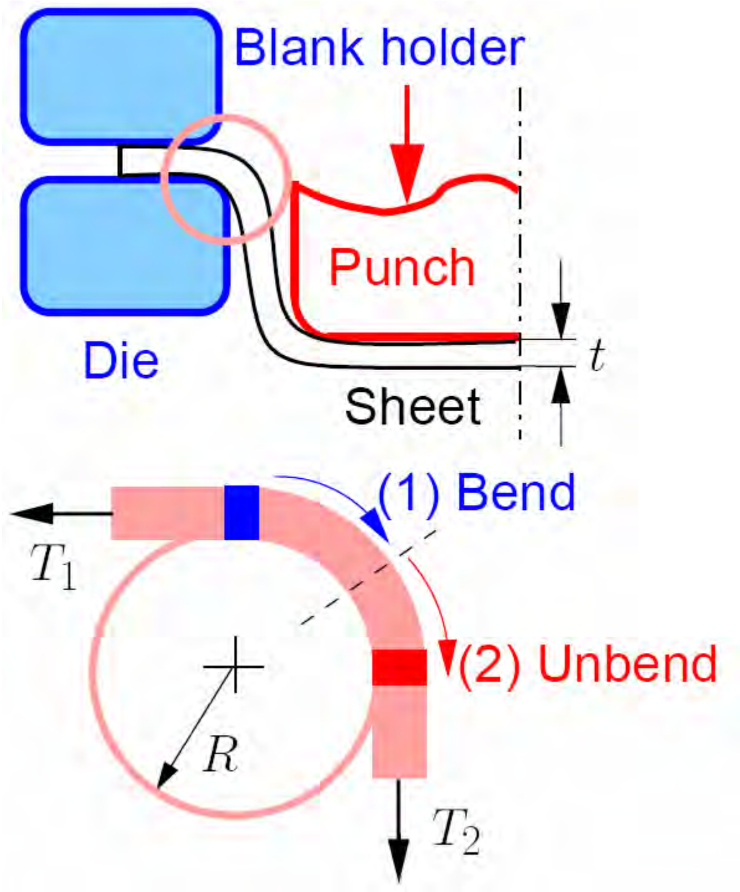
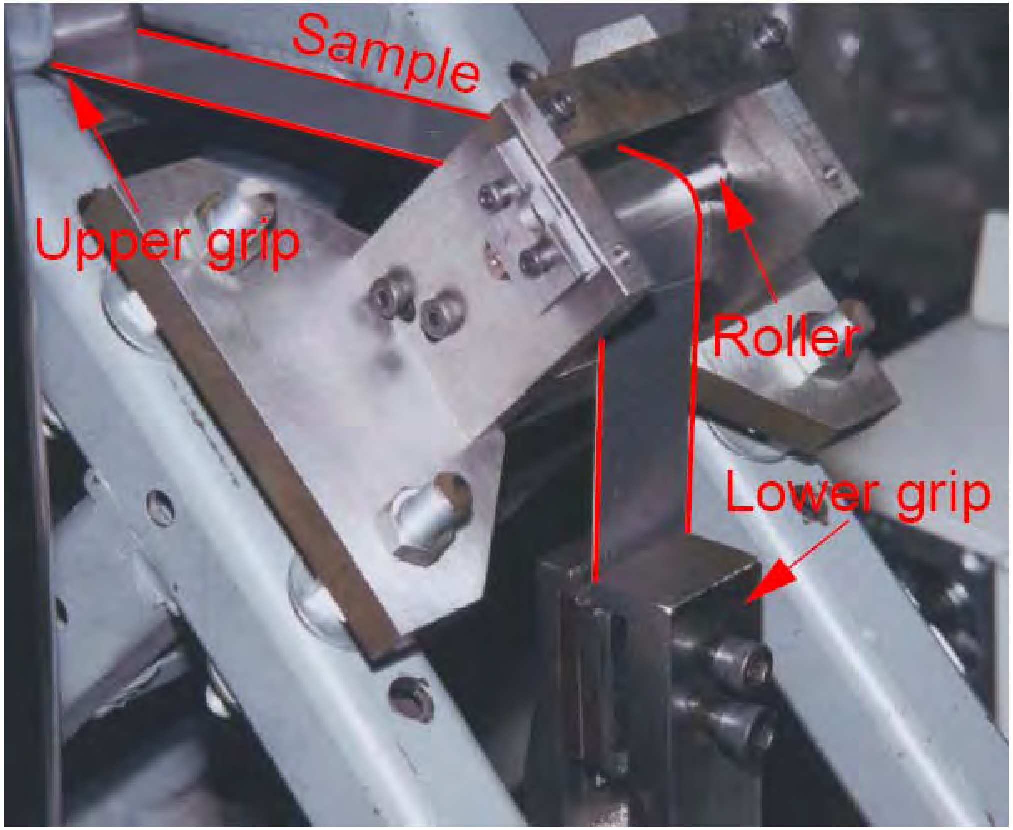
Automotive
Components

Draw-Bend Test Machine

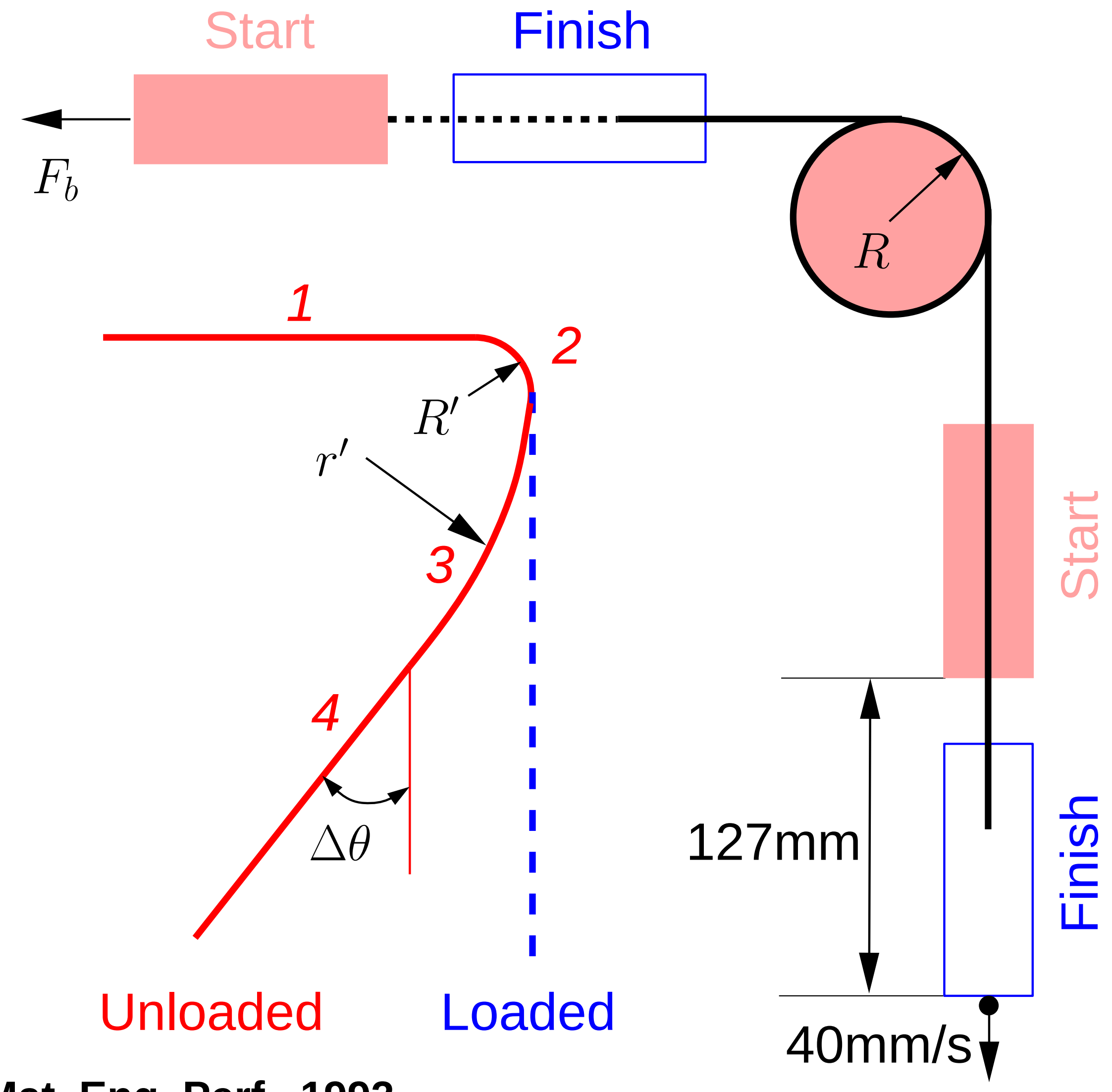


Draw-Bend Test



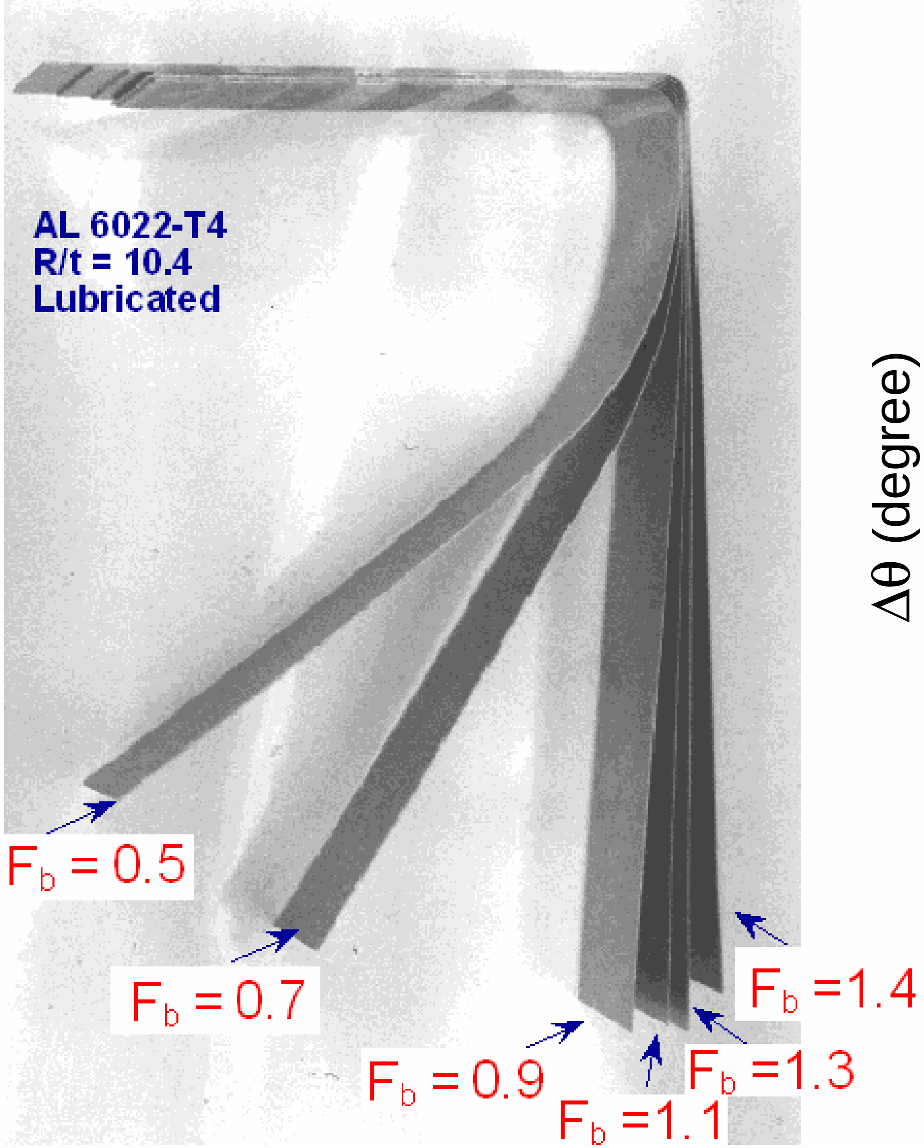


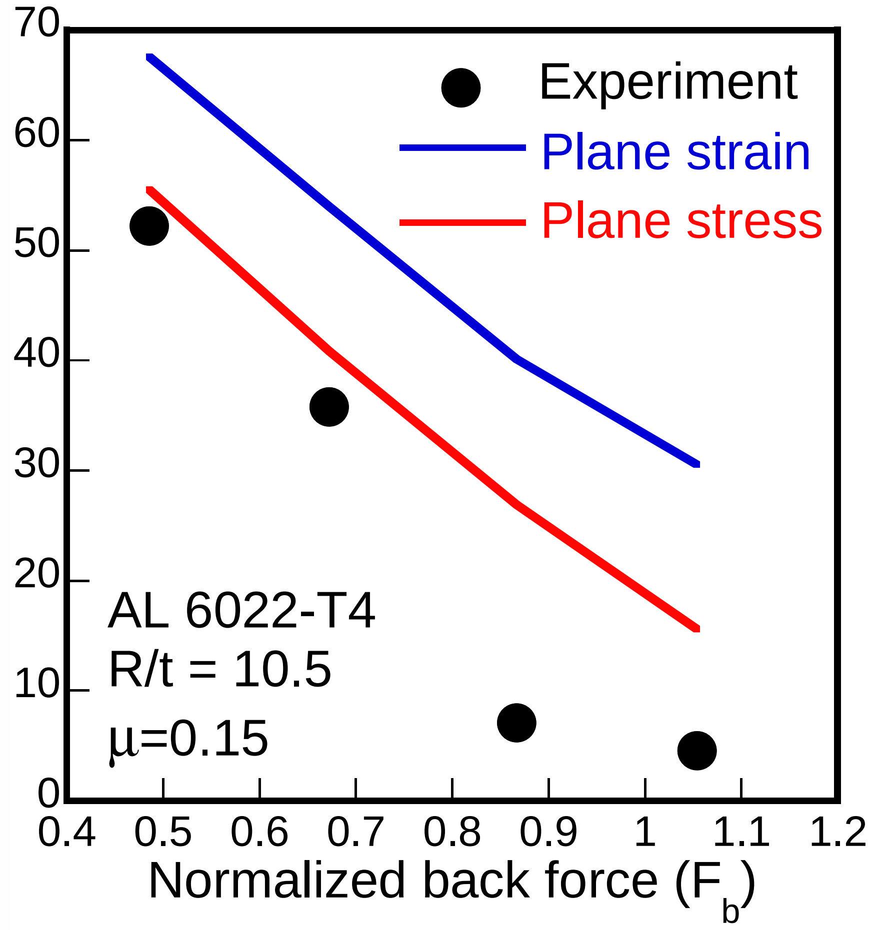
Draw-Bend Test Procedure



Matlock et al., J. Mat. Eng. Perf., 1992

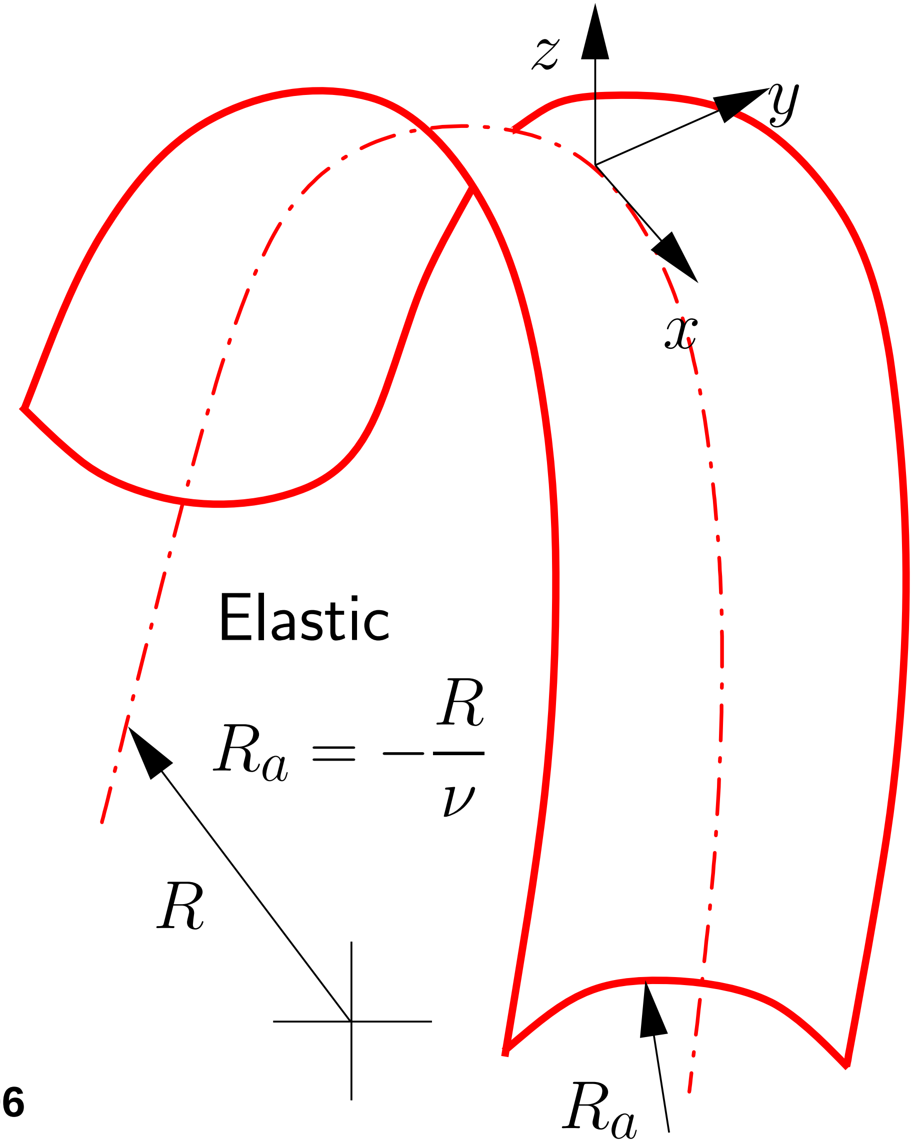
Effect of Back Force





Wagoner et al., IPMM'97

Anticlastic Curvature

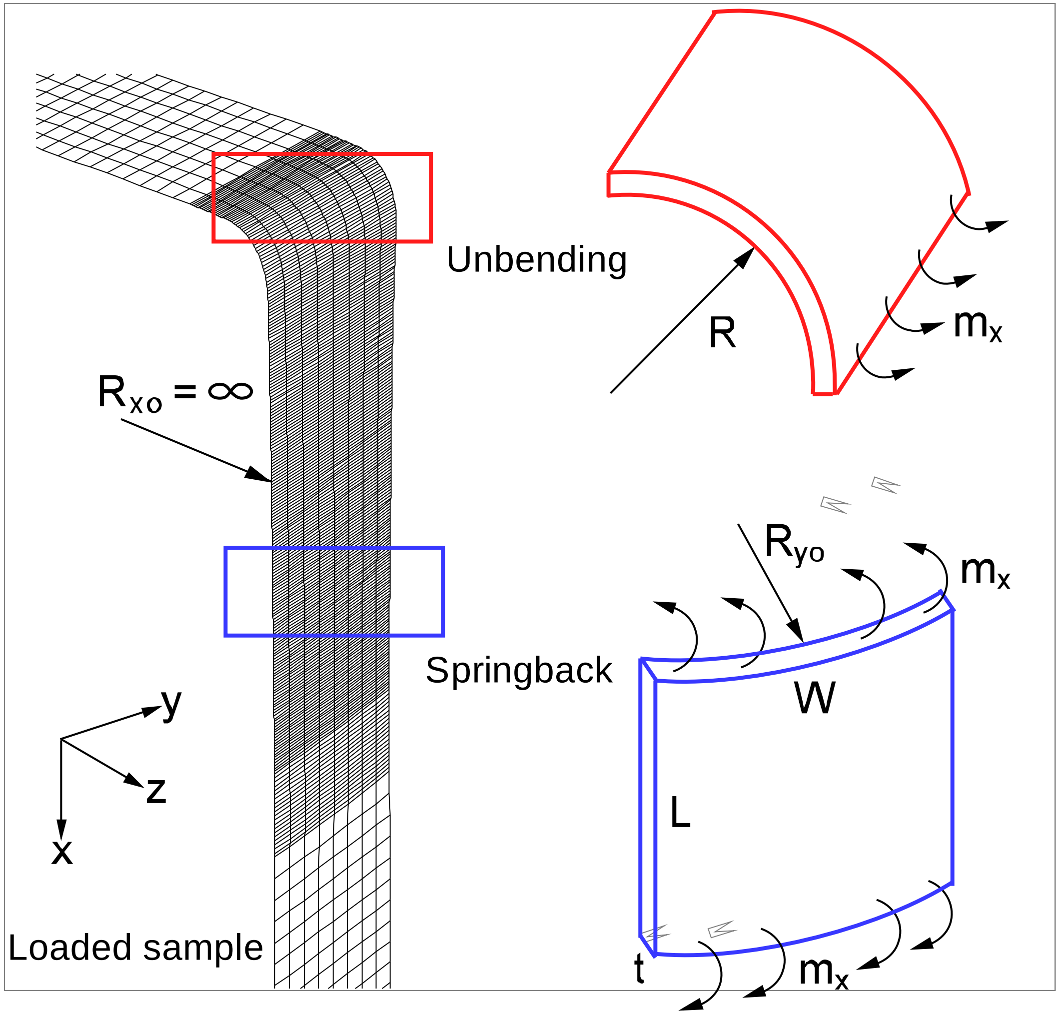


Elastic

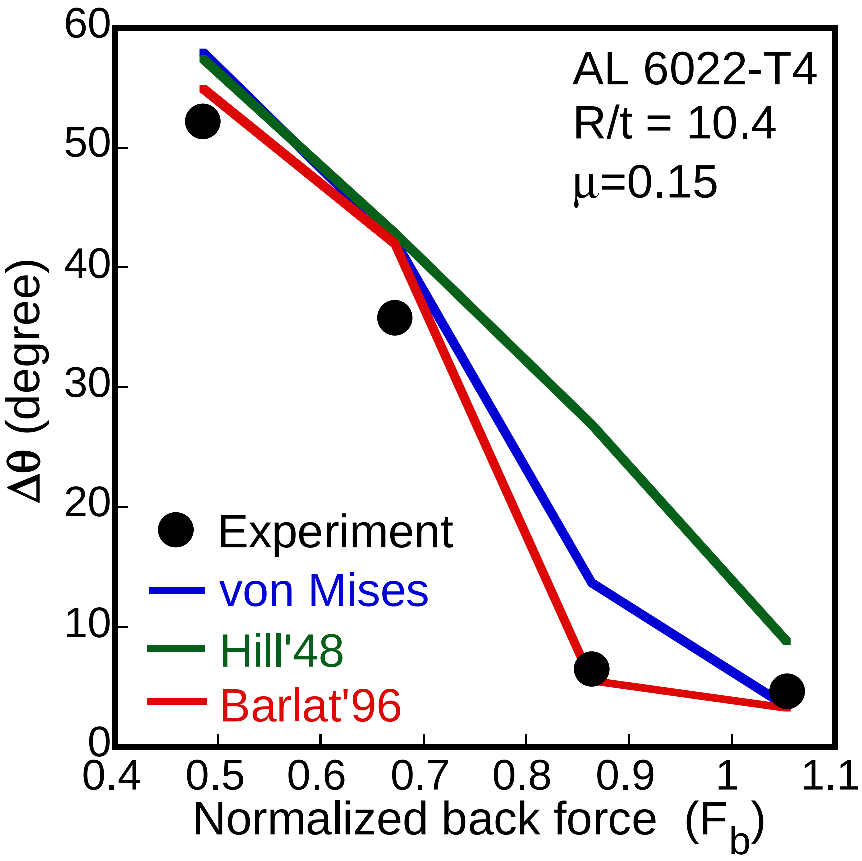
$$R_a = -\frac{R}{\nu}$$

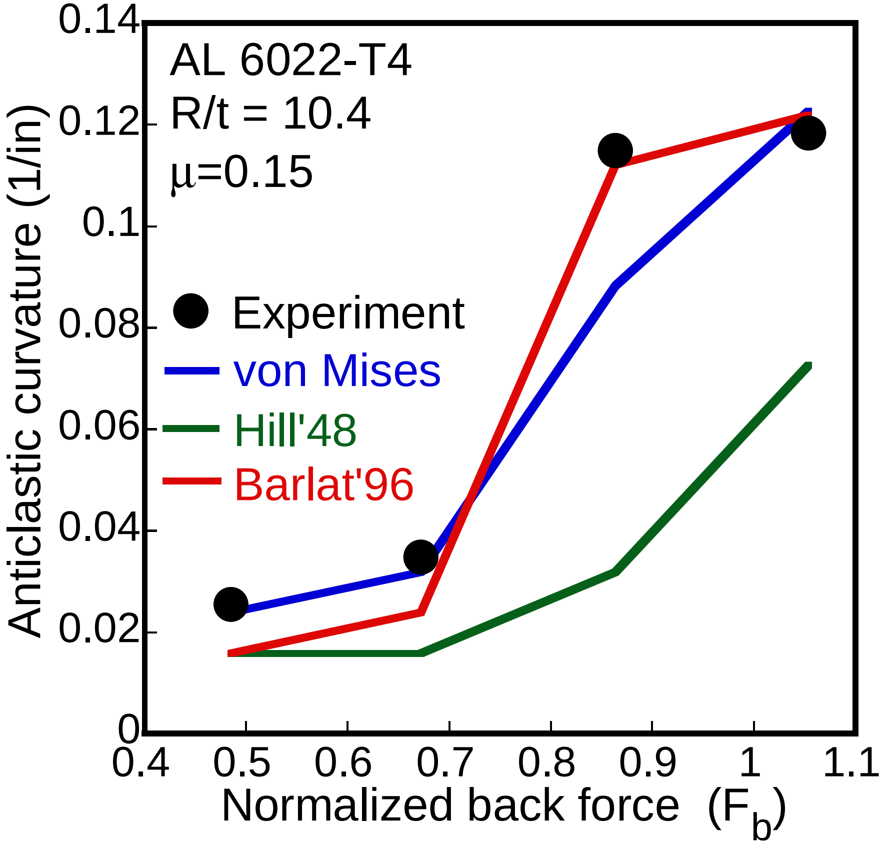
Yu and Zhang, 1996

Figure 17 (2005-3)

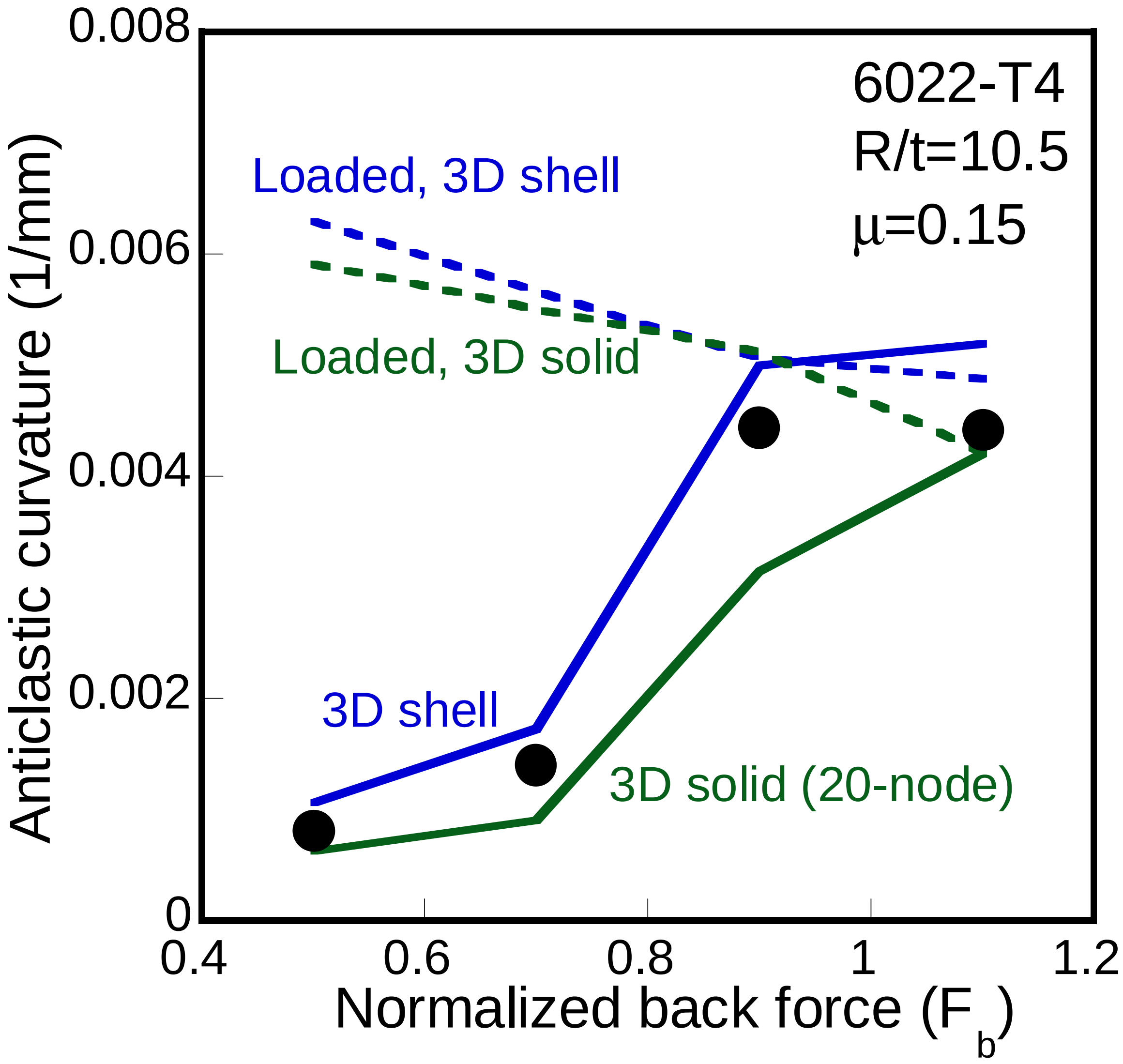


Springback vs. Anticlastic Curvature

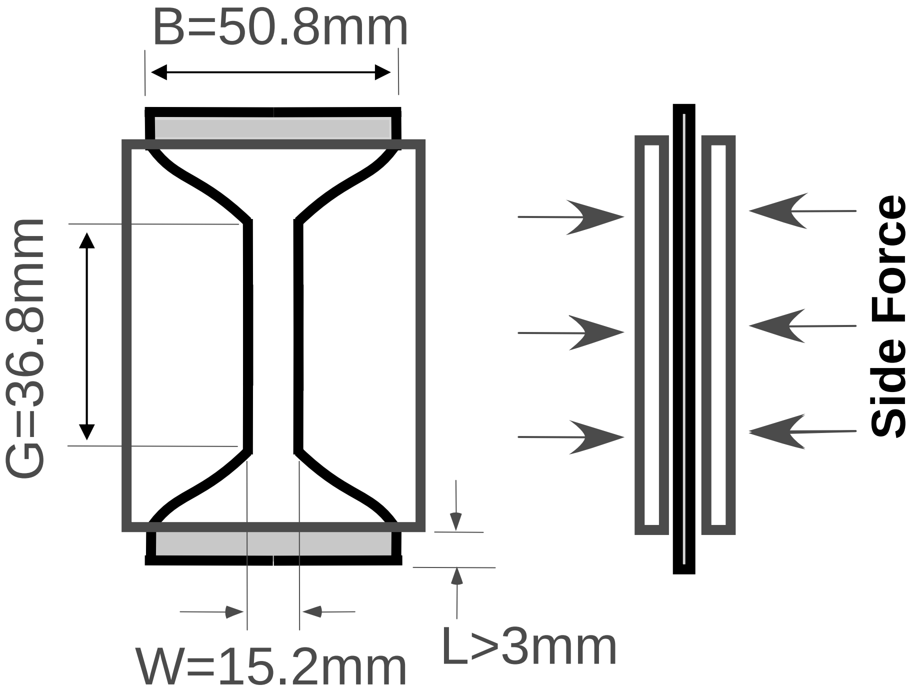




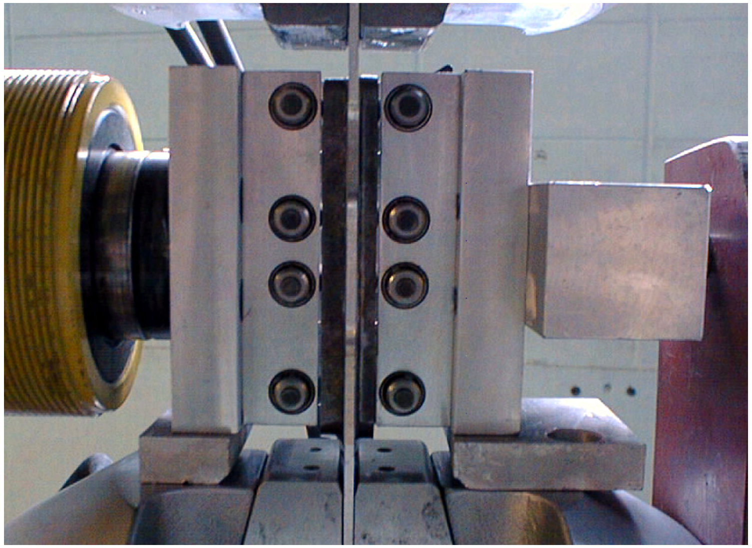
Anticlastic Curvature: Loaded/Unloaded



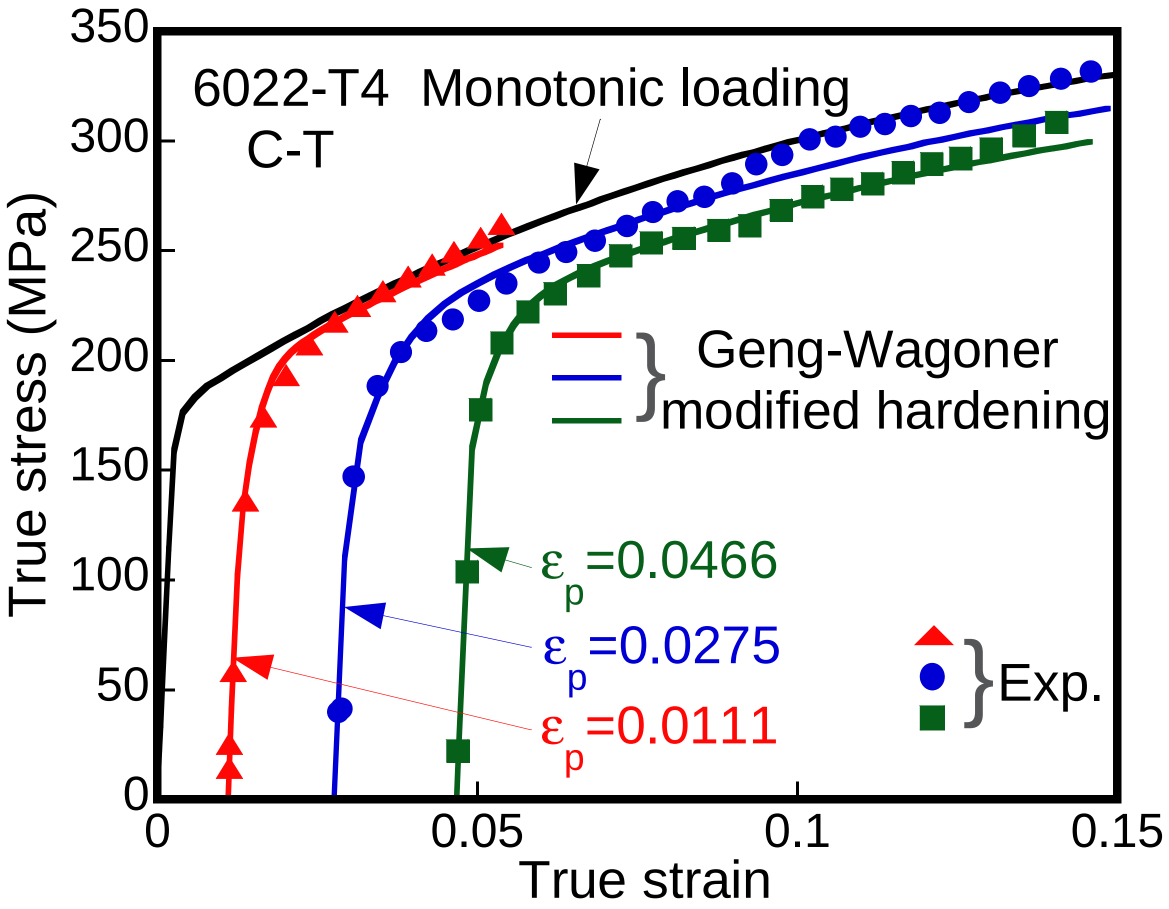
Tension / Compression Test



Boger et al., Int. J. Plasticity, 2005



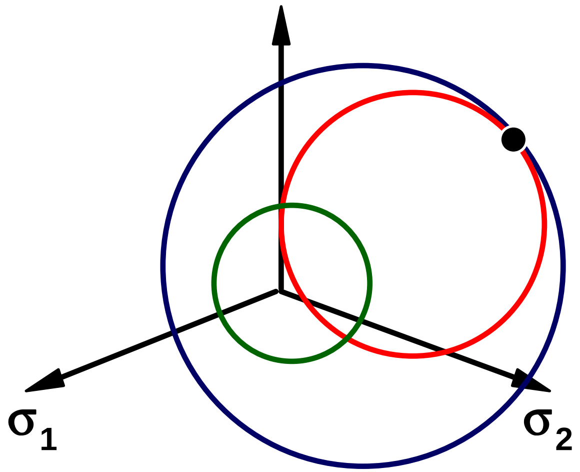
Modified Nonlinear Hardening



Modified Hardening

$C(\varepsilon^p)$ $\gamma(\varepsilon^p)$

$\sigma_0(\varepsilon^p)$ $m(\varepsilon^p)$



Geng and Wagoner, Int. J. Mech. Sci., 2002

Draw-Bend CONCLUSIONS

The draw-bend test is very promising for friction coefficient measurements for sheet forming. It allows independent variation of R/t, speed, pressure, draw distance.

But, obtaining a true μ requires careful analysis and knowledge of the material behavior. Current analytical methods are not sufficient.

Conditions of $\mu \sim 0$ can be attained by novel aspects of the OSU draw-bend machine.

OVERALL CONCLUSIONS

Measurement of friction under practical sheet-forming conditions remains challenging.

Forming friction depends on many variables, including material, lubricant, displacement, velocity, radius, pressure, strain.

FE analysis is essential for arriving at proper values of μ with virtually any friction test applicable to sheet forming conditions.

Thank you.

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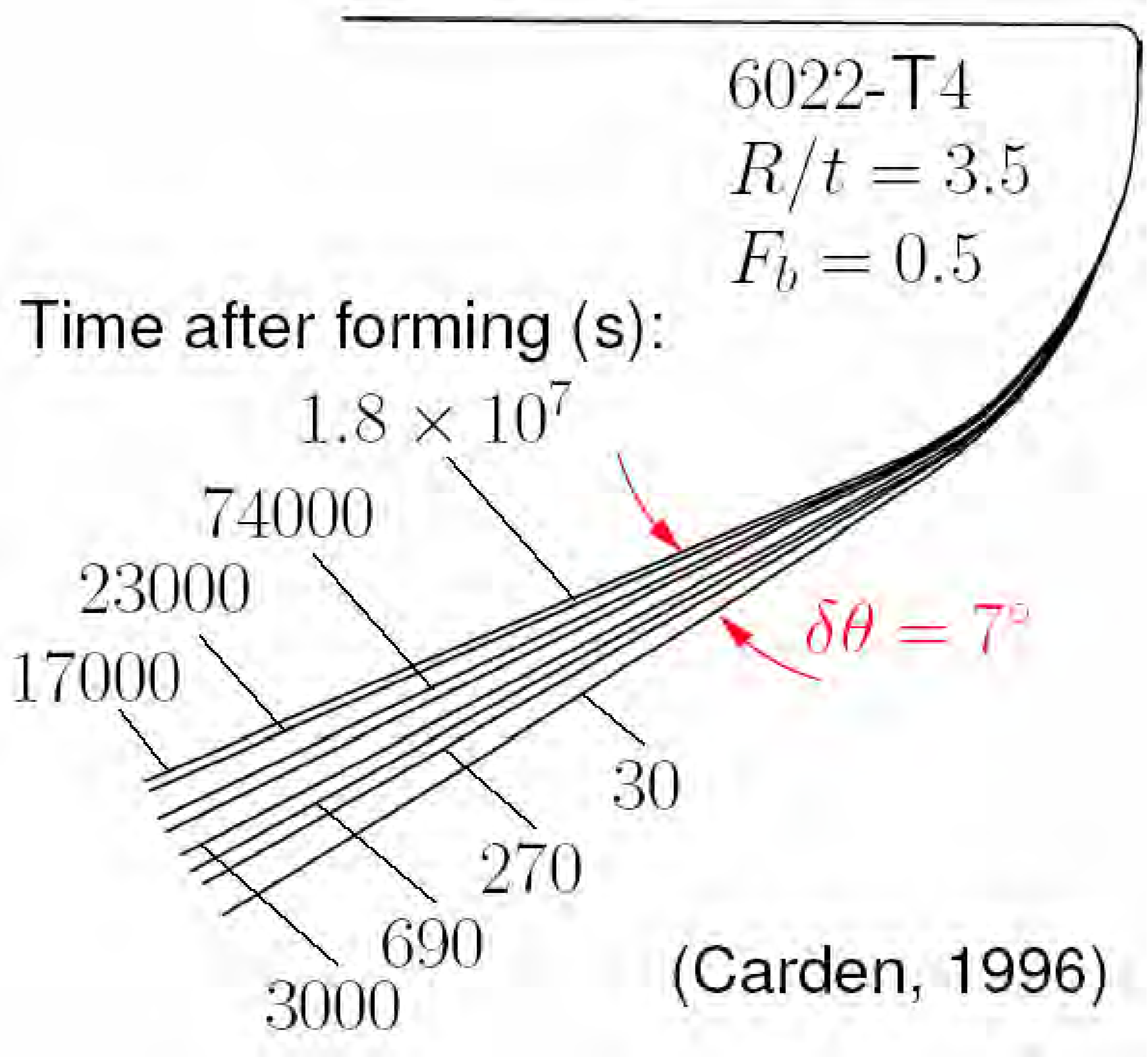
Automotive
Components

Time-Dependent Springback



(Carden, 1996)

Typical Projects, 1994-2001

- **Light Material Substitution (EMTEC)**
- **FEM Code Development, NUMISHEET, NUMIFORM**
- **Tailor-Welded Blanks (Hyundai, EWI)**
- **High-Rate Sheet Forming (Toyota, BMW, GM…)**
- **Stainless Steel Formability (EMTEC, ArvinMeritor, AK)**
- **Multi-Scale Modeling (NSF, AFOSR)**
- **Springback Measurement and Prediction (USCAR)**

Recent / Current Projects

- **Time-Dependent Springback (USCAR)**
- **Friction Stir Welding (GM)**
- **Magnesium Sheet Formability (DOE, ORNL)**
- **Complex strain hardening (NSF)**
- **AHSS - Advanced High Strength Steels (AISI)**
- **Robust Implicit FEM (NSF)**

Improving Surface Roughness Measurements for Better Assessments of Friction Behavior

M. R. Stoudt,
Materials Science & Engineering Laboratory,
N.I.S.T.

Thanks To: J. B. Hubbard, S. P. Mates, D. J. Pitchure

NIST
National Institute of Standards and Technology
Technology Administration
U.S. Department of Commerce

NIST/USCAR Workshop on Friction Issues During Metal Forming

July 11, 2006

Surface Character

Overview

Issue:

- An integral component in design process due to increased dependence on numeric predictions of mechanical behavior during metal forming.
- Discrepancies between numerically predicted roughness and measured roughness reduce reliability of numeric models.

Impact:

- Determines suitability of a particular alloy for specific applications. *(e.g., exterior panels)*
- Creates unexpected variations in friction between work piece and forming die during stamping.
  - Stress localization (cracking or tearing).
  - Inaccurate predictions of springback.
  - Progressive die shape degeneration via accelerated wear

Background

A Simple Friction Model*

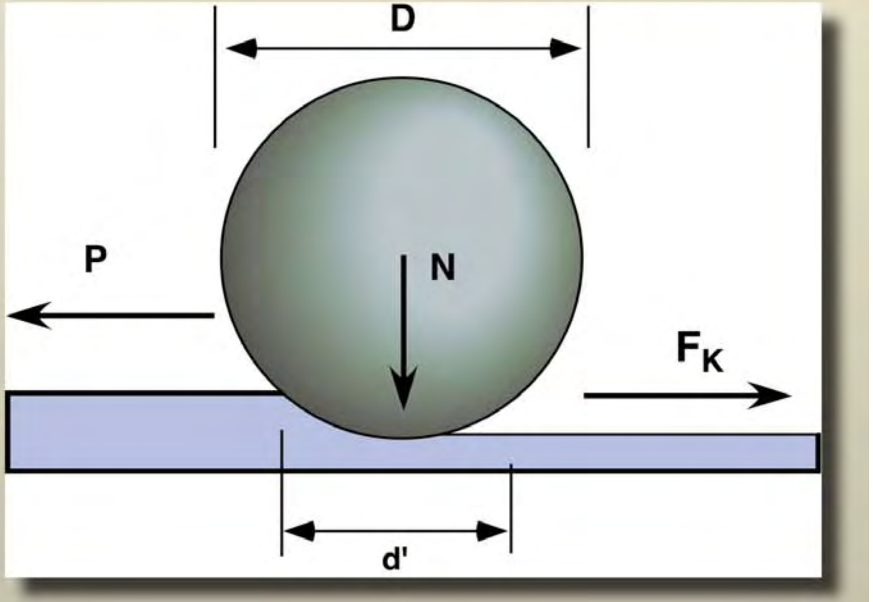
Real Area of Contact ≈ Geometrical Area

Area of Contact

$$A = \frac{N}{\sigma_y}$$

Homogeneous Surfaces

Elastic-Perfectly Plastic Material



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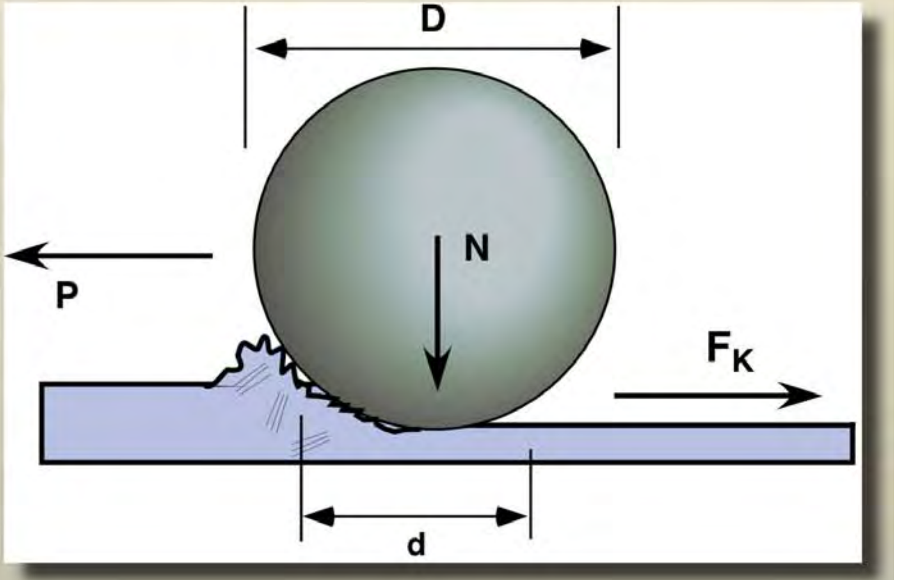
*F.P. Bowden and D. Tabor, The Friction and Lubrication of Solids, (London: Oxford University Press, 1950), 391.

Real Surfaces

Real Area of Contact ≠ Geometrical Area

Inhomogeneous Surfaces



Area of contact becomes a **complex** function of:

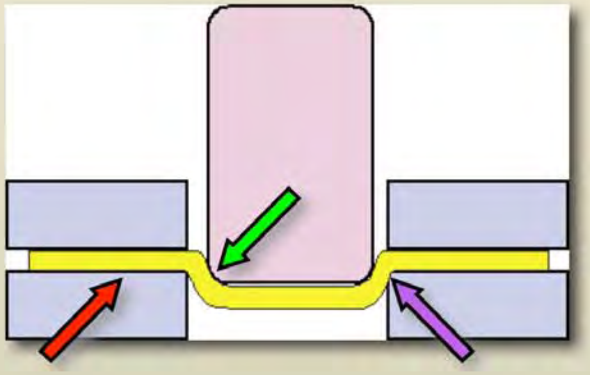
- Elastic & plastic properties of the material & indenter
- Rate of asperity generation
- Size & distribution of asperity heights
- Number of asperities per unit area
- Rate of asperity destruction

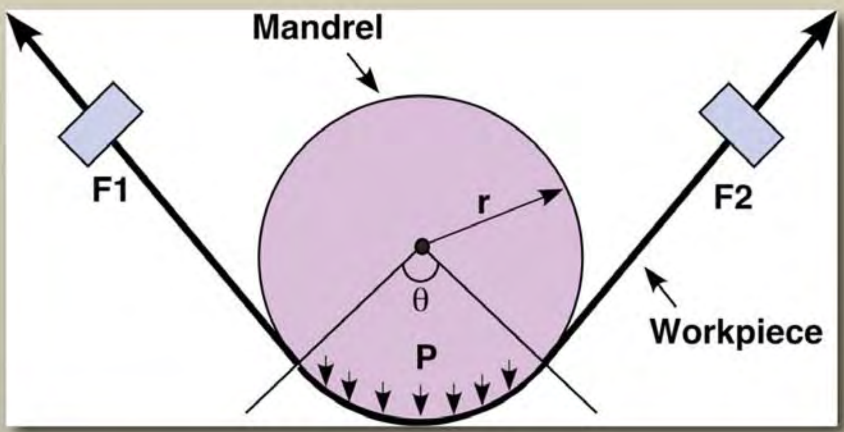
✶ Simple force relationships are **NOT** valid in this situation

Measuring Friction

Traditional measurement approaches:

- Typically draw metal sheet over a mandrel.
- Are appropriate for regions with a bend radius but not for contacting surfaces.
- Primarily focus is on the friction mechanics and not on material properties.





*After Wilson, et al.

! One test cannot provide all of the critical data needed to accurately predict friction behavior.

Measuring Friction

This approach generally can not account for:

- Material property variations in response to the dynamic forming loads.
- Strong influence variations in metallurgical condition have on friction behavior.

Friction values used in FEA predictions may not accurately represent the actual material behavior under the simulated conditions.

Strong need for measurements that *augment* existing methods by:

- Evaluating both the static and dynamic material properties.
- Providing a broad-based understanding of the relationships between friction behavior and microstructural variations that affect the properties during metal forming.

Approach

✓ View the problem from a materials perspective:

Develop a measurement protocol that determines ***how*** variations in material properties actually influence friction behavior…

- Microstructural variations:
  - Slip homogeneity
  - Surface roughness distribution

- Metallurgical variables:
  - Composition
  - Grain size
  - Orientation effects (texture)
  - Strengthening mechanisms

- Strain mode:
  - Uniaxial, Biaxial
  - Mixtures
  - Strain rate effects

ALL of these factors strongly influence the evolution of surface roughness…

Objective

Develop & integrate better surface characterization tools that:

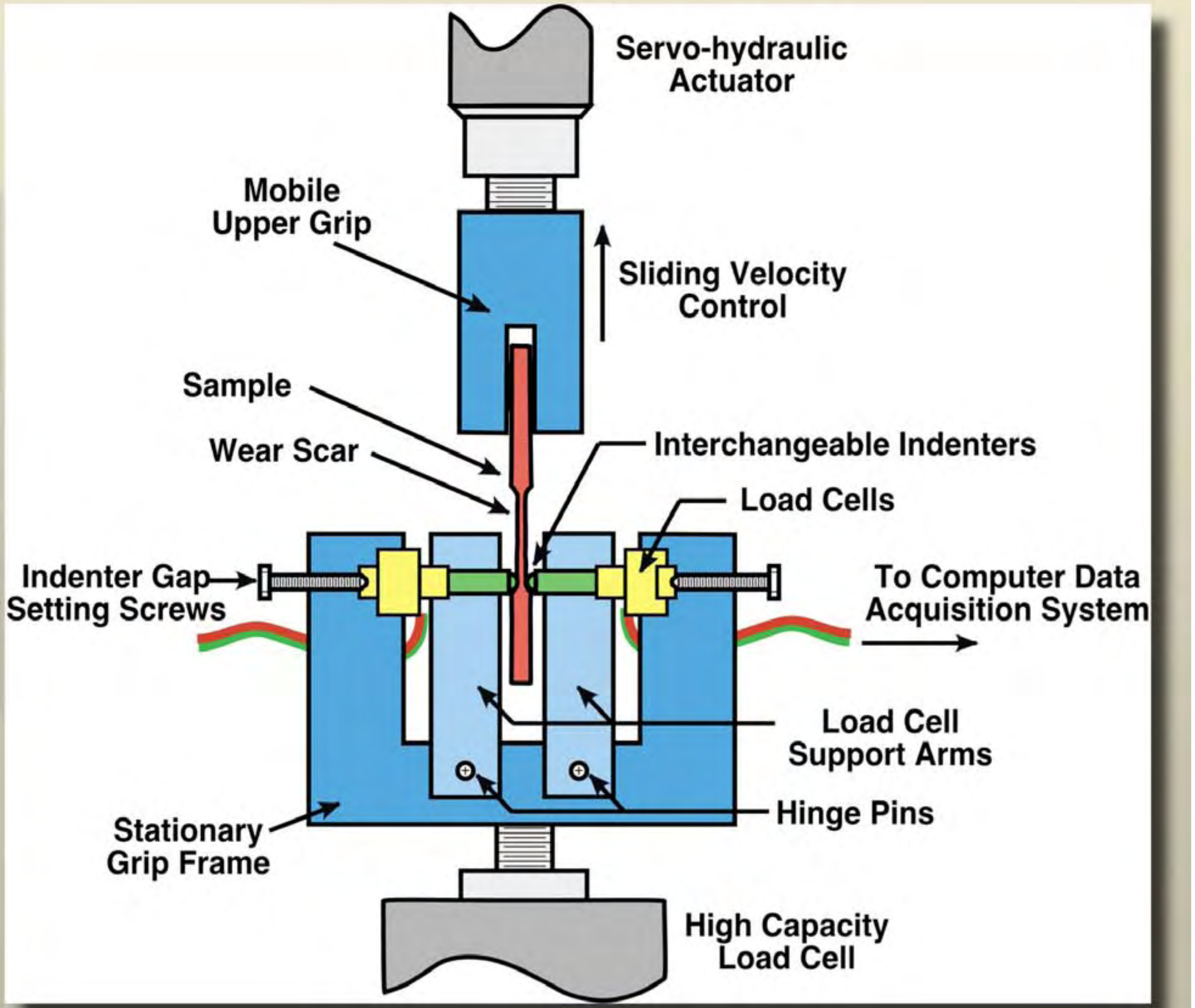
- Accurately describe both the magnitude and the distribution of the roughness that occurs over the *entire* surface.
- Utilize high-resolution topographic imaging techniques.
- Maintain a high level of fidelity with the complex 3-dimensional surface structure.
- Produce results that are easy to understand and use.

Improve the accuracy/reliability of the numeric data used to predict the friction behavior

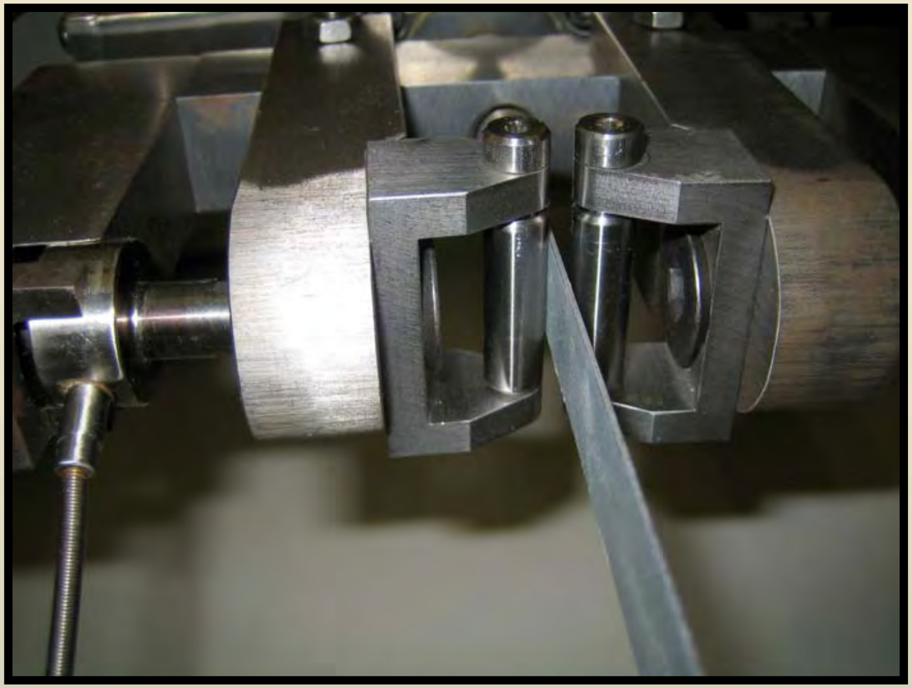
Test Apparatus

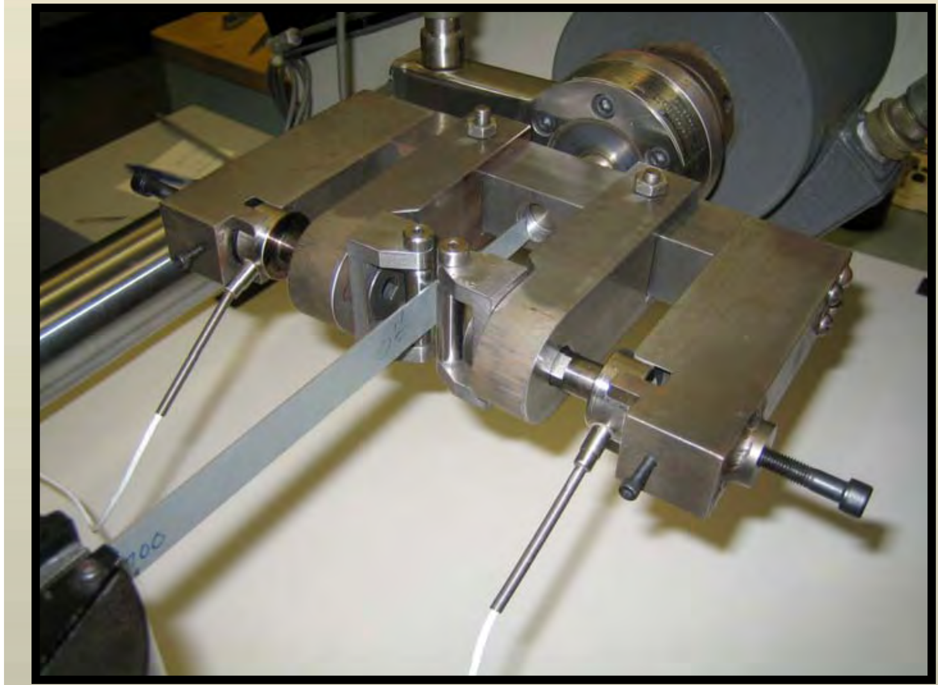
Prototype Design

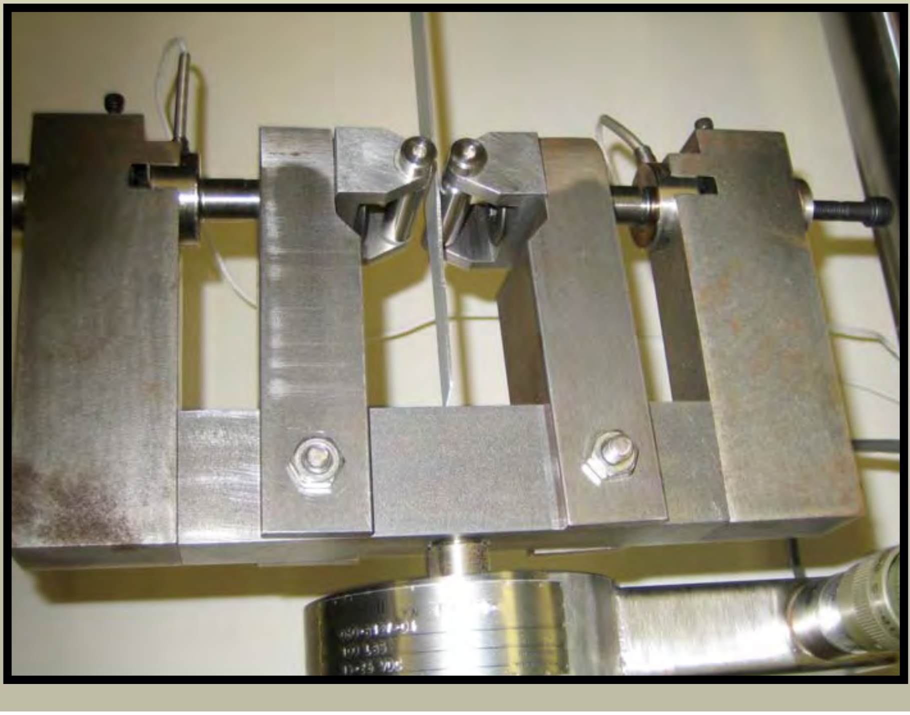
- Complete interchangeability of components
- Small sample size
- Single wear scar enables post-test characterization of sample surfaces



NIST Friction System







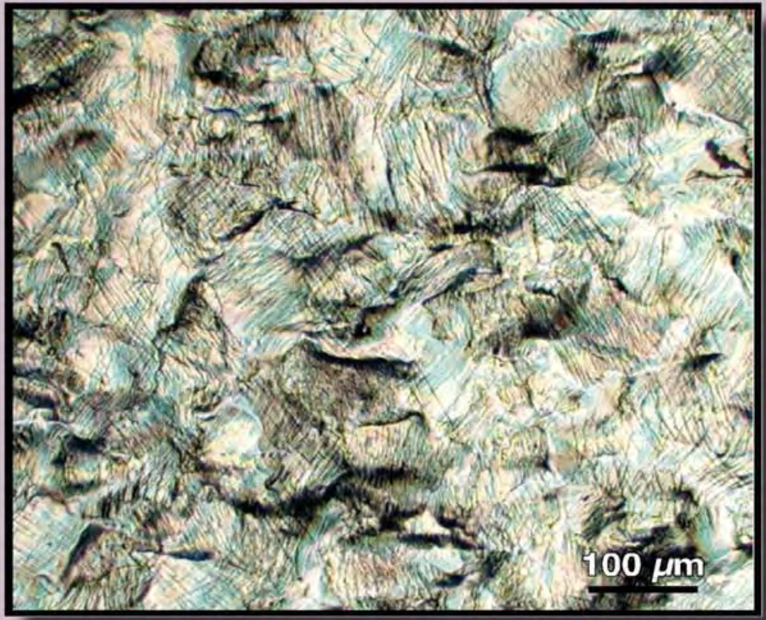
Surface Roughness Measurements

From Solid Geometry:

Full characterization of an 3-dimensional object (e.g., a rough surface) requires measurements of 3 independent coordinates. (x, y, z) or (r, Θ, Φ)

Surface roughness parameters:

- Height distribution- (z)
  Ra, Rq, etc.,
- Spatial distribution- (x, y)
  Autocorrelation
  Spectral Power Density



Profile-Based Analysis

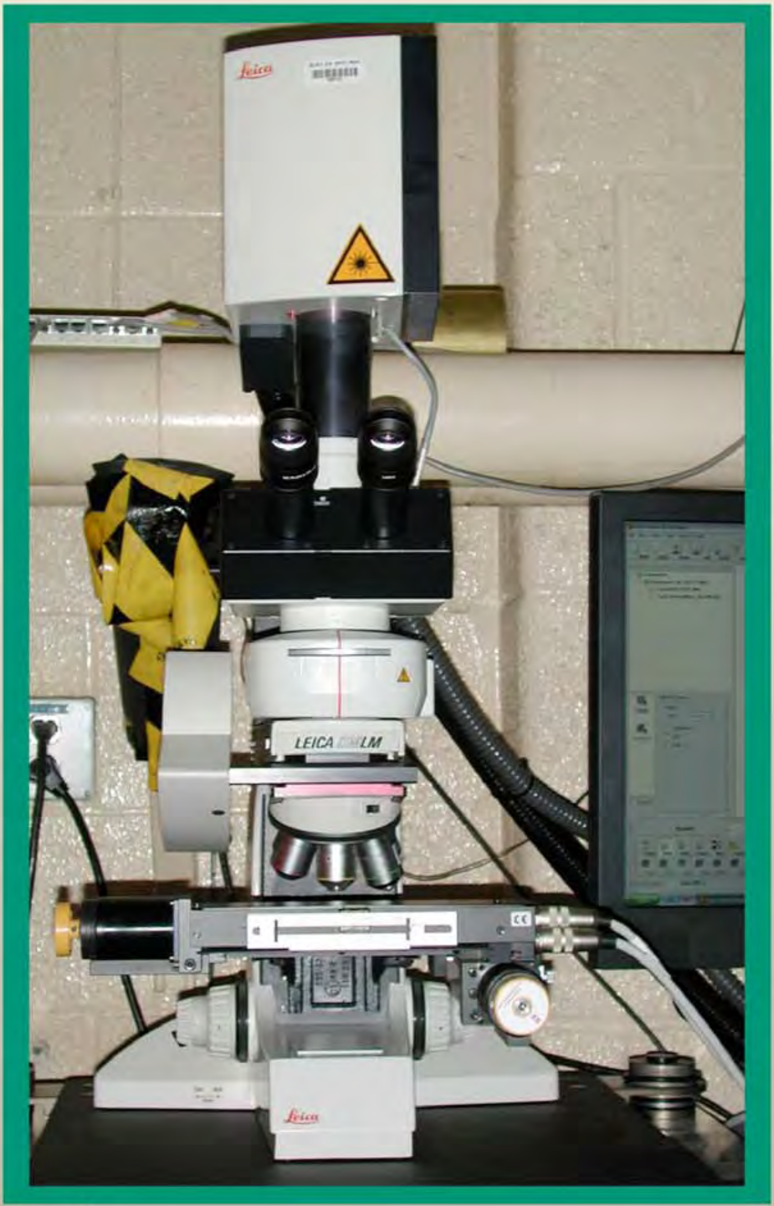
Height Distribution

- Profiles are 2-D ‘traces’ over the original surface (lines)
  - Widely spaced, *independent* (no influence from neighboring traces)
  - More profiles produces better representation of original surface
- Roughness characterized by:
  - Evaluating statistical properties of the individual profiles
  - Interpreting an ‘average’ of roughness parameters (**Rq**)

Spatial Distribution

- Multiple profiles degrades and distorts accuracy of spatial distribution analyses. ✗
  - Creating a 3-D surface requires projection and interpolation of line profiles measurements.

NIST Confocal Microscope



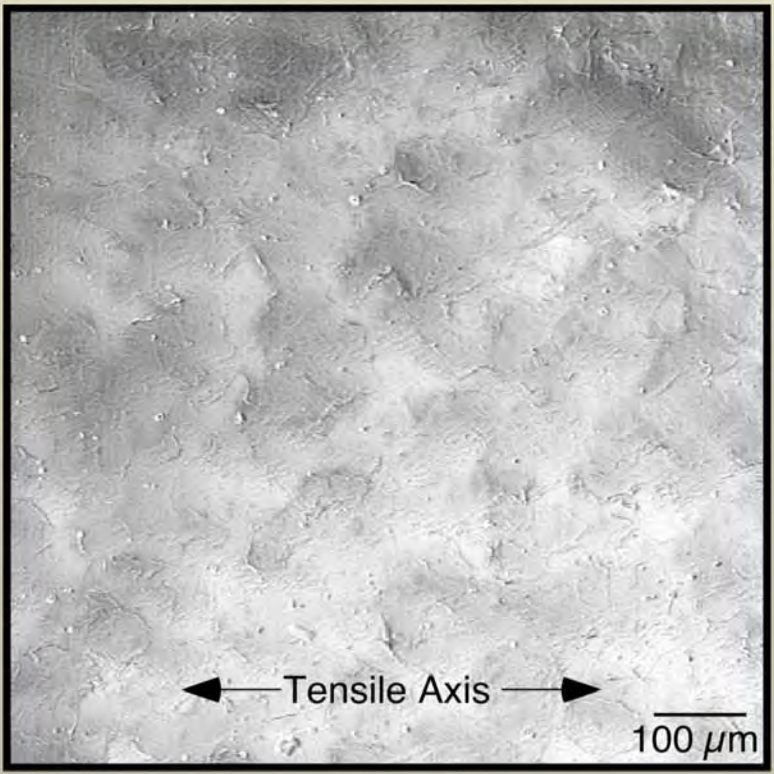
- Reflective Imaging Mode
- Optimized for Opaque Surfaces
- Single λ (635 nm) Optical Source
- HIGH resolution (25 nm Z-spacing)
- 12 Bit resolution at each voxel
- Designed to map surface topography

Matrix-Based Analysis

A “New” Approach

Matrix Generation:

- SLCM output is standard 640 x 512 TIFF file format
- Convert bitmap into ‘square’ numeric matrix
- Use matrix algorithms to maximize computer power



High Density of Data Points

512 x 512 matrix of topography data

- 800 µm x 800 µm image area @ 100x
- Distance between samples: 1.5625 µm
- Vertical resolution: ≈ 100 nm
- 262144 high-resolution topographic samples

Pixel by pixel analyses:

- Changes in evolved surface area
- Grain effects

Advantages of Matrix-Based Analysis

Greater Analytical Power (a high density of surface samples) ✓

Height Distribution

- Can evaluate ALL of the surface data with a single measurement *or*
- Can evaluate data in 'ensembles' (blocks, rows, columns, sub-sets)

Spatial Distribution

- Preserves geometrical aspects of 3-dimensional surface structure
  - Better integration of visual intuition (3-D geometry) and characterization (statistical analysis) **A *reality* check!!**
  - Spatial relationships can be assessed directly (i.e., Projections are not necessary)

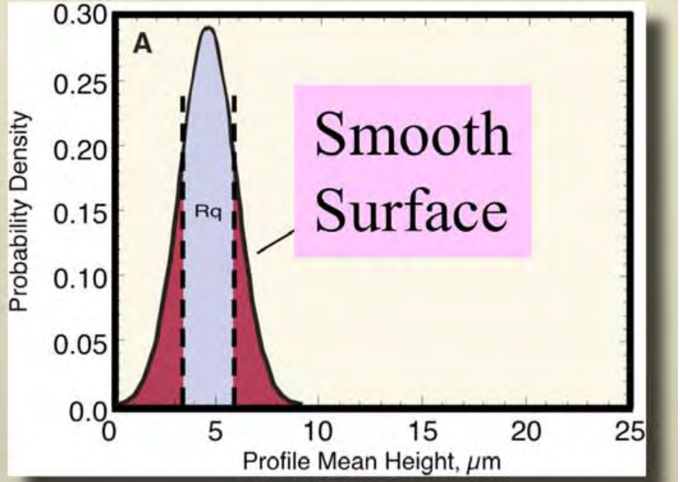
Comparing the approaches

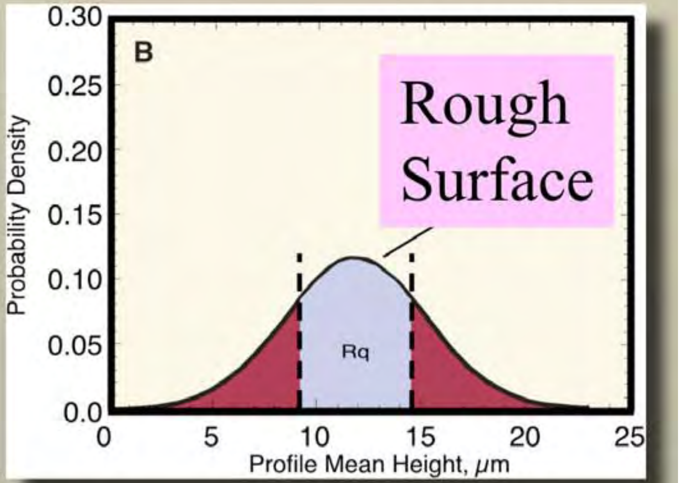
$$a_i = \left(Z_i - \mu\right)$$

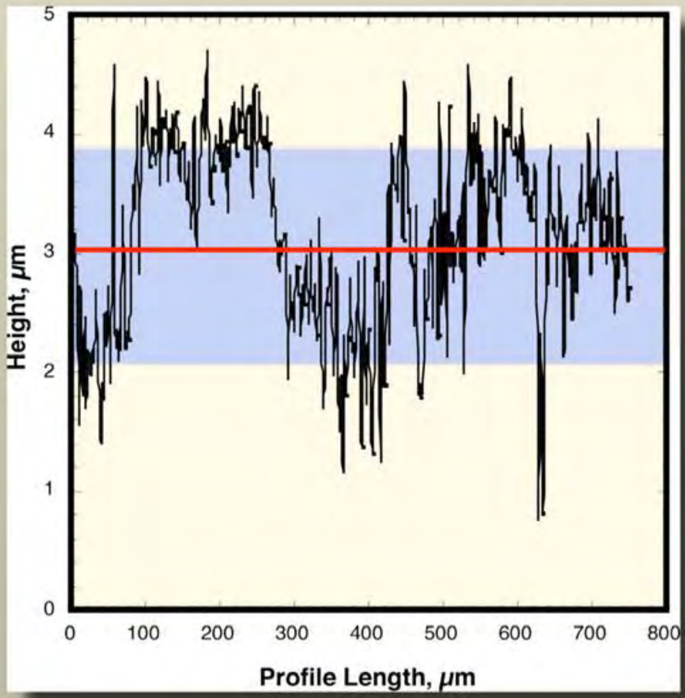
Profile-Based Parameters		Matrix-Based Parameters
$\sigma = \left[\frac{\sum_{i=1}^{n}\left(a_i\right)^2}{n}\right]^{1/2}$	Rq (dispersion)	$\sigma = \left[\frac{\left[\sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij}^{\ 2}\right]^{1/2}}{\mathrm{n}}\right]$
$Sk = \left(\frac{1}{\sigma^3}\right)\left[\frac{\sum_{i=1}^{n}\left(a_i\right)^3}{n}\right]$	Skewness (symmetry)	$Sk = \left[\left(\frac{1}{\sigma^3}\right)\frac{\left[\sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij}^{\ 3}\right]}{\mathrm{n}^2}\right]$
$K = \left(\frac{1}{\sigma^4}\right)\left[\frac{\sum_{i=1}^{n}\left(a_i\right)^4}{n}\right]$	Kurtosis (shape)	$K = \left[\left(\frac{1}{\sigma^4}\right)\frac{\left[\sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij}^{\ 4}\right]}{\mathrm{n}^2}\right]$

A Closer Look at Rq:

- Describes the dispersion of peaks about the Mean, (μ)
  - Mathematically equivalent to the st. dev., (σ)
  - Average (not a unique or single value)
  - Roughness inversely proportional to peak height
  - No info regarding the spatial distribution

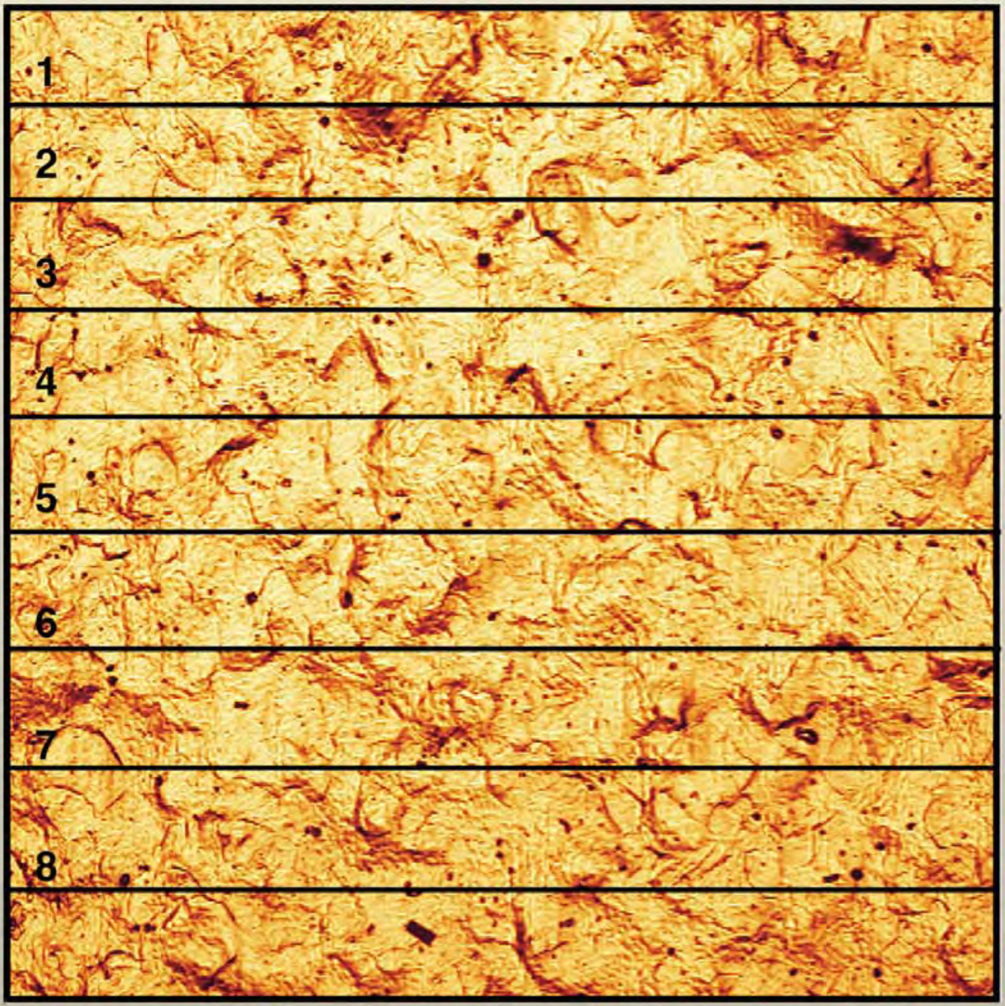




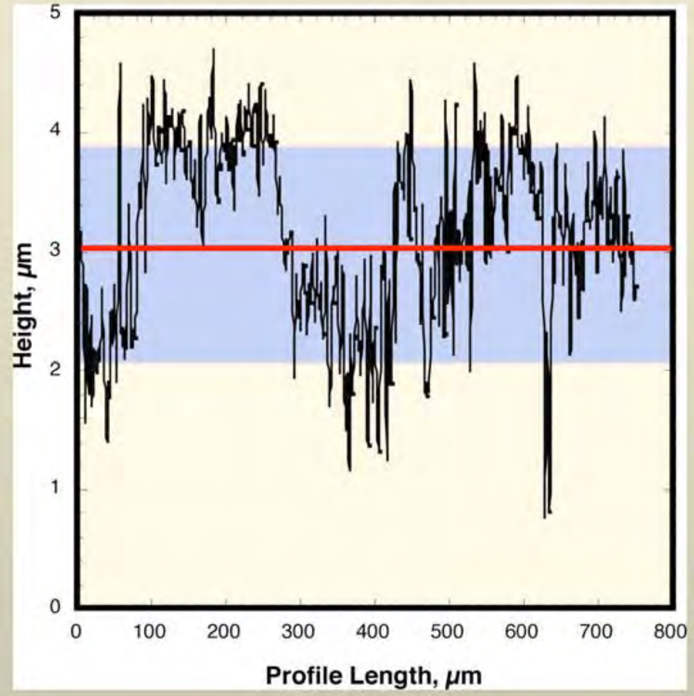


Profile-based Characterization

Widely-spaced, "independent" profiles:



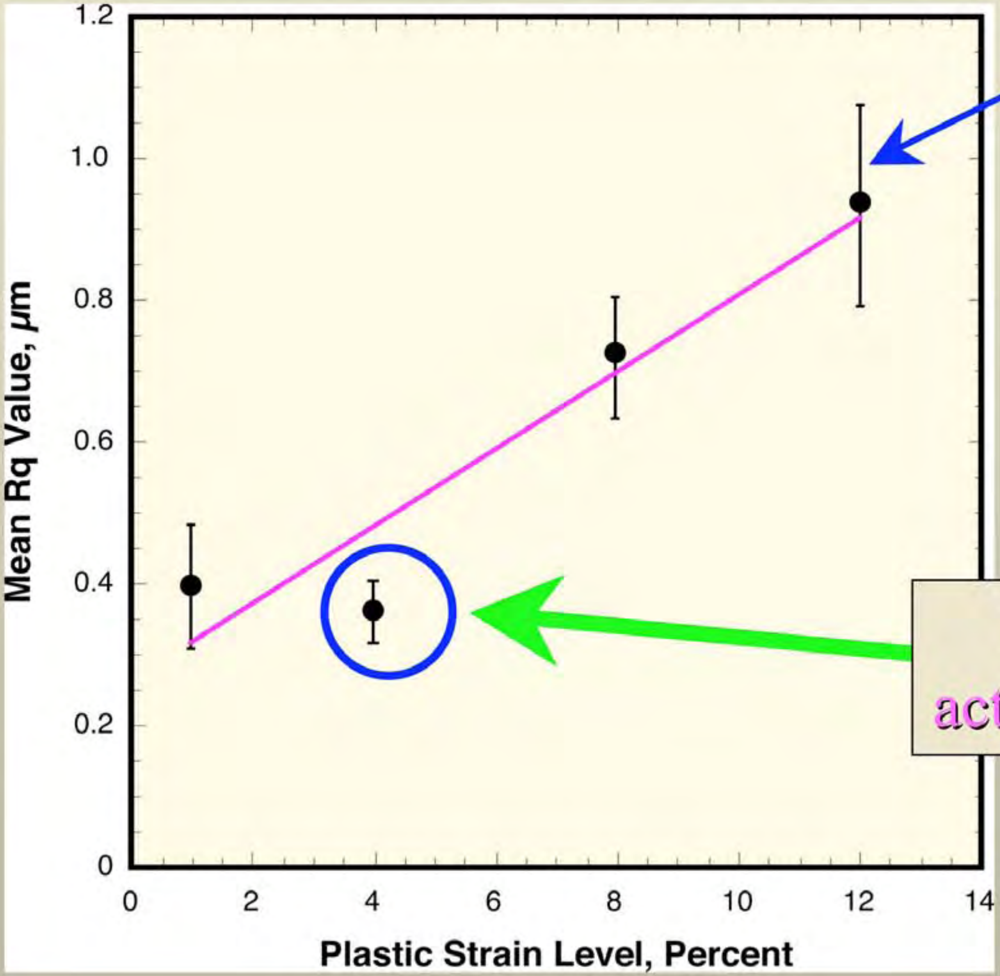
Surface of AA6022-T4
with 12% uniaxial strain



$$R_q = \sqrt{\frac{1}{L}\left(\int_0^L y^2(x)\,dx\right)}$$

Profile-based Characterization

Measurement uncertainty permits a linear fit…

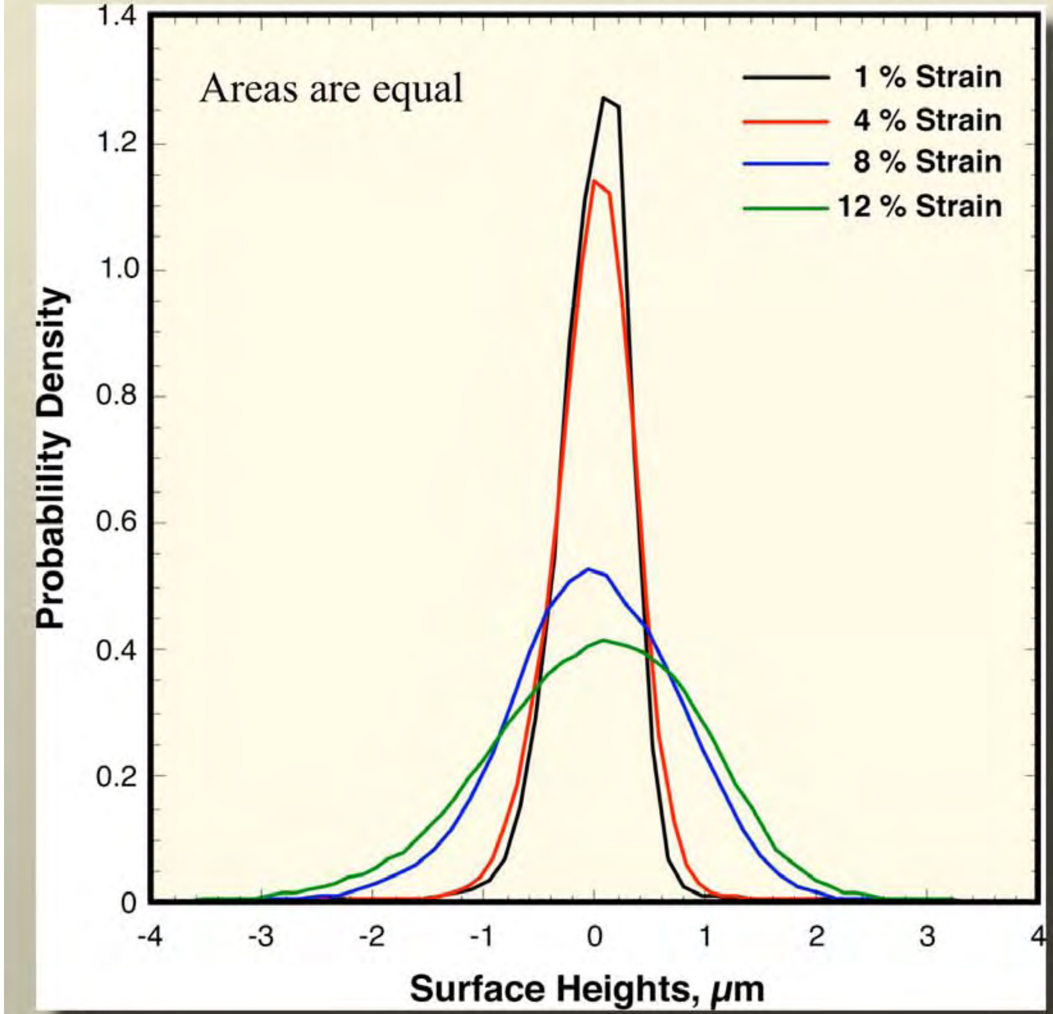


Mean & Uncertainty of 8 individual profiles taken at each strain level

Does this represent the actual roughening behavior??

Matrix-Based Characterization

Normalized Probability Density Distributions



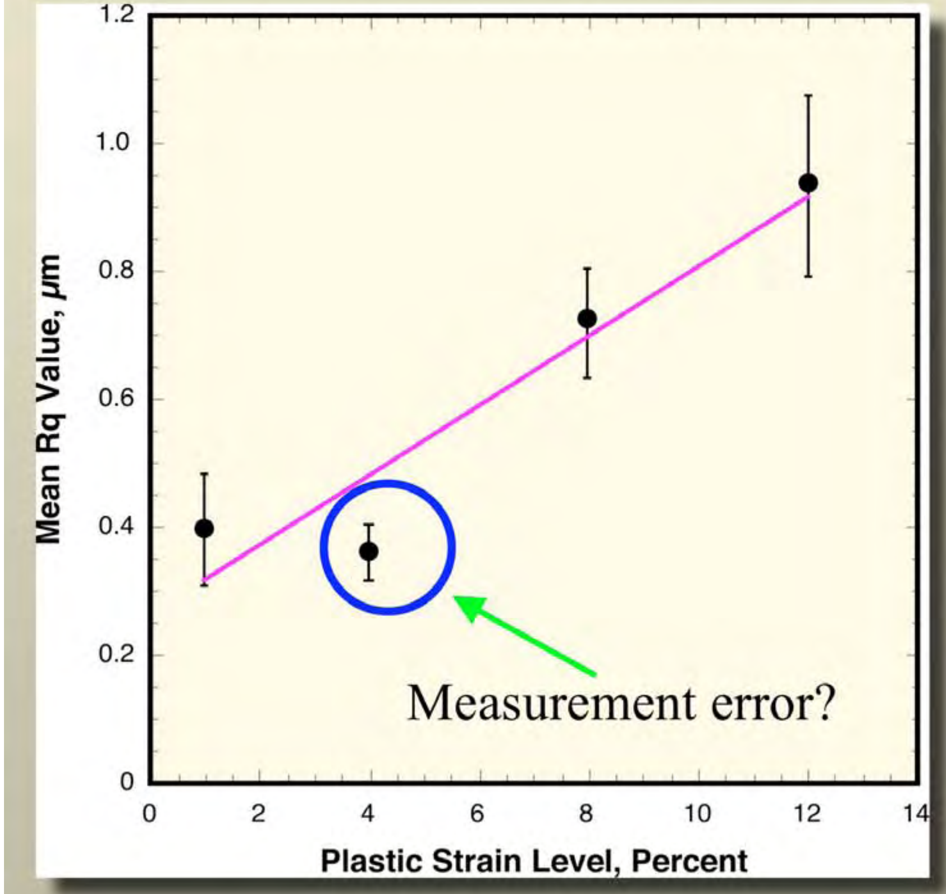
Based on **all** surface heights contained in the image matrix (i.e., 262,144 data points)

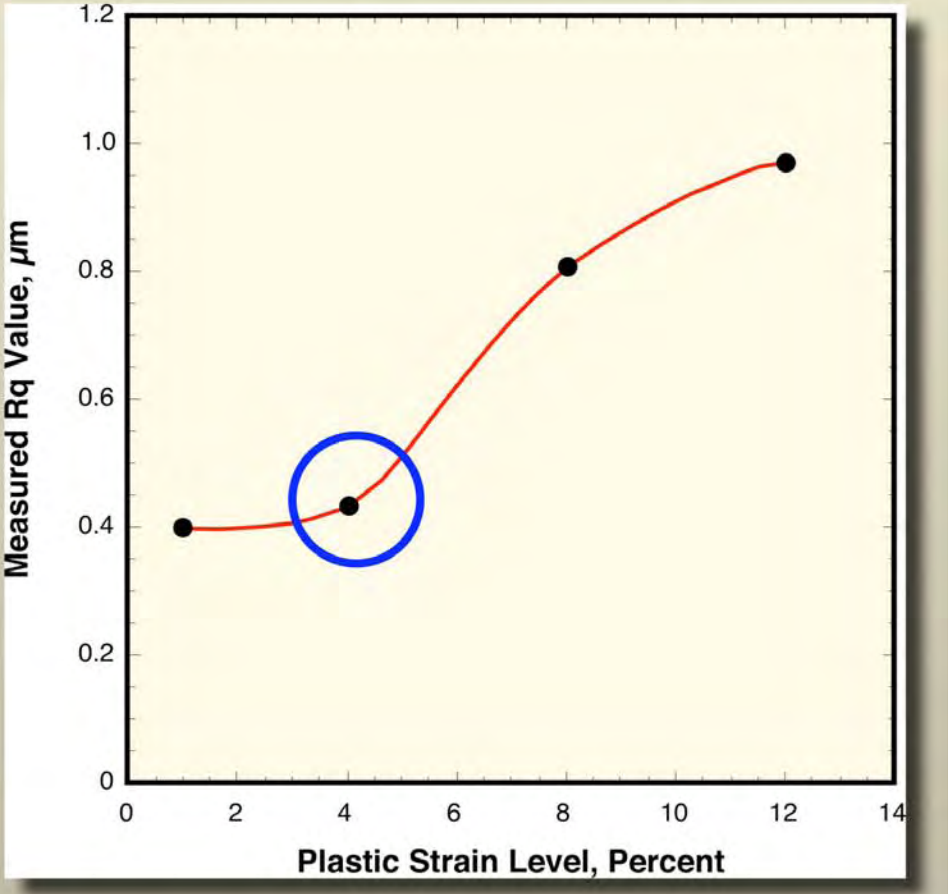
Changes in distribution shape are consistent with topographies.

- Higher surface roughness with increasing strain
- Wider range of probable heights

Protocol Comparison

A linear fit is **NOT** supported after uncertainty is minimized

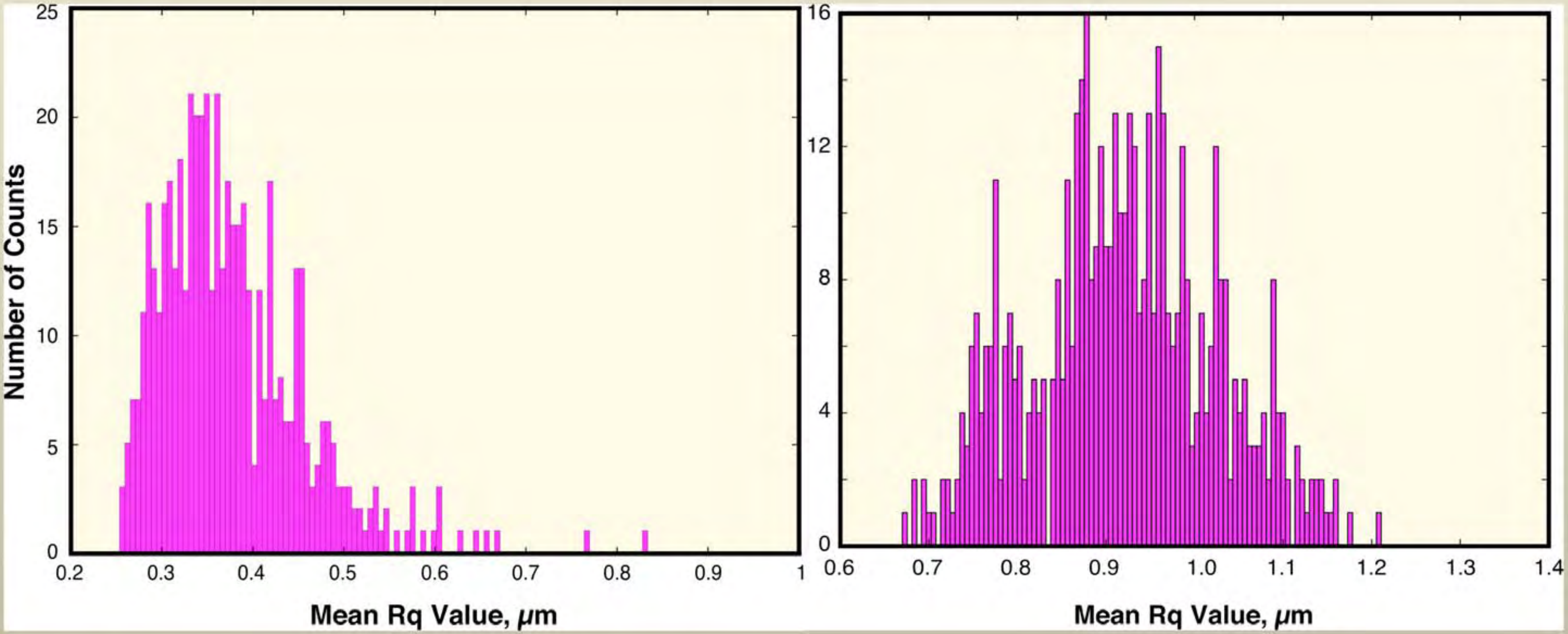




Height Distribution

Variability in Rq

"Hit or Miss"

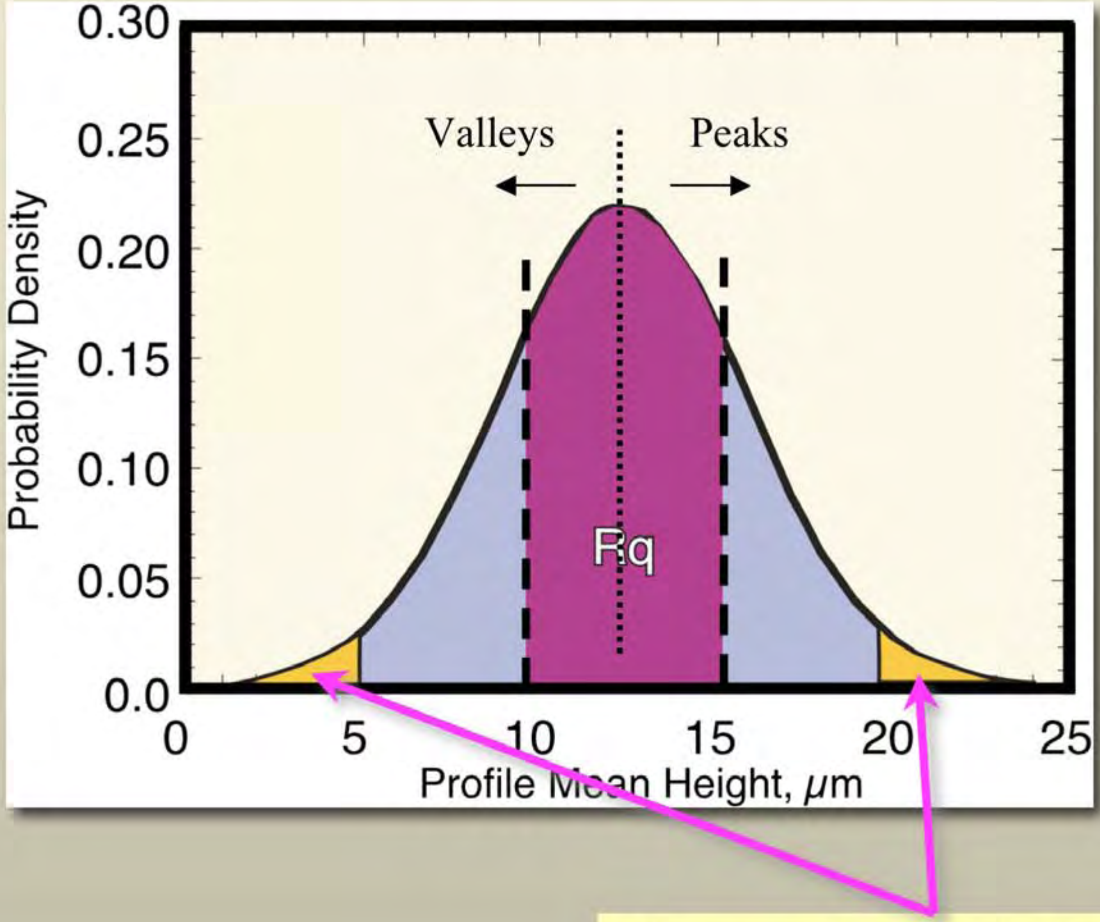


1% Plastic Strain

12% Plastic Strain

Frequency Histograms

Analysis of Height Distributions

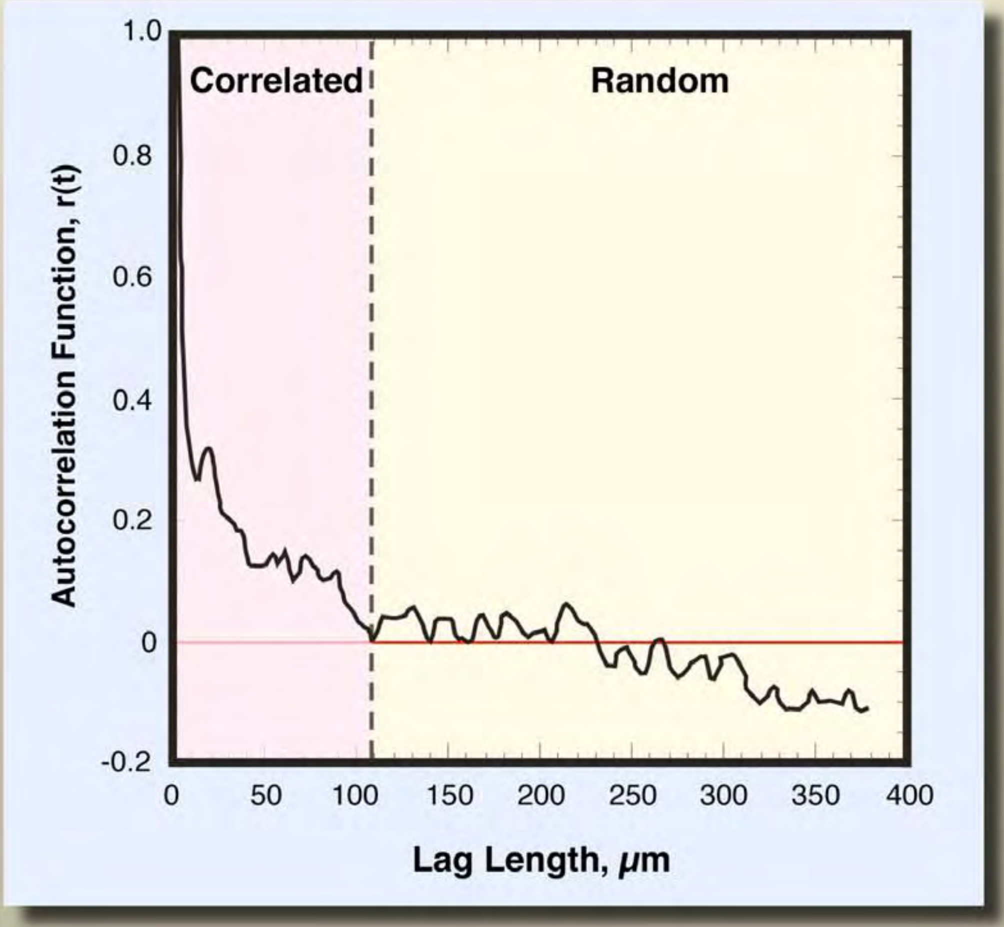


The greatest variations in contact area (friction behavior) occur at the extremes in the surface roughness distributions.

A Look at Spatial Distribution:

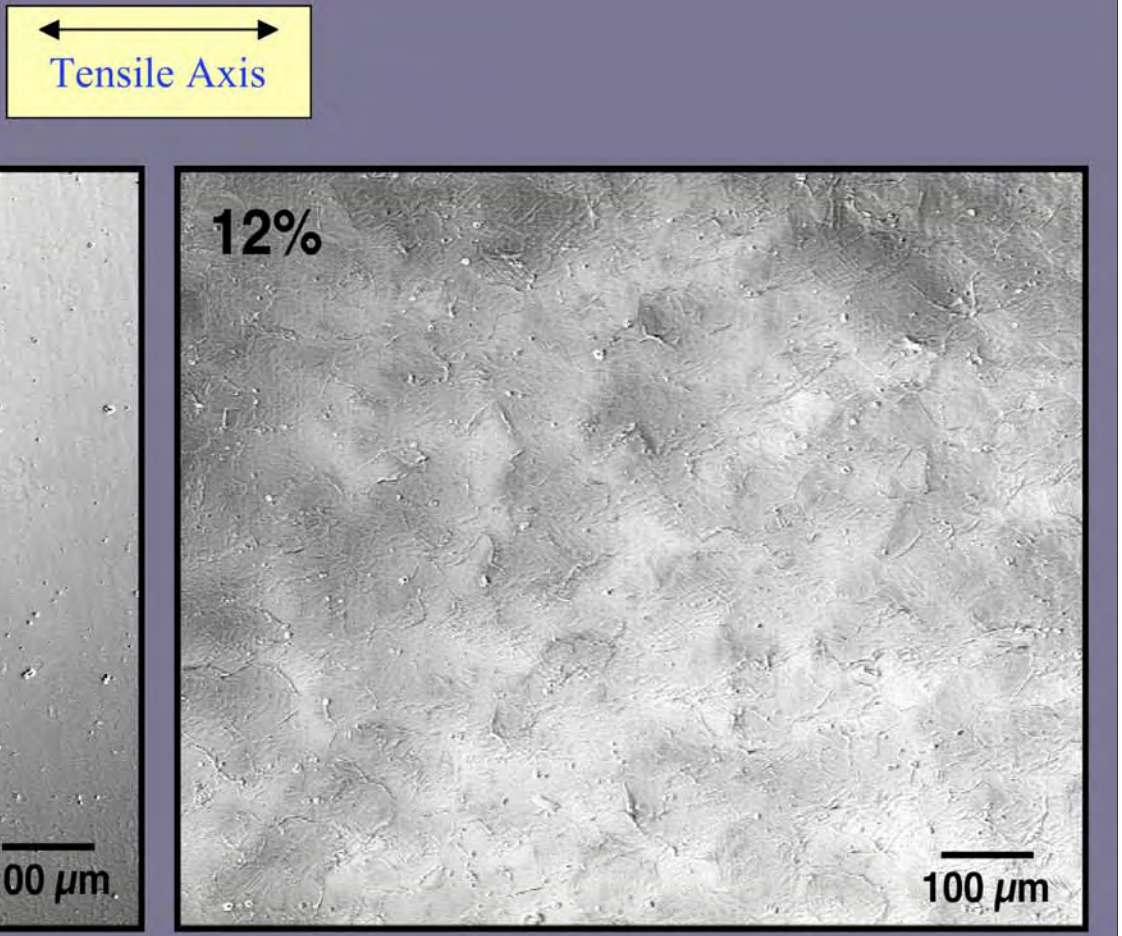
$$\rho(\tau) = \lim_{L \to \infty} \frac{1}{L} \int_0^L z(x) * z(x + \tau)\, dx$$

2-Point or
Auto-correlation Function
(ACF)



+1- fully correlated
0- uncorrelated (random)
-1- fully anti-correlated

Plastic Strain & Spatial Distribution

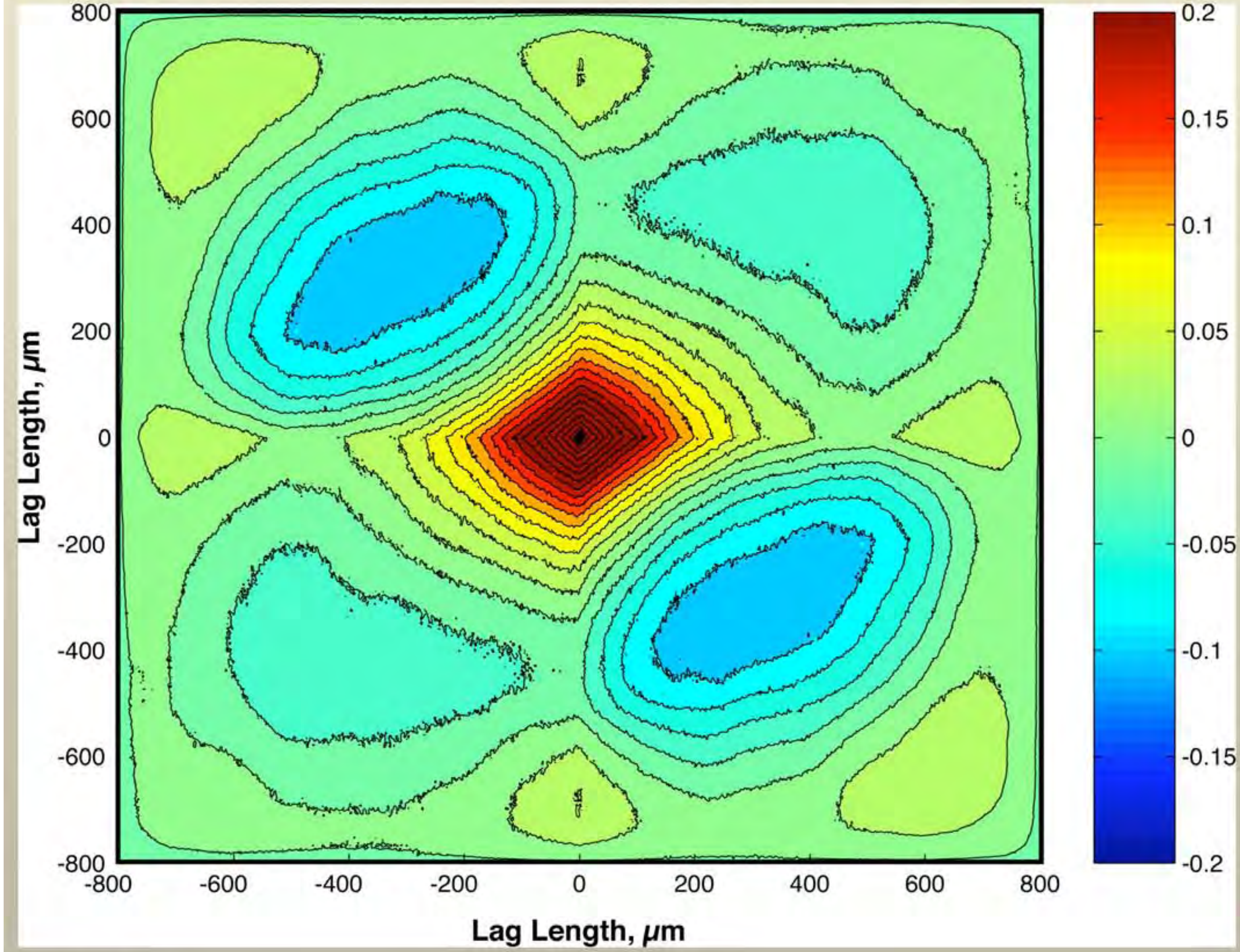


AA 6022-T4 in Uniaxial Tension

Matrix-Based Characterization

Spatial Distribution

2-Point Correlation Surface at 1% Plastic Strain



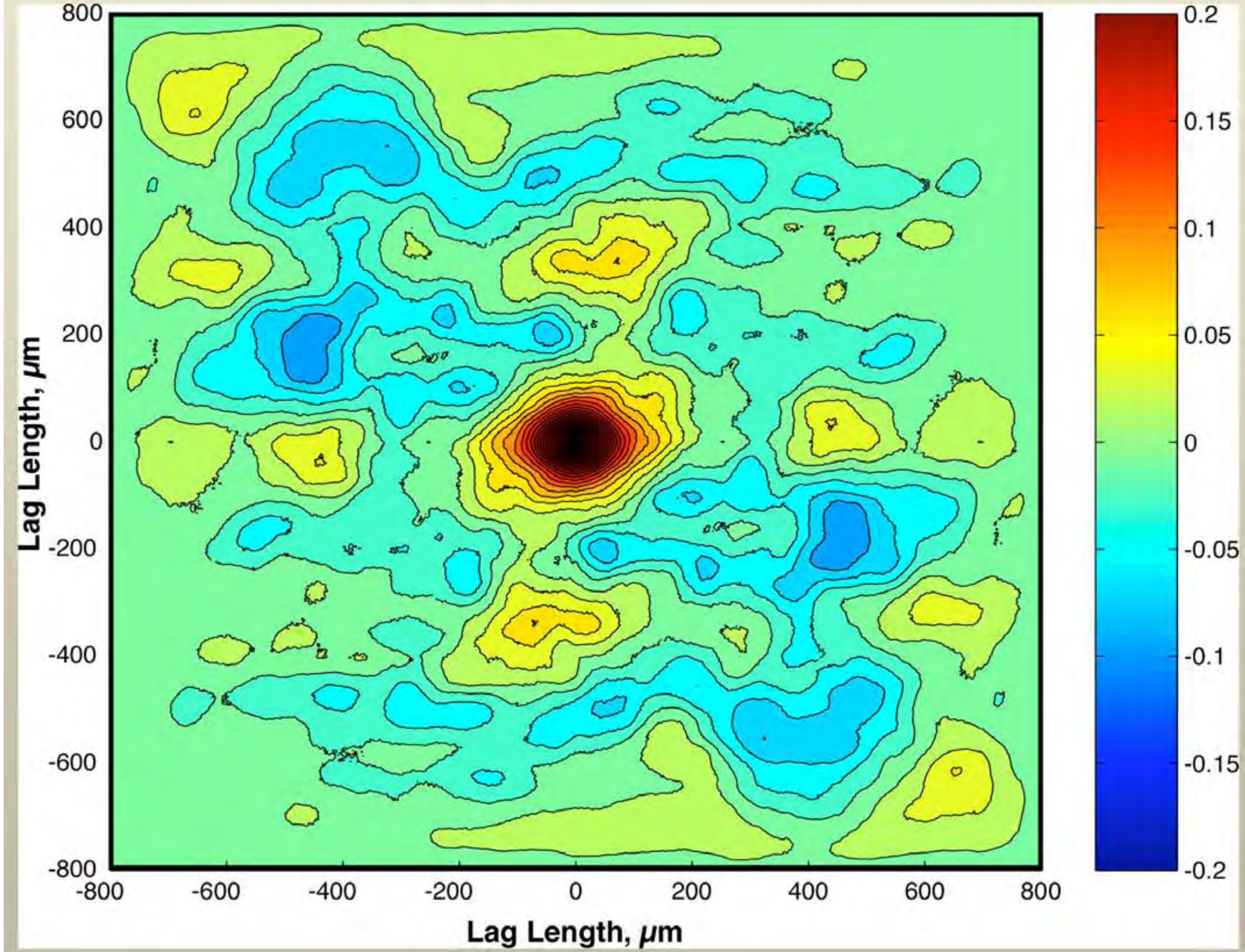
3-Dimensional Correlation "*Fingerprint*"

Surface structure is relatively simple and well defined at *low* strain.

Colors represent regions of similar correlation (height)

Spatial Distribution

2-Point Correlation Surface at 12% Plastic Strain



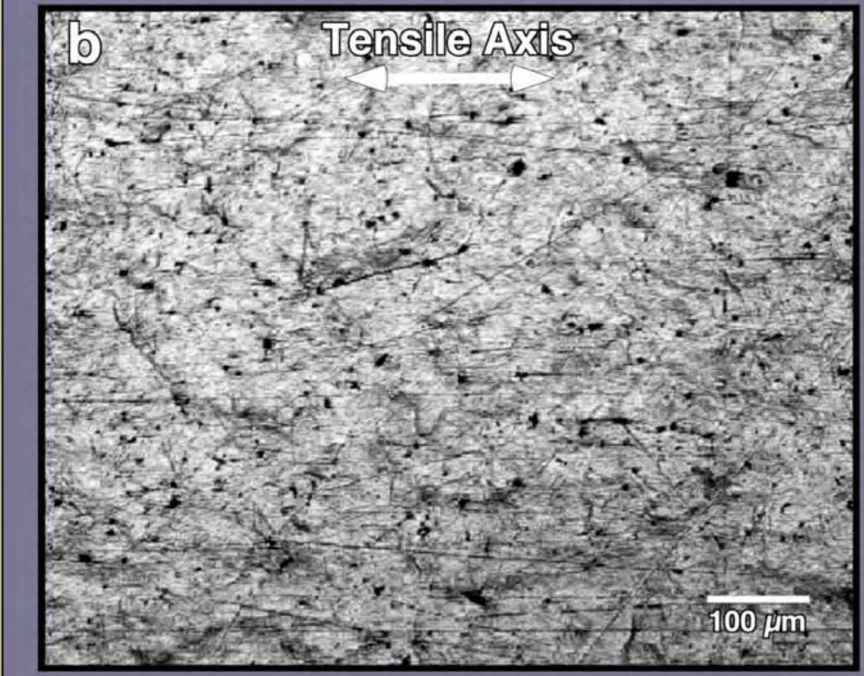
Surface structure becomes more *complex* with plastic strain.

Colors represent regions of similar correlation (height)

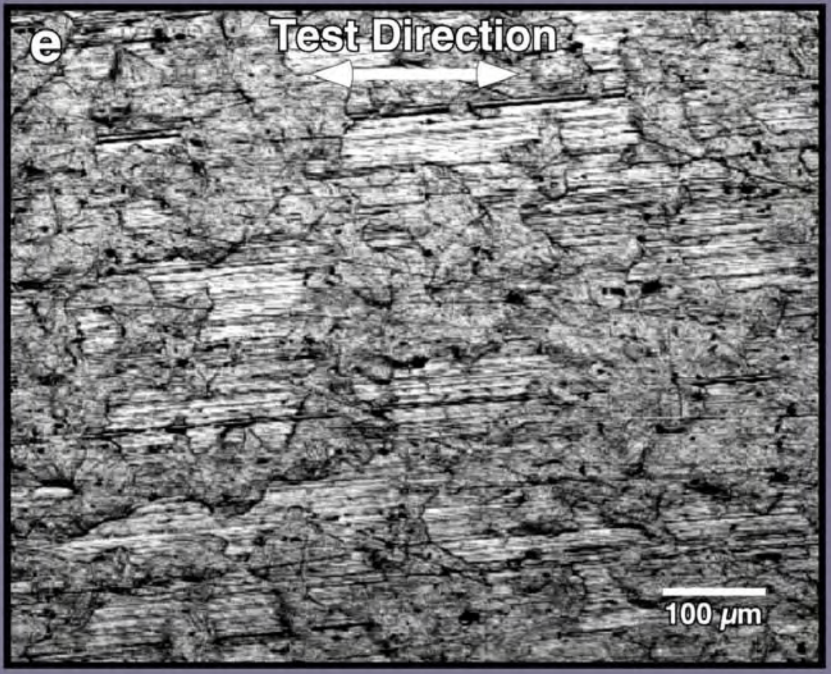
Friction Testing & Spatial Distribution

8% Uniaxial Strain

Before



After



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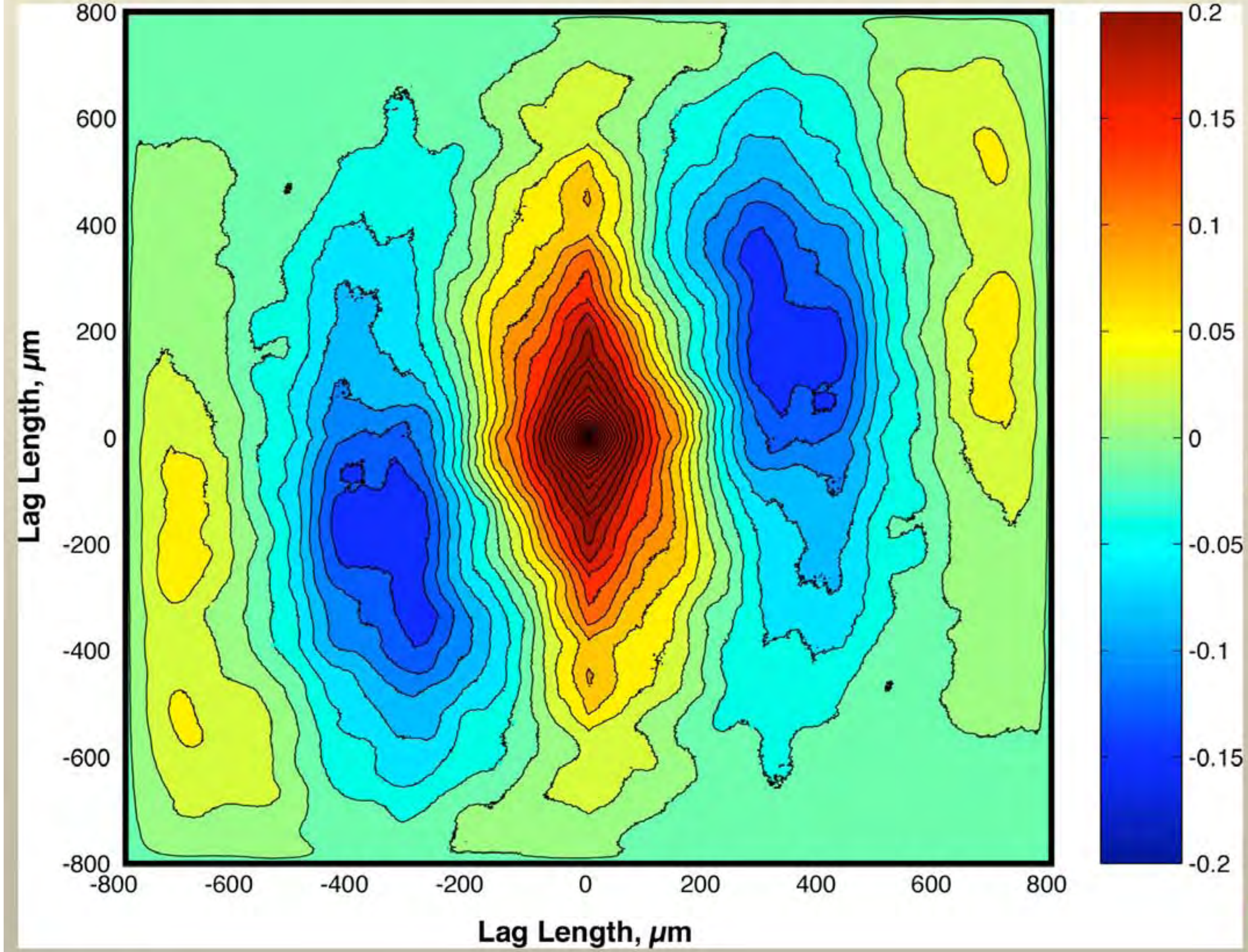
Spatial Distribution Analysis

Before Friction Test

2-Point Correlation Surface at 8 % Plastic Strain



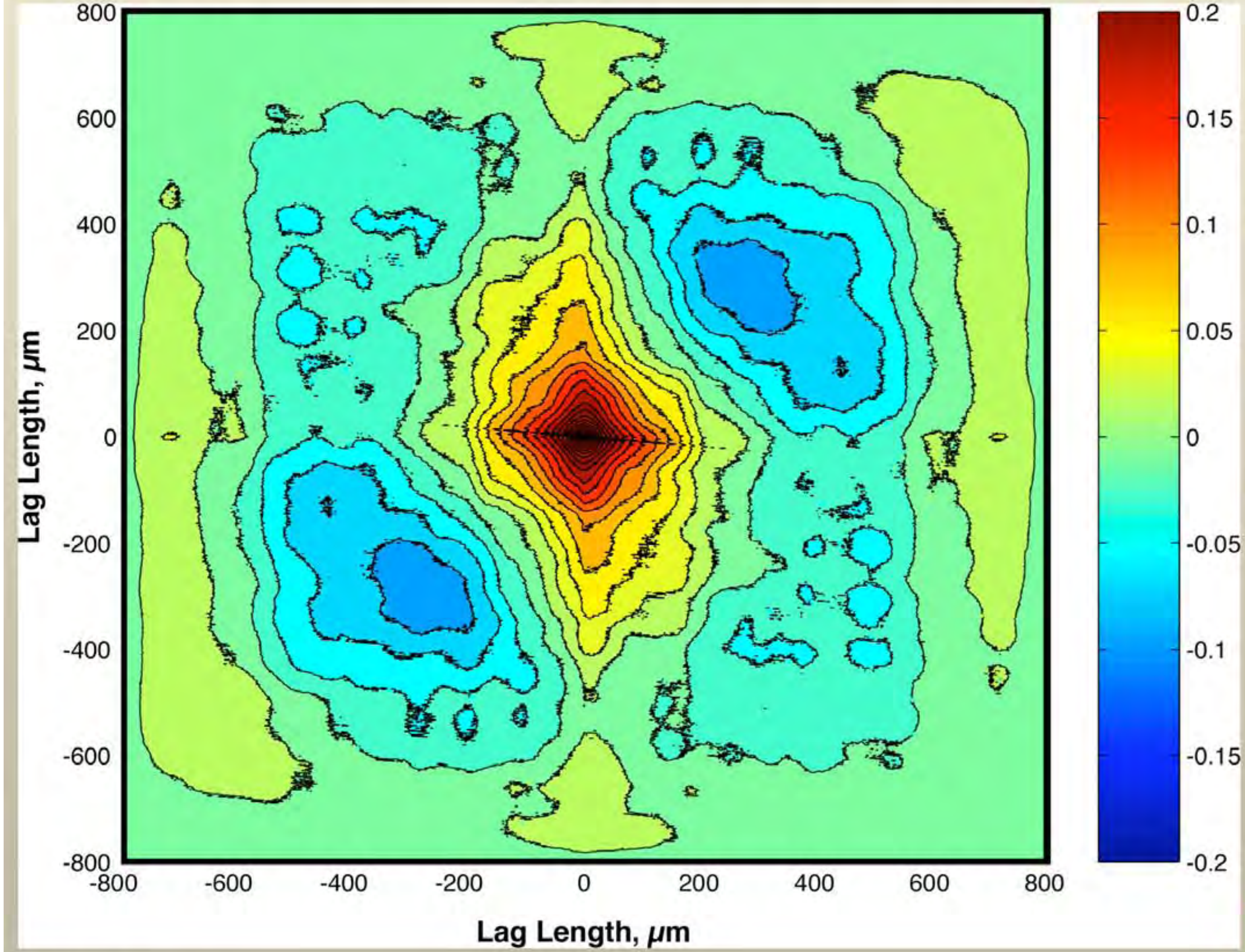
Plastic strain creates a complex surface structure.

Colors represent regions of similar correlation (height)

Spatial Distribution Analysis

After Friction Test

2-Point Correlation Surface at 8 % Plastic Strain



Friction test dramatically altered the original surface structure.

Colors represent regions of similar correlation (height)

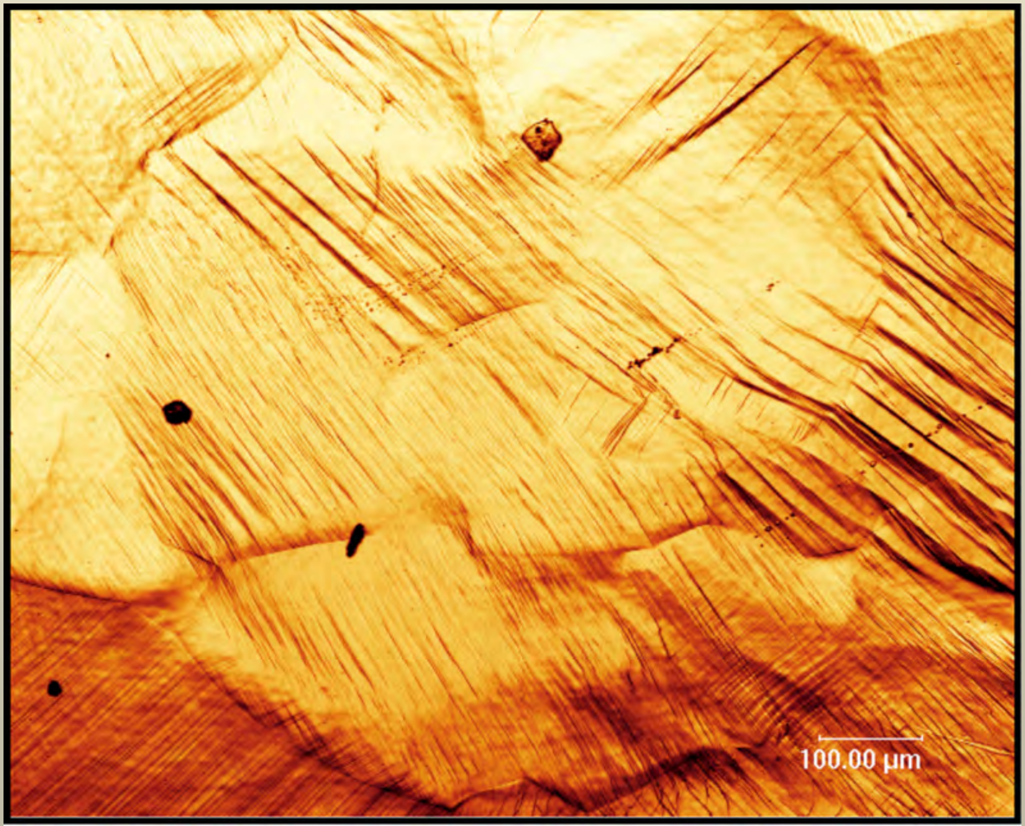
Summary & Conclusions

- Accurate evaluation of surface roughness requires high measurement fidelity for both the height and spatial distributions.
- Linear profiles may be adequate to characterize the height distributions of some surfaces. However, low measurement fidelity makes this technique inappropriate to characterize the complex topography of plastically strained surfaces.
- Matrix methods enable direct characterization of both the height and spatial distributions and preserve the geometrical aspects of the 3-dimensional surface structure.
- Any height parameter used for linear profilometry can also be computed directly for a matrix.

Summary & Conclusions

- The measurement uncertainty contained in the multiple profile approach is minimized by the high density of data points contained in a topographic image.
- Both the quantity and the quality of the numeric data derived from the SLCM images enhance the accuracy of the surface analysis.
- The real power of the matrix-based approach lies in the analytical tools that are available to characterize the spatial distribution.
- This appears to be an appropriate approach to ✓ characterize the Friction/Surface Roughness relationship.

Questions & Feedback??



Experimental and Numerical Investigations of Friction & Lubrication in Sheet Metal Forming

By

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July 11th, 2006

Outline

1. Introduction
2. Background
3. Case Study 1: The Deep Drawing Test
4. Case Study 2: The Ironing Test
5. Case Study 3: Ring Compression Test
6. Case Study 4: Galling in Forming Galvanized AHSS
7. Conclusions

1. Introduction – Tribology R&D

- National Science Foundation grant (2002 ~ 2006)
  - *Enhancement of tribological conditions in tube hydroforming by using environmentally friendly lubricant systems and textured tubes*
- Department of Energy project (2000 ~ 2002)
  - *Replacements of zinc phosphate coating lubrication systems used in metal forming processes*
- International Lead Zinc Research Organization (ILZRO) grant (2006 ~ 2007)
  - *Control of Galling During Forming Galvanized Advanced High Strength Steel*

- **Industry sponsors – Evaluation of lubricants using tribotests**

- Sheet forming (8 comp.)

- Forging (13 comp.)

- Tube Hydroforming (16 comp.)

- **Metal Forming Companies**
- **Lubricant/additive Manufacturers**
- **Lubrication Equipment Builders**

- **A workshop on “Lubrication in Metal Forming” was held in Columbus, Ohio on Dec. 1st 2005 (72 attendees)**

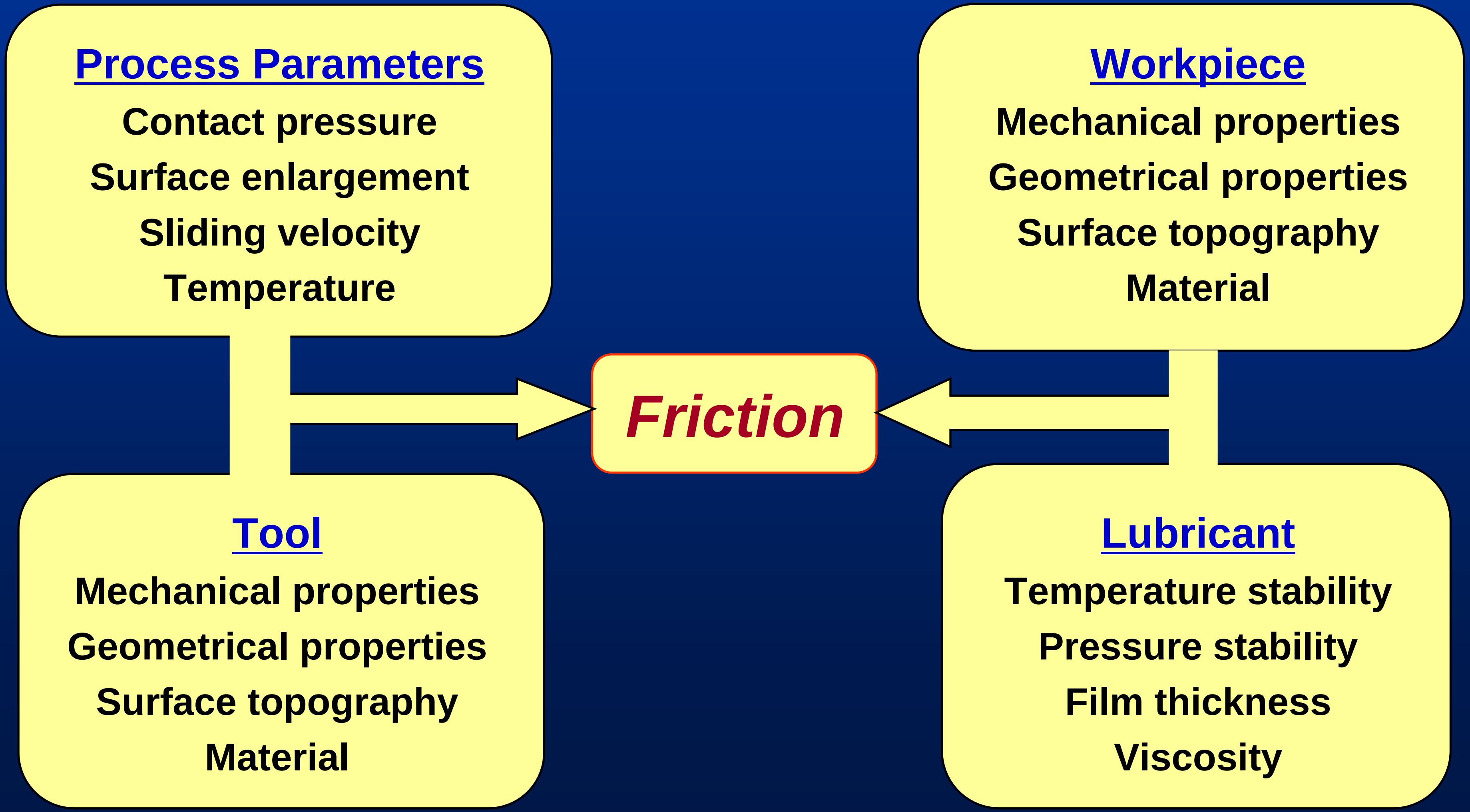
1. Introduction

Tribology R&D Objectives

- Understand lubrication mechanisms / fundamentals of tribology in metal forming and develop reliable friction models for use in process simulation
- Develop tributests that emulate actual process conditions
- In cooperation with lubricant manufacturers, identify/formulate suitable lubricants for metal forming processes
- Estimate the coefficient of friction for use in process simulation
- Develop and evaluate innovative methods for reducing friction
- Work towards replacing conversion coating lubricants and graphite based lubricants with environmentally friendly lubricants

2. Background

Variables Influencing Friction



Process Parameters
Contact pressure
Surface enlargement
Sliding velocity
Temperature

Workpiece
Mechanical properties
Geometrical properties
Surface topography
Material

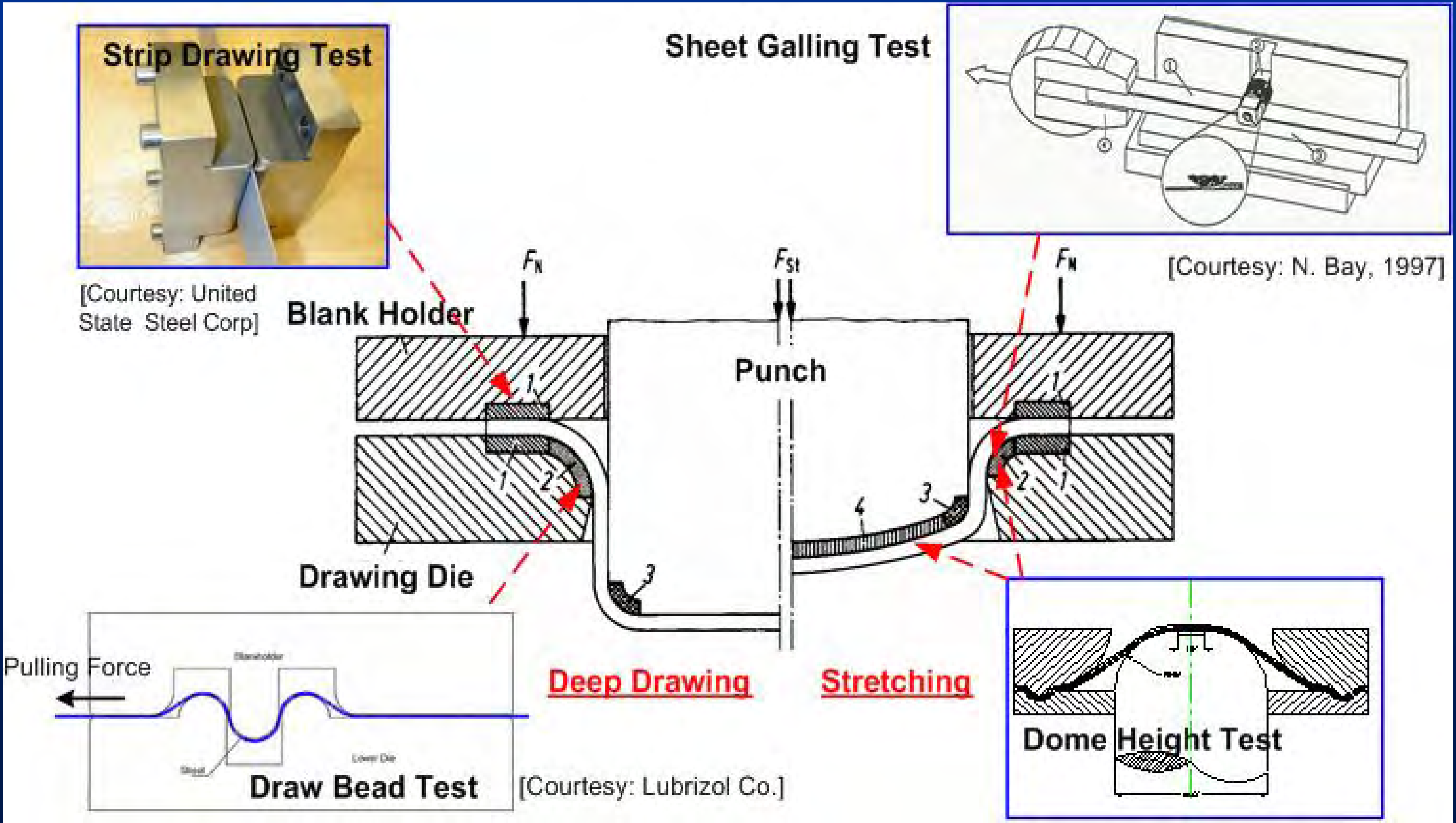
Friction

Tool
Mechanical properties
Geometrical properties
Surface topography
Material

Lubricant
Temperature stability
Pressure stability
Film thickness
Viscosity

2. Background

Various Techniques for Evaluating Stamping Lubes



Strip Drawing Test

[Courtesy: United State Steel Corp]

Sheet Galling Test

[Courtesy: N. Bay, 1997]

Deep Drawing

Stretching

Draw Bead Test

[Courtesy: Lubrizol Co.]

Dome Height Test

2. Background

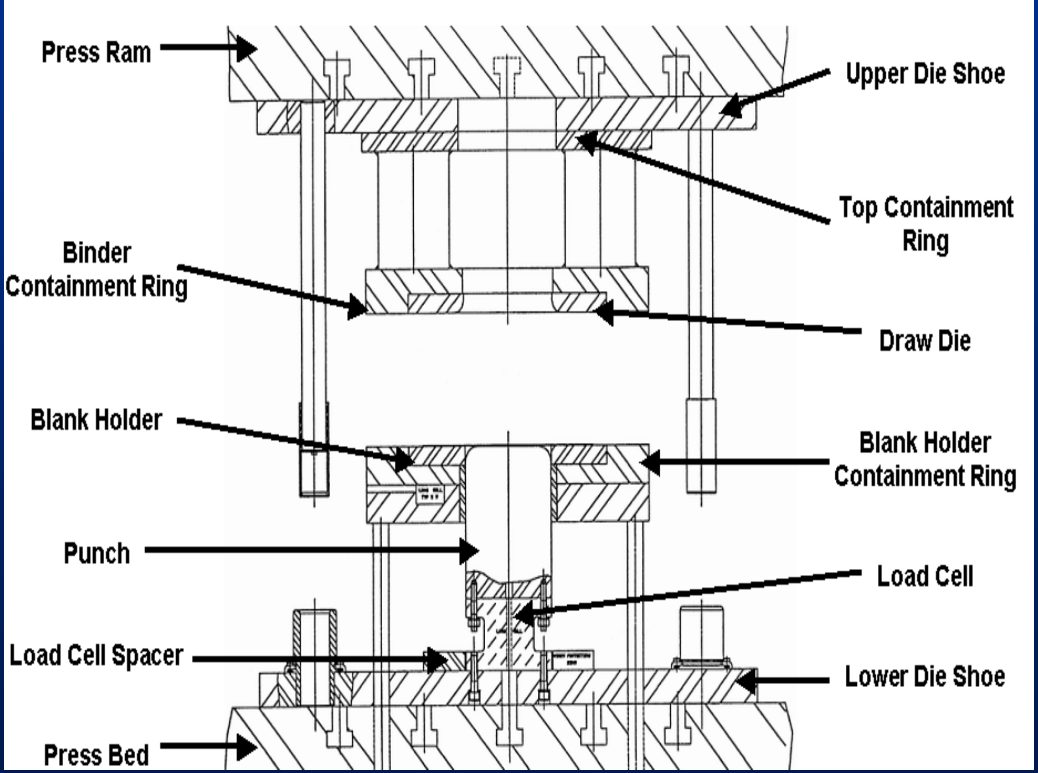
Tribotests for sheet metal forming should be able to:

- Screen lubricants/coatings/additives
- Determine reliable friction values which are applicable to FE simulation
- Emulate relevant testing conditions which exist in real stamping production

➡ **These goals are best achieved by using an integrated experimental and numerical approach for characterizing friction conditions**

3. Case Study 1: Deep Drawing Test

Deep Drawing Tooling is installed in Hydraulic Press (160 ton max. force and 100 ton max. Blank Holder Force)

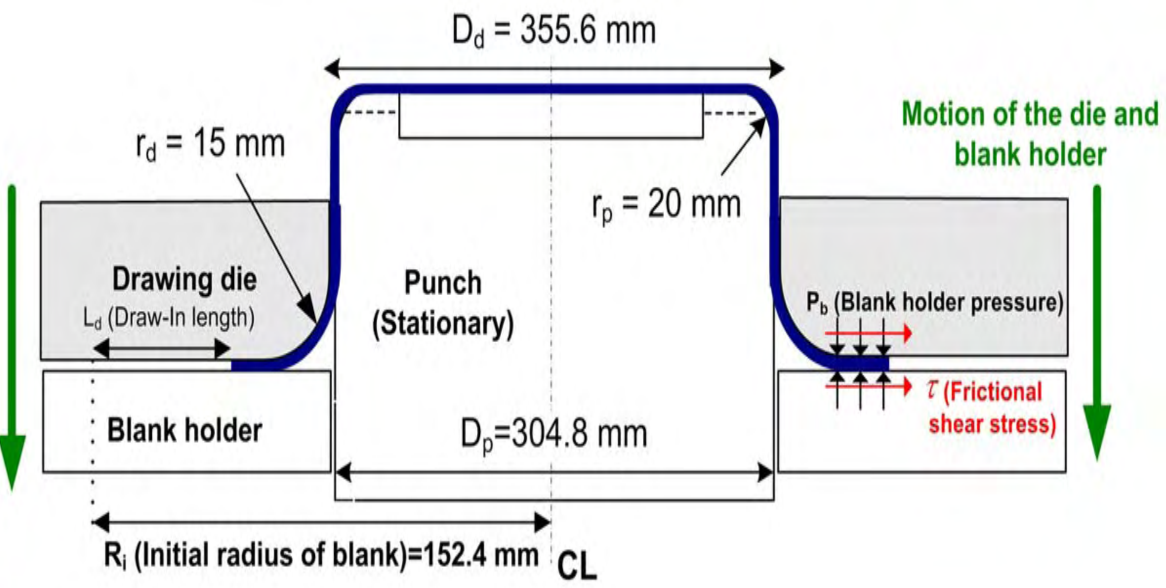


Deep Drawing Tooling at CPF

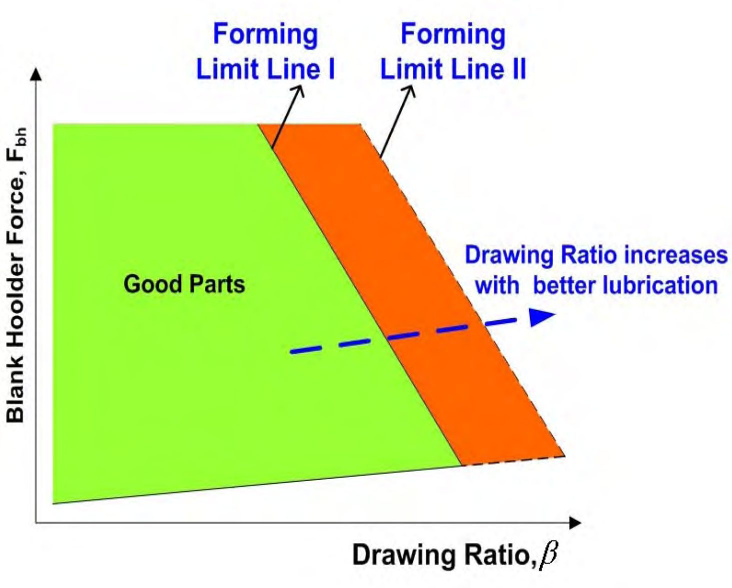
3. Case Study 1: Deep Drawing Test

- Principle of Deep Drawing Test

Schematic of drawing process



Process window



As blank holder pressure (P_b) increases, frictional stress (τ) increases based on Coulomb's law.

Coulomb's law

$$\tau = \mu \cdot P_b$$

where τ = the frictional shear stress

μ = the coefficient of friction

P_b = the blank holder pressure

3. Case Study 1: Deep Drawing Test

- Principle of Deep Drawing Test

CPF

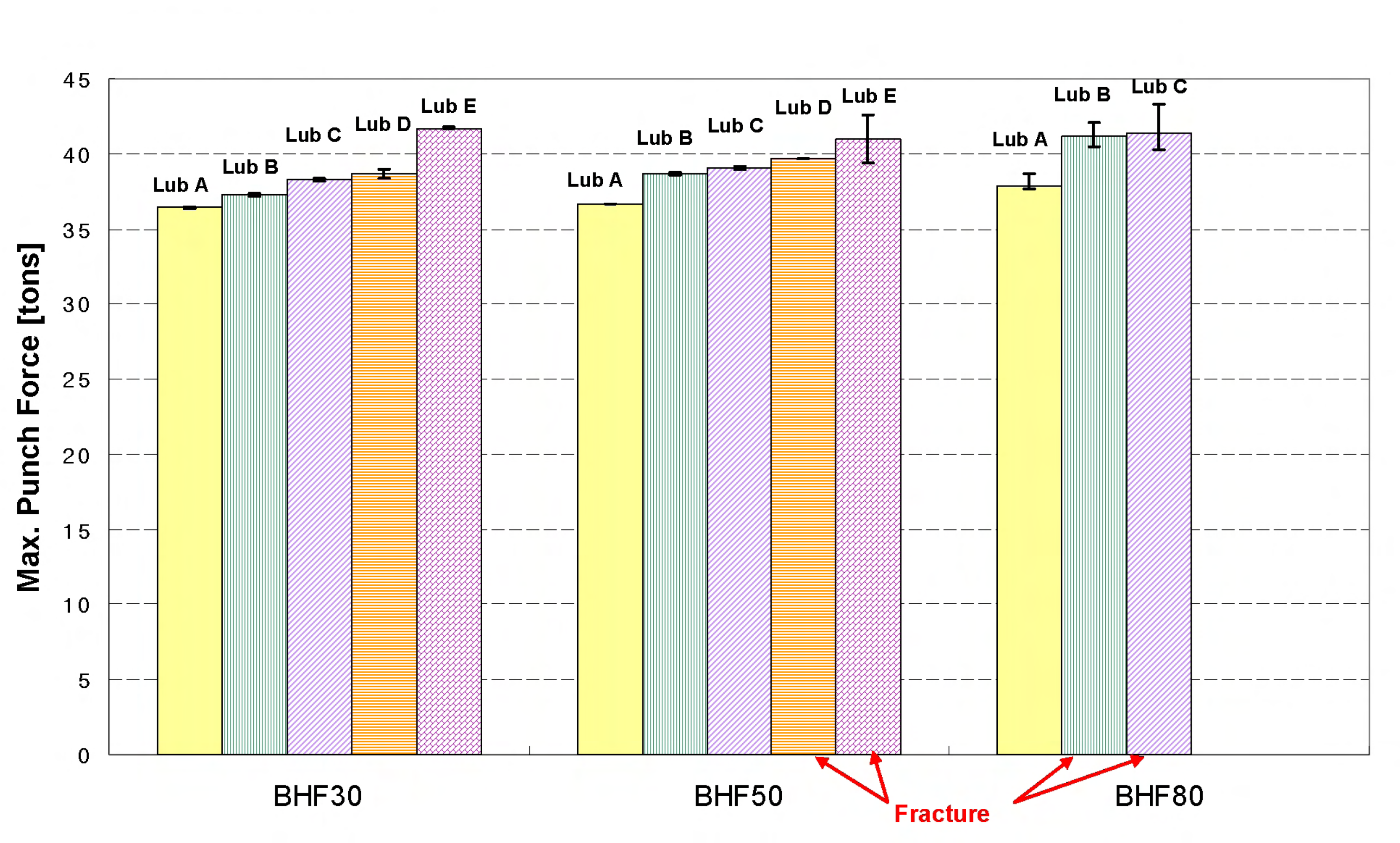
Performance evaluation criteria:

- **The max. drawing load attained**
- **The max. applicable blank holder force without tear in cup wall**
- **Measurement of draw-in length, L_d, (the larger L_d, the better the lubricant) and perimeter at the drawn flange (the shorter perimeter, the better the lubricant)**
- **Evaluation of lubricant build-up on the die for dry film lubes**

3. Case Study 1: Deep Drawing Test

- Experimental Results

Max. punch force for various BHF's (test speed = 2.6 inch/sec)



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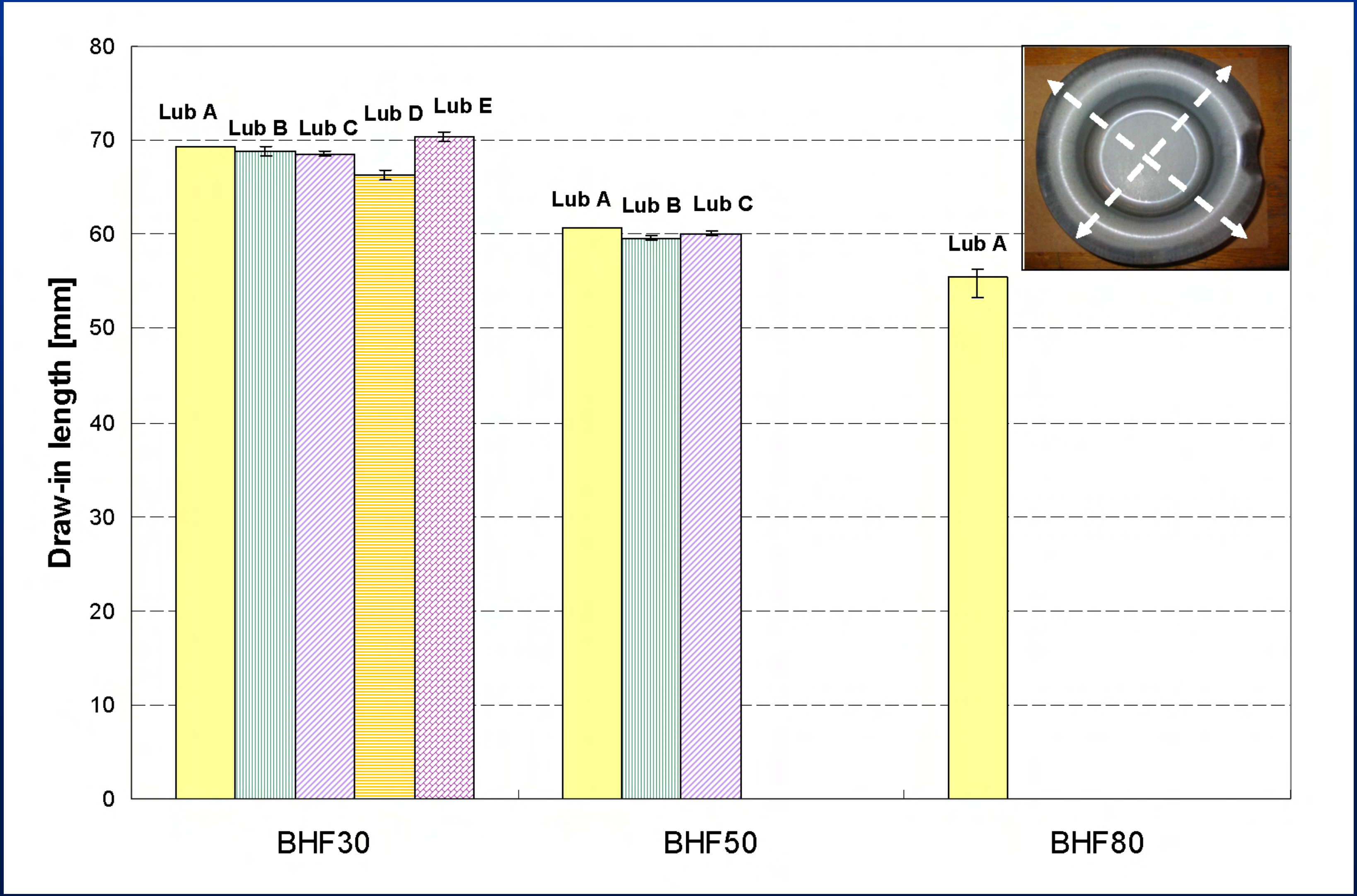
3. Case Study 1: Deep Drawing Test

- Experimental Results

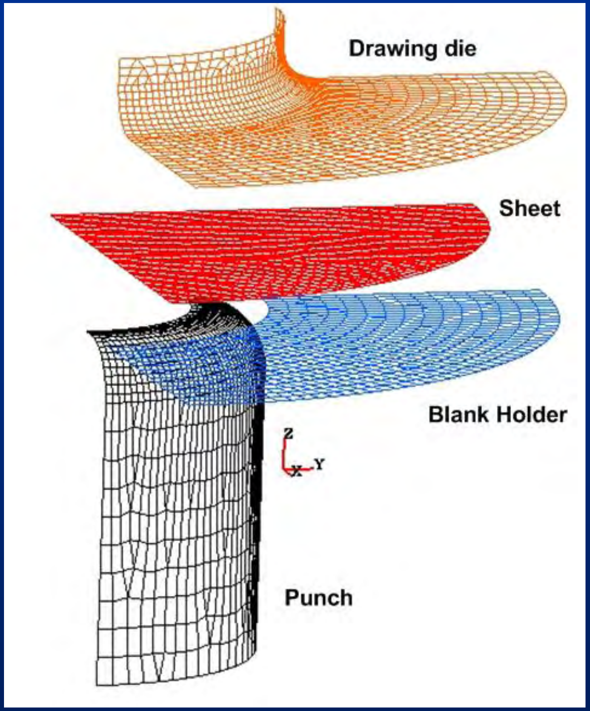
Draw-in length for various BHF’s (test speed = 2.6 inch/sec)



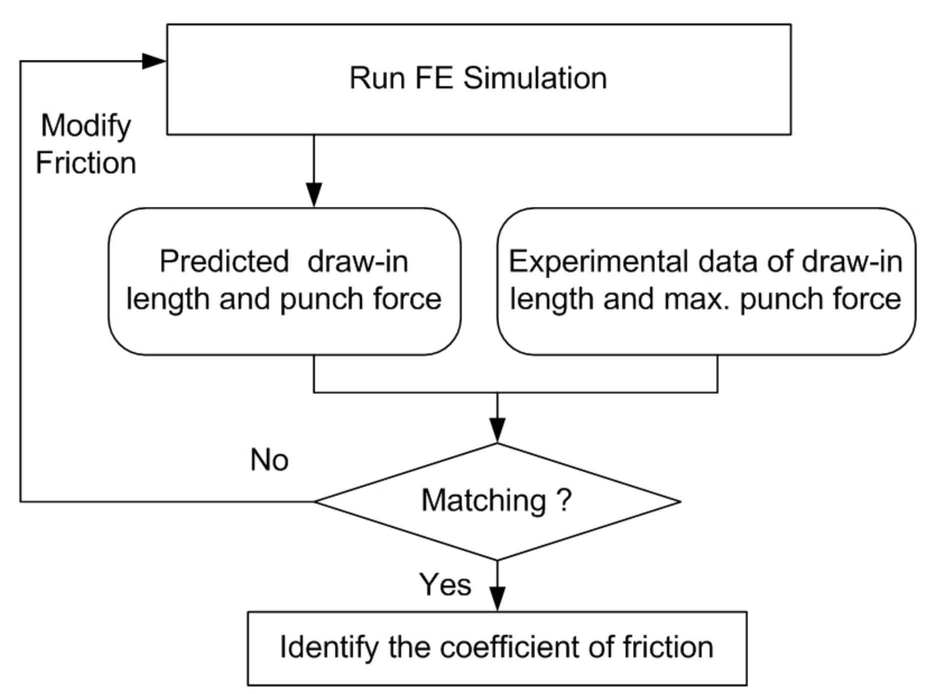
3. Case Study 1: Deep Drawing Test

- FE analysis

FE Model (PAM-STAMP)



Flow chart of FE based inverse analysis



Run FE Simulation

Modify Friction

Predicted draw-in length and punch force

Experimental data of draw-in length and max. punch force

Matching ?

No

Yes

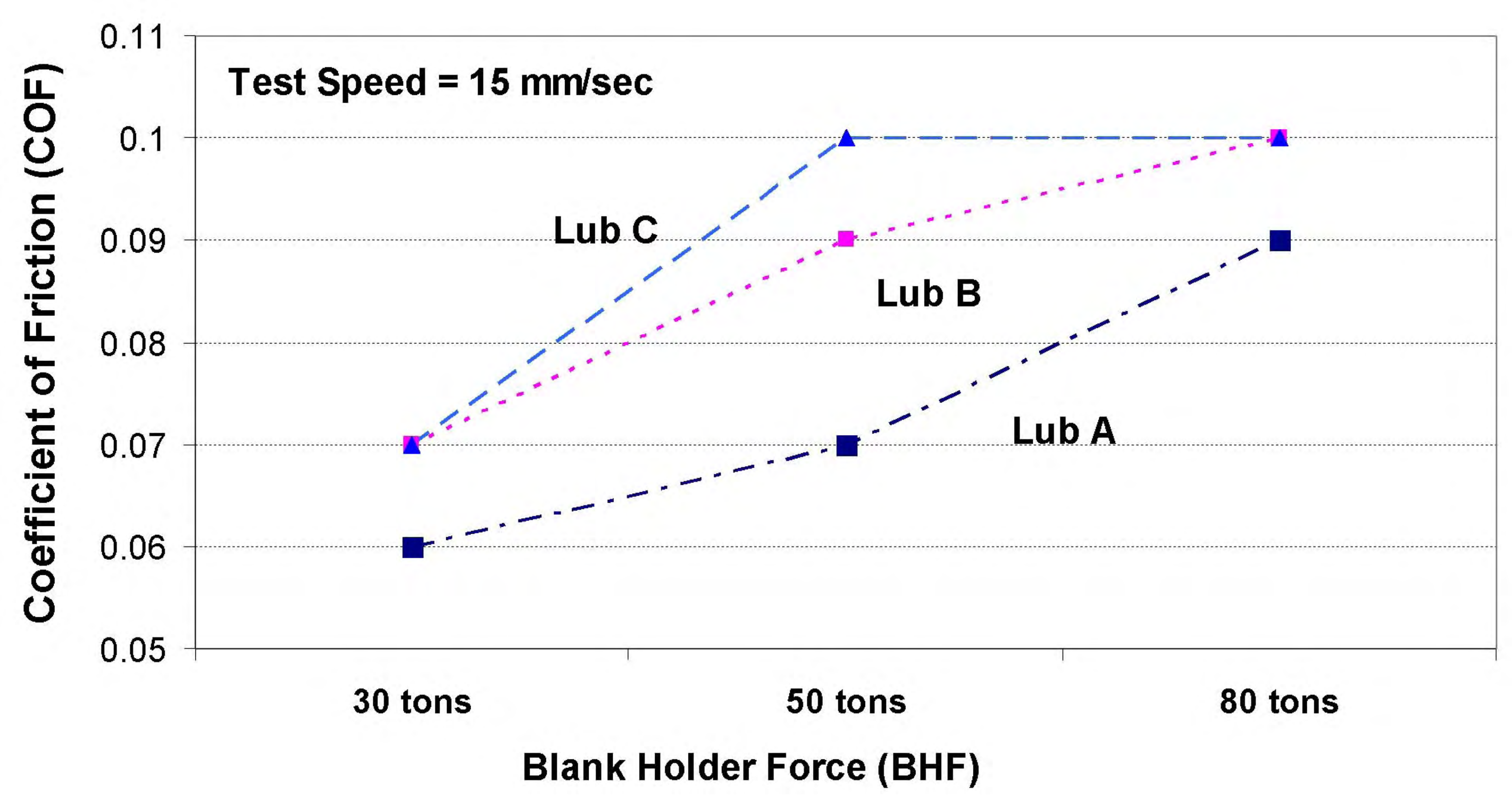
Identify the coefficient of friction

Material Properties of Sheet (ASTM A1011 DS Type-B)	
Young’s Modulus (E)	210 GPa
Poisson ratio (ν)	0.3
Flow stress	$\sigma = 498.8\ \varepsilon^{0.131}$ MPa
Friction Coefficient (μ)	0.05 ~ 0.2
Normal Anisotropy	1.5

3. Case Study 1: Deep Drawing Test

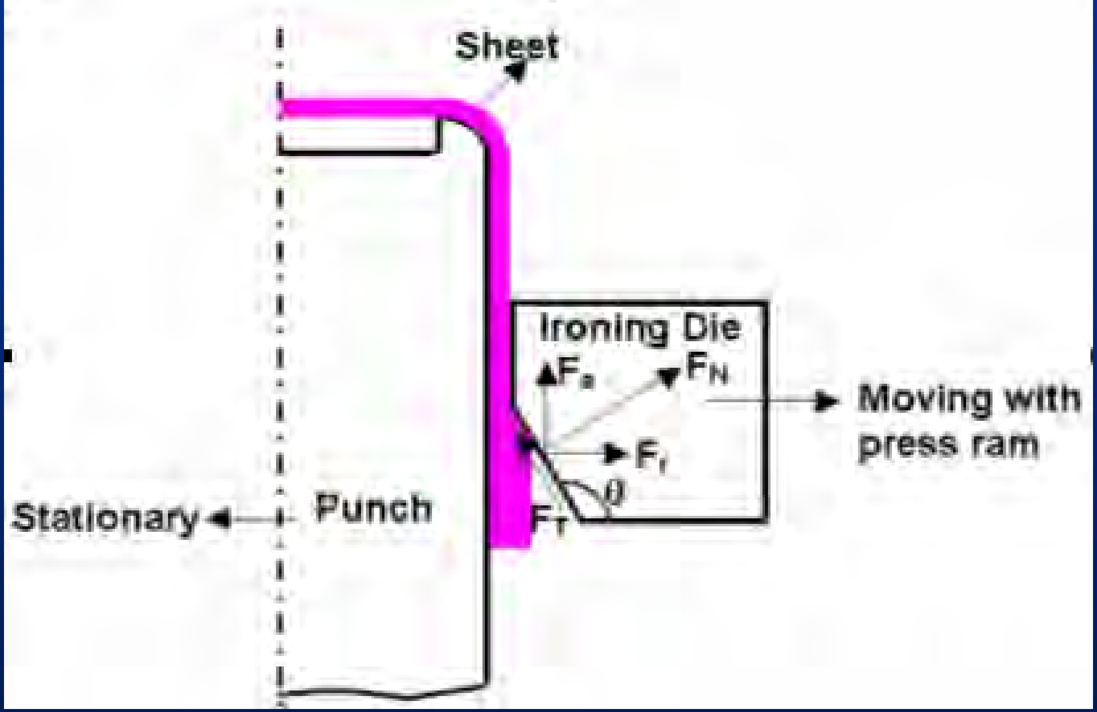
- FE results

Effect of BHF on friction coefficient of lubricants tested



4. Case Study 2: Ironing Test

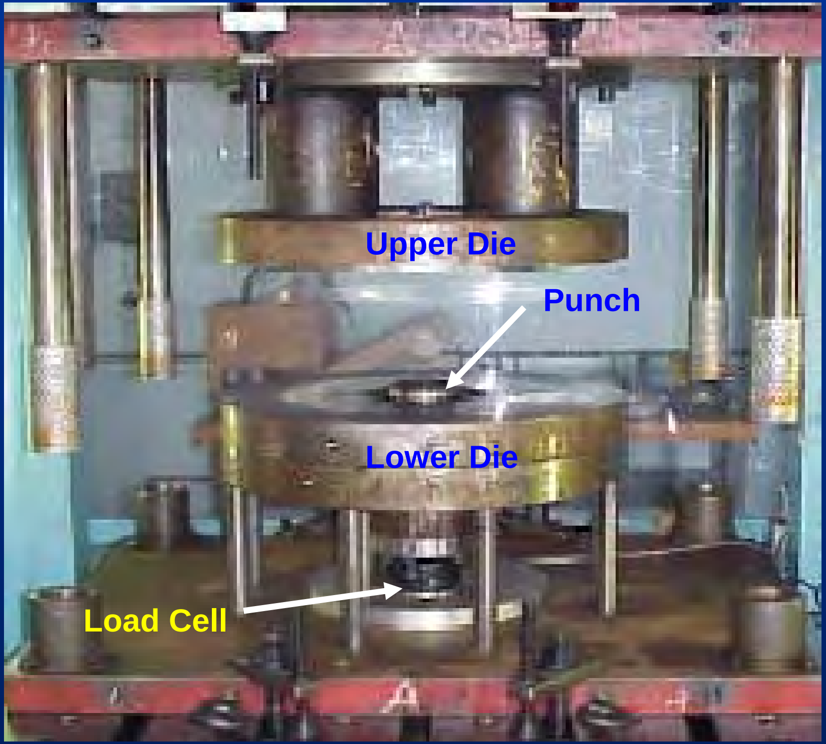
Schematic of Ironing Process

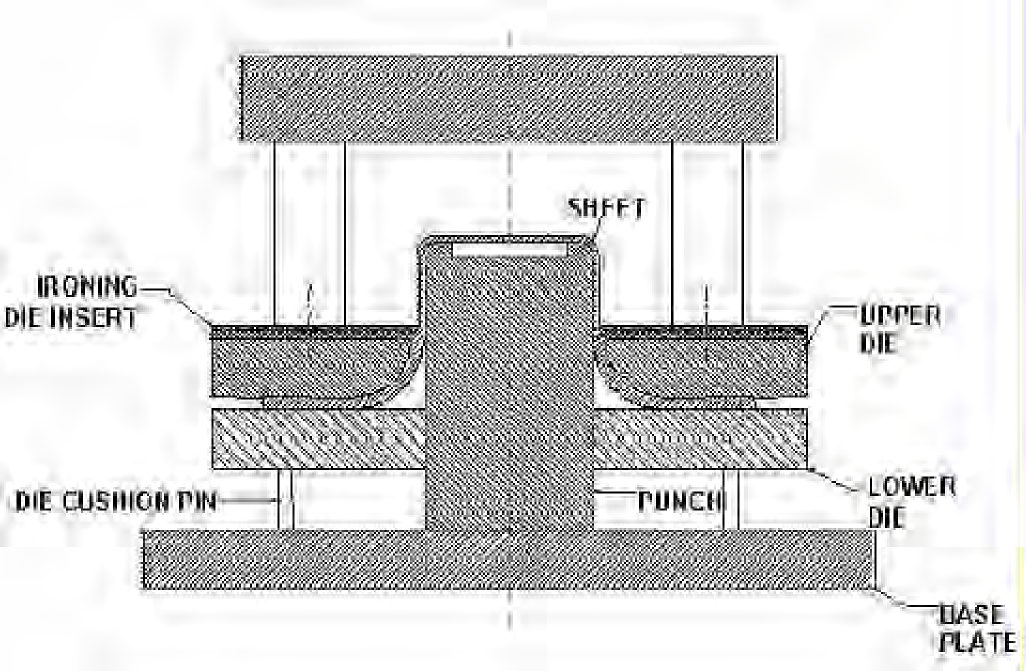


Ironing Test developed at ERC/NSM successfully reproduces production conditions [contact pressure up to 650 MPa (= 94.2 ksi) and temperature up to 200 ˚C (=392 ˚F) in a laboratory setup]

4. Case Study 2: Ironing Test

- ERC Ironing Tooling and Test Procedure





Ironing Test Sequence

Circular Blank

→

Deep Drawn Cup

→

Trimmed Cup

→

Ironed Cup

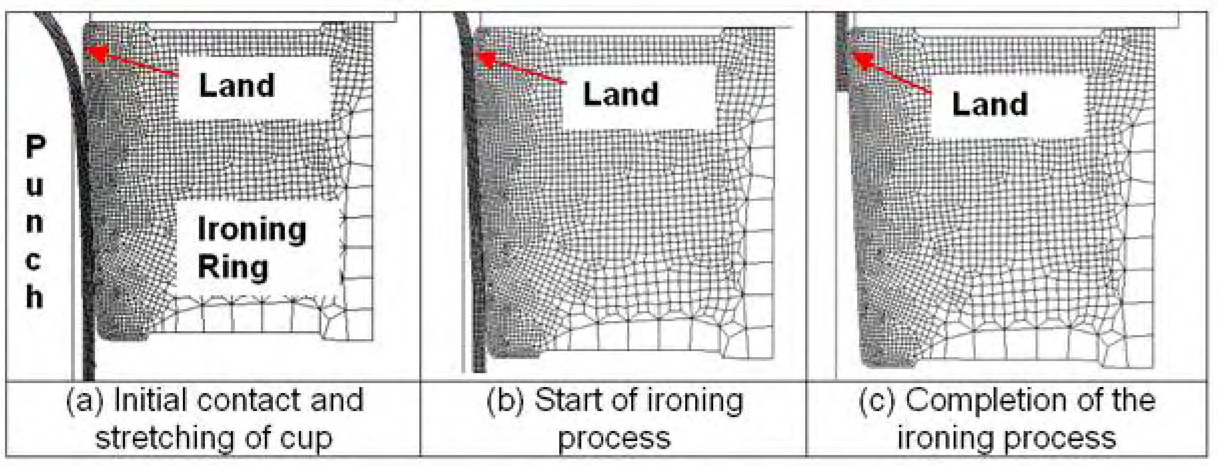
4. Case Study 2: Ironing Test

- Performance Evaluation Criteria

The performance of lubricants is evaluated based on the following evaluation criteria:

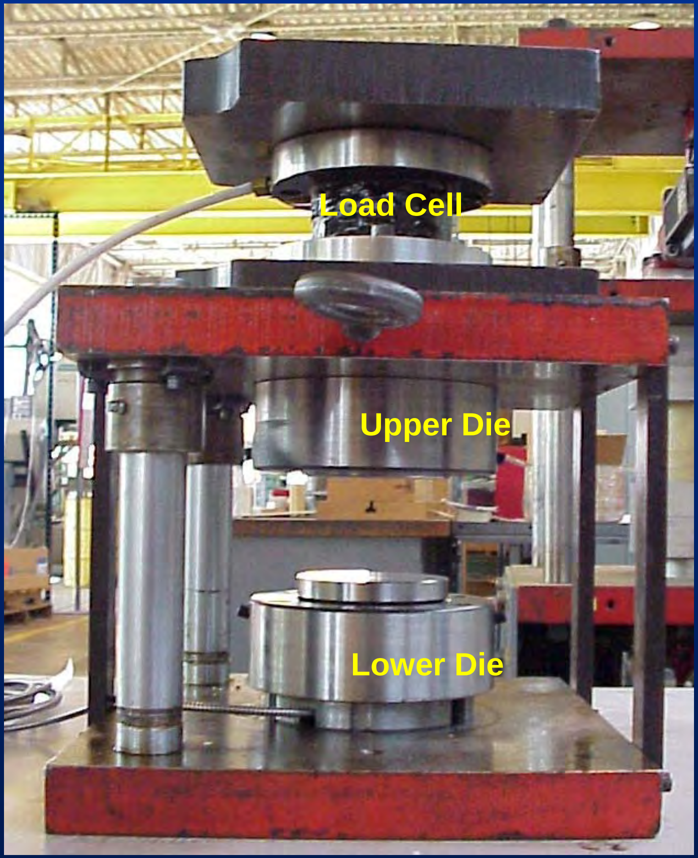
- The maximum ironing load attained
- Surface topography of the ironed cups after test
- Sidewall thinning of drawn cups
- Temperature range at which the lubricant fails
- Coating weight loss or lubricant build-up on die
- Friction factor calculated from the FE simulation

FE model of Ironing process (DEFORM-2D)



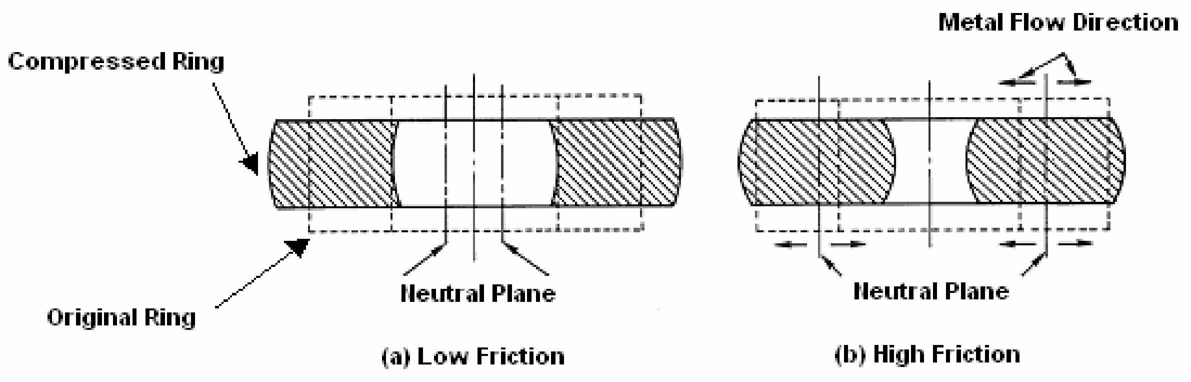
(a) Initial contact and stretching of cup (b) Start of ironing process (c) Completion of the ironing process

5. Case Study 3: Ring Compression Test



Compression tooling at CPF

Operation: The ring shaped workpiece is compressed between two flat dies



Note: The internal diameter after compression is an indication of lubricity (i.e. the larger the internal diameter, the better the lubricant)

5. Case Study 3: Ring Compression Test

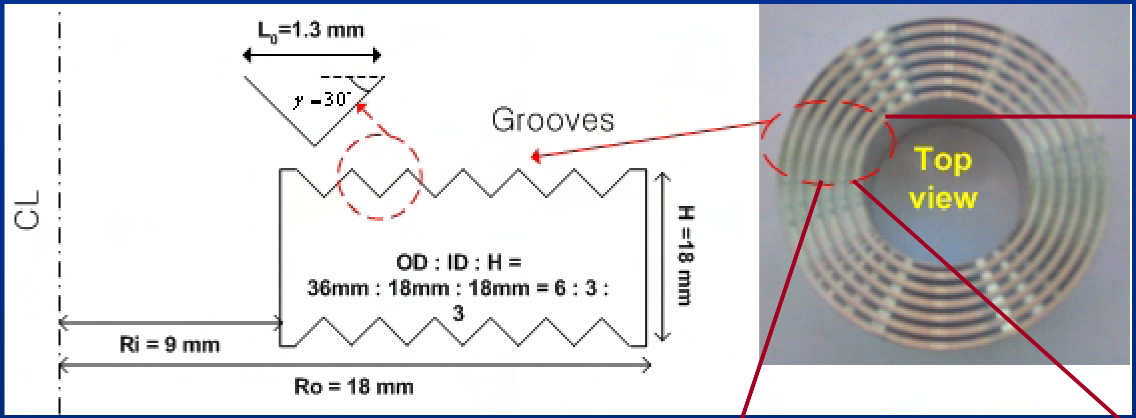
Objectives

- Investigate the effect of surface topography (i.e. surface roughness and real area of contact) on friction and lubrication
- Determine a variable friction formulation, initially, as a function of time (stroke) and/or position (on surface) using the ring compression test and FE simulations.
- Develop an empirical friction model (as a function of surface topography, lubricant viscosity and contact pressure) for metal forming analyses
- Verify the proposed friction model with the FE simulation of ring compression

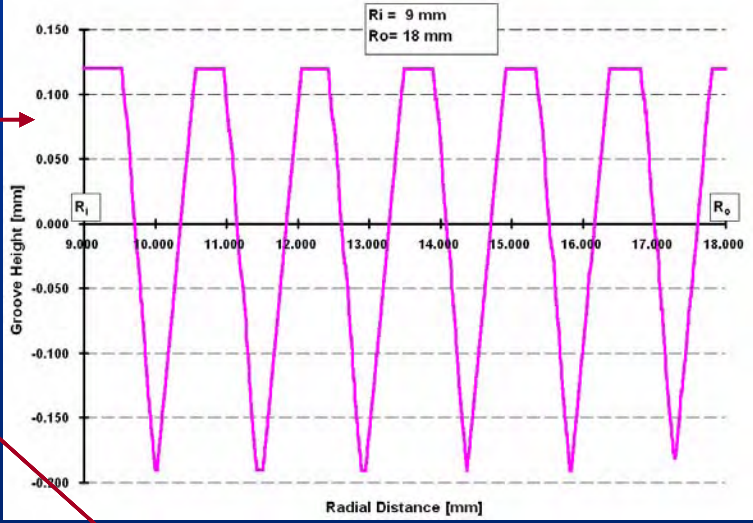
5. Case Study 3: Ring Compression Test

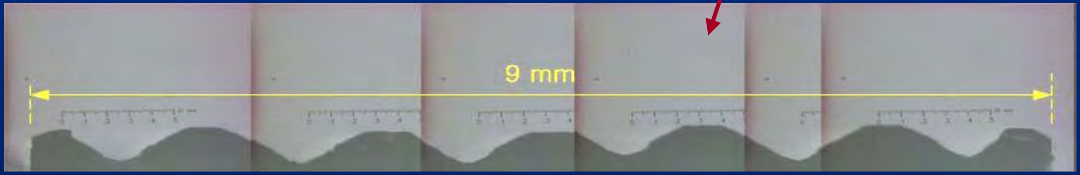
- Experimental and numerical models

Grooved ring specimen

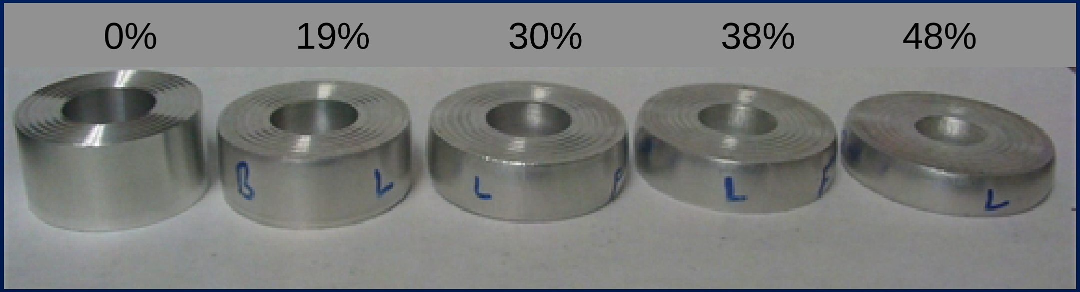


Initial surface profile

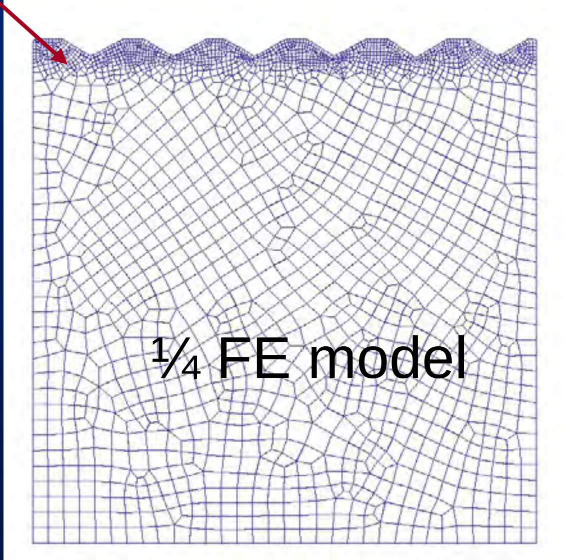




Optical image of surface profile



Specimens tested in various reduction in height



6. Case Study 4 : Galling in Forming Galvanized AHSS

Rationale

- ☐ Advanced/Ultra High Strength Steels (AHSS/UHSS) are used increasingly in forming complex auto body panels.
- ☐ Forming of AHSS/UHSS involves higher contact pressure and temperature at the tool-workpiece interface.
- ☐ These severe tribological conditions may result in failure of lubricants, may lead to galling and may reduce tool life.
- ☐ It is useful to understand the fundamentals of interface conditions to reduce/eliminate galling.

6. Case Study 4 : Galling in Forming Galvanized AHSS

Objectives

1. Investigate the effect of process parameters (interface temperature, pressure and relative sliding speed) on galling during forming AHSS/UHSS
2. Determine the conditions (process parameters, sheet characteristics, tool characteristics and lubrication) that result in galling
3. Select the best/practical tribological system (chemical, mechanical surface treatments of die & sheet, and lubricant) that reduces/eliminates galling

➡ **Use TCT, deep drawing and ironing tests to compare FEM predictions with experiments**

7. Summary and Conclusions

- *For practical application, lubricants must be evaluated in the laboratory under near-production conditions (speed, temperature, interface pressure)*
- *Reliable test conditions can be determined by FE analyses of tribotests*
- *Reliable evaluation criteria should be used to distinguish lubricant performance based on experimental measurements and FE analyses*
- *The coefficient of friction / friction factor for tested lubricant can be calculated using FE based Inverse Analysis (comparison of experiments with FE simulations)*
- *Empirical friction model can be used in actual process simulations*

Questions

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