Fundamentals of Friction and Wear of Automobile Brake Materials

Shyam Bahadur, PhD., Fellow ASME, Fellow ASTM
University Professor and Professor of Mechanical Engineering, Iowa State University, Ames, IA

Outline of Topics

A tribological system

Tribological interactions and wear

Friction materials

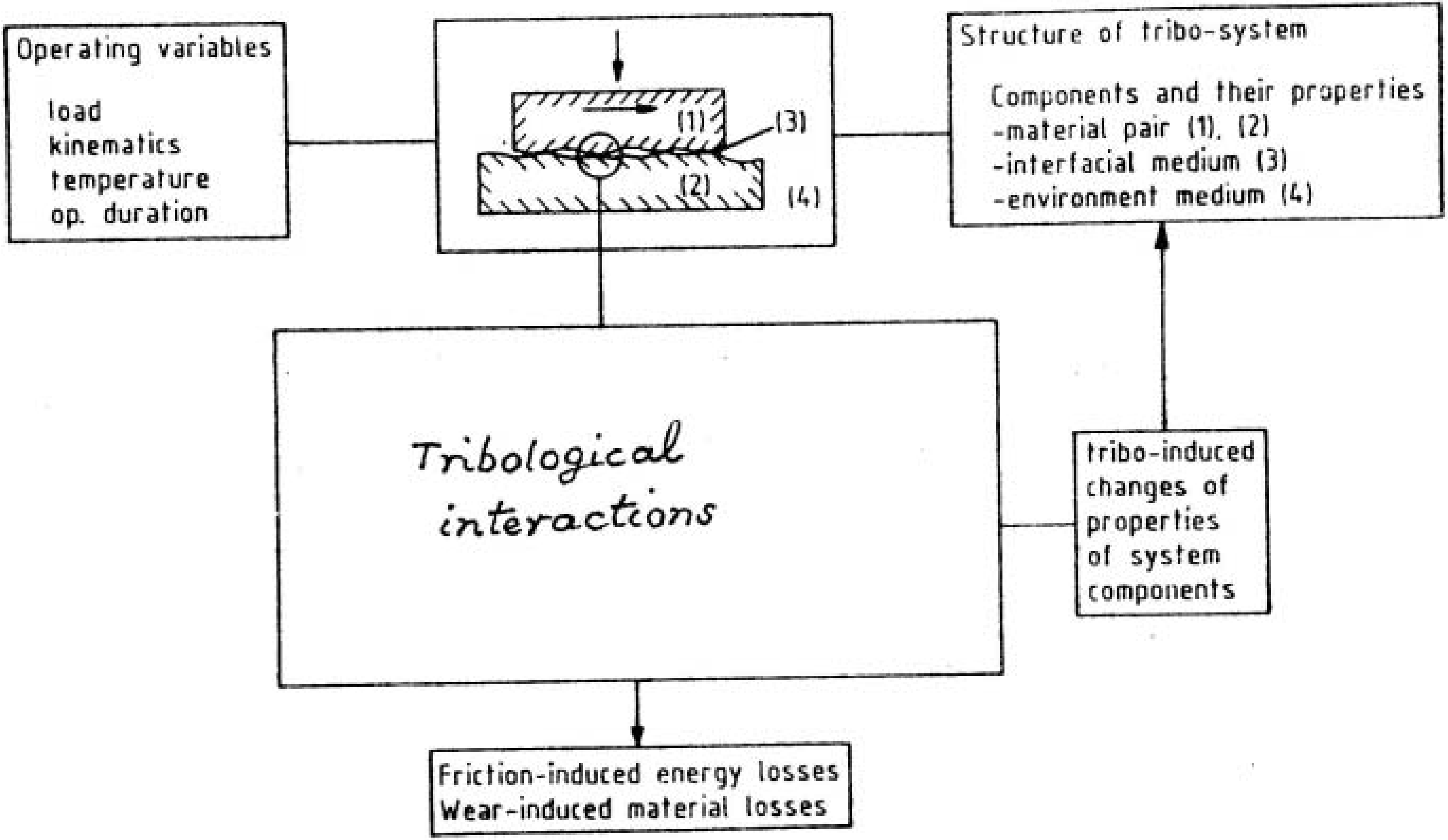
Friction mechanism

Wear of friction materials

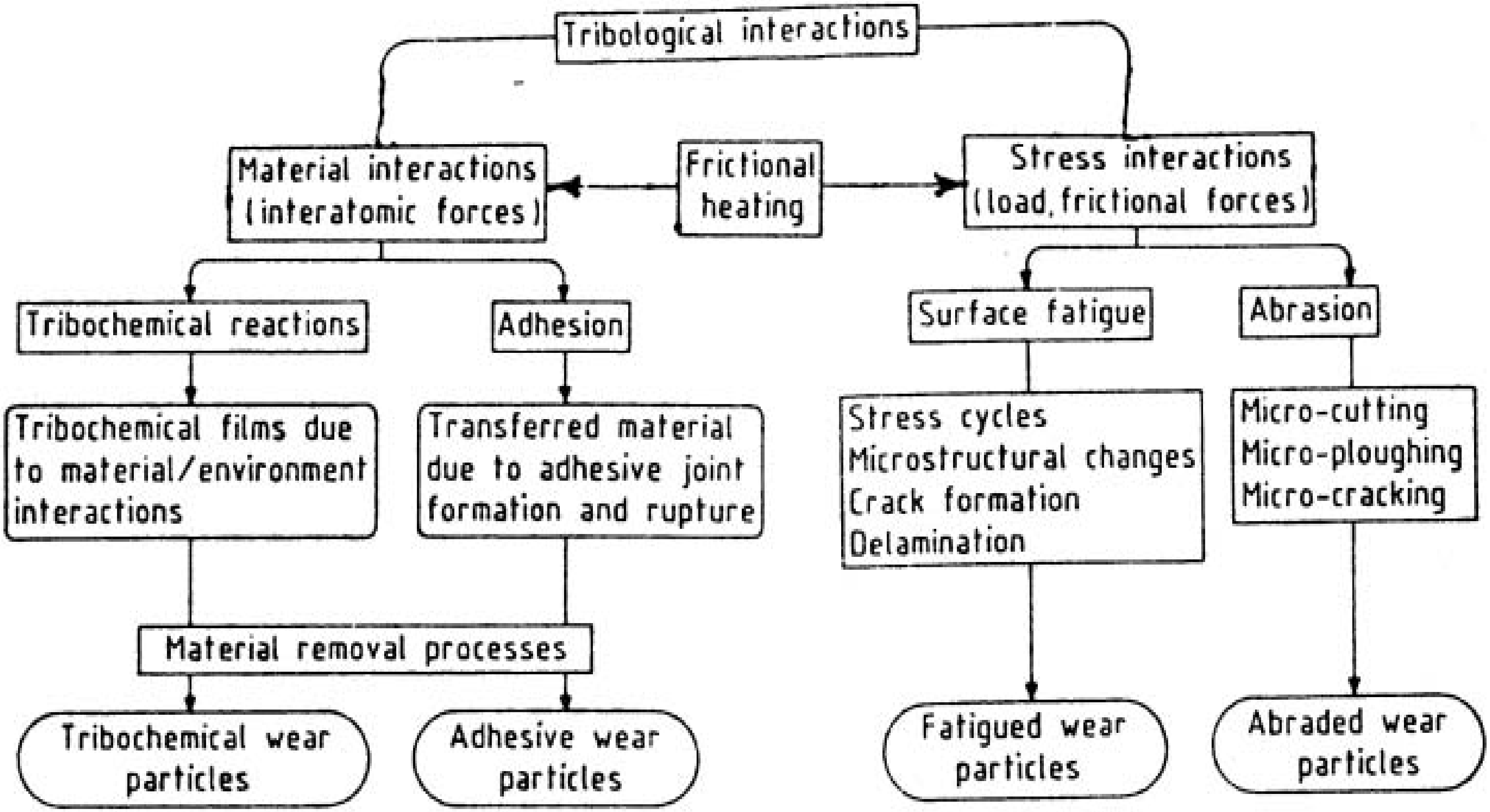
Aluminum composite vs. cast iron for counterface

Transfer film and its role

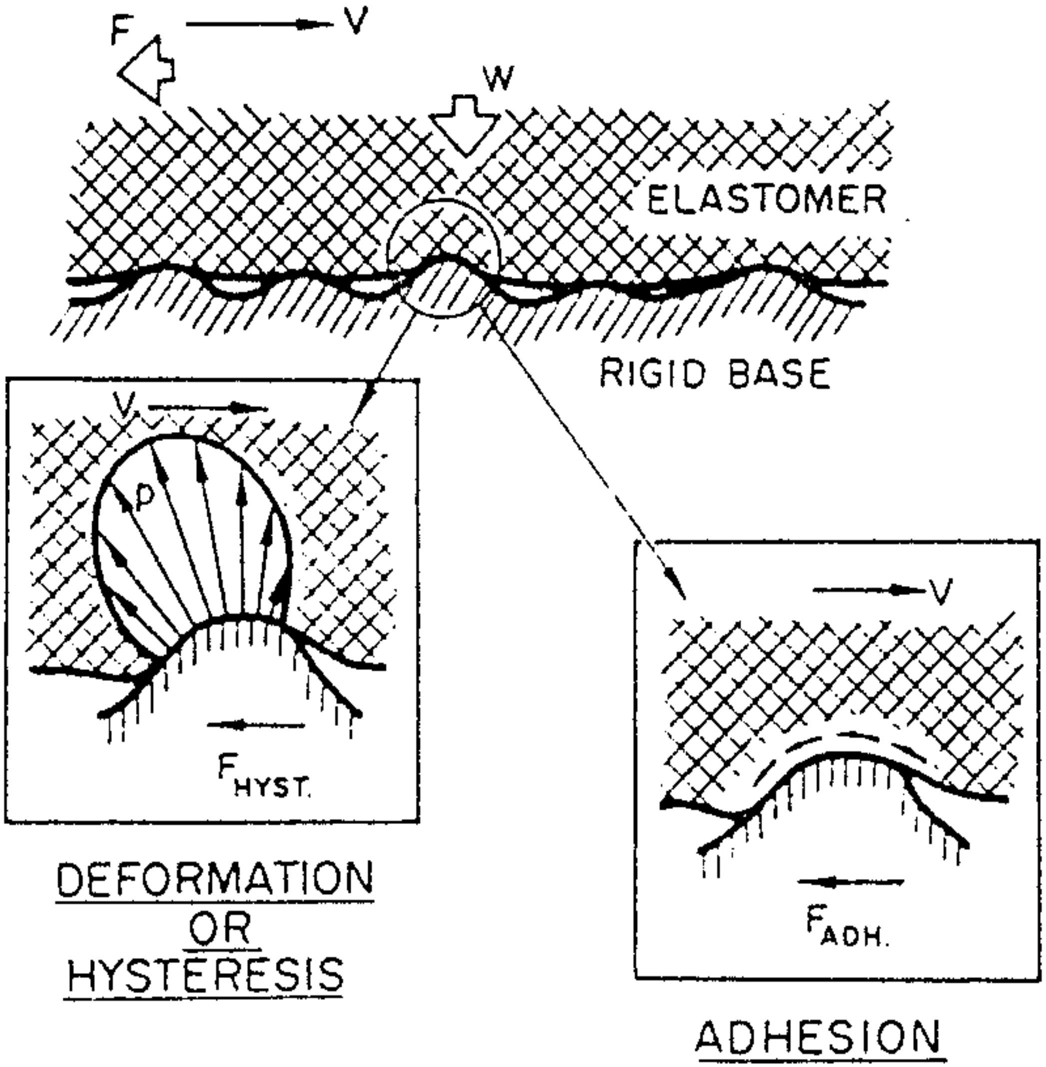
Concluding remarks



Elements of a tribological system



Tribological interactions and wear mechanisms



Contact between a soft material and a rigid surface with asperities

Friction

Contribution from adhesion and deformation:

Friction force, $F = F_{adh} + F_{def}$

Adhesion: van der Waal's forces, dipole interactions, hydrogen bonding, electrical charge

Deformation: deformation of polymer asperities – energy loss due to hysteresis, and grooving

Hysteresis depends upon contact pressure, deformation rate, and temperature

Viscoelastic effects make friction rate and temperature dependent

Adhesion Component of Friction

Friction force due to adhesion,

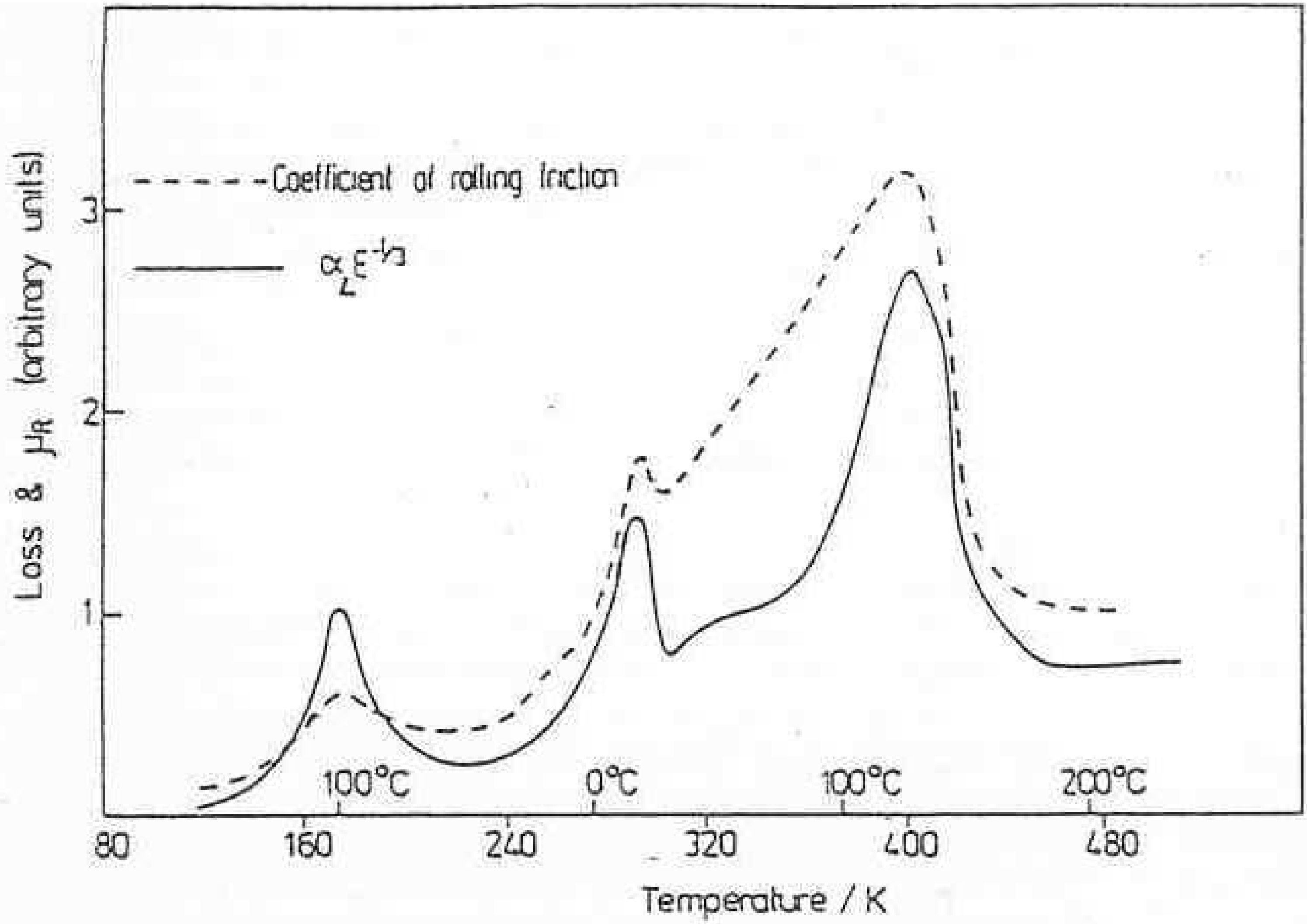
$F_{adh} = AS$

A = real area of contact

S = shear strength of adhesion bonds

Sliding velocity-to-strain rate dependence for area of contact is about 5. This dependence for shear is $10^5 – 10^6$.

The thickness of polymer film affected by shearing is about a micron thick.



Rolling friction μ_R and $\alpha_L E^{-1/3}$ vs. temperature for a hard sphere rolling over a flat PTFE surface. Here $\alpha_L E^{-1/3}$ is proportional to rolling friction where $\alpha_L = \pi \tan\delta$ ($\tan\delta$ is a measure of hysteresis).

Sliding Wear

Archard’s equation for sliding wear

$V/L = K.P/H$

V - wear volume L - sliding distance

P – load H – polymer hardness

K - a proportionality constant. It is a cure-for-all factor and needs to be determined experimentally.

- Wear volume is not often linearly proportional to load.
- Wear volume is not inversely proportional to hardness.

Wear Equation for Friction Materials

Wear volume, $V = K\,P^{a}.\,v^{b}.\,T^{c}$

v - sliding velocity

T - time of sliding

P – load

K – proportionality constant

The exponents, a, b and c depend upon the material combinations and sliding conditions.

S. K. Rhee, Wear, 16 (1970) 431-445. S. K. Rhee, Wear, 18 (1971) 471-477. S. K. Rhee, Wear, 80 (1970) 992-998.

Friction Materials as Composites

Reinforcing fiber materials: 5 - 25 vol.%

Aramid, metal, ceramic, glass, acrylic, and others

Aramid pulp – good filler retention provides green strength for preform, strong covalent bonding

Ceramic fibers – potassium titanate ($K_2O.6TiO_2$) whiskers - high thermal stability and compatibility with binder material, high modulus and high strength

Fillers– Barite ($BaSO_4$), MoS_2 ,, inorganic fillers

3 Binder – phenolic resin: high hardness and compressive strength, temperature resistant (300 – 500° F), creep resistant, moldability, wetting capability

Friction Materials: Organic, metallic and carbon

Organic friction materials are the composites of

Polymer as binder resin- phenolic, rubber, cashew

Fibers - organic

Additives - improved strength, thermal expansion and heat absorption, modification of friction and wear, reduced cost, improved processing

Examples of organic friction materials:

Asbestos (also called organic) brake linings with asbestos and binder

Non-asbestos organic (NAO) brake linings with fibers of materials other than asbestos, and binder. Fiber material examples are glass, mineral wool, metal, ceramic, Kevlar, etc. Also other shapes of reinforcements are used.

Metallic and Carbon Friction Materials

1. **Semi-metallic or resin-bonded metallic materials:** Example: Wt.% Fe 65 including 10-25% steel fiber, graphite 15, phenolic binder 10
2. **Metallic Friction Materials:** suited for heavy duty applications, copper or iron based materials sintered with inorganic additives

   Examples: solid state sintered bronze with mullite, sintered iron with graphite.
3. **Carbon Friction Materials**: high performance (2000° C operating temperature) and light weight material

   Example: carbon-carbon friction material which is carbon fiber bonded with amorphous carbon

Factors affecting the Friction and Wear of Brake Materials

Brake design – disk or drum: loading areas different, faster cooling in disk brakes

Disk/ Drum and Lining materials composition

Operating temperature range

Rubbing speed

Contact pressure

Exposure to environmental contaminants such as road dust, local rust debris, moisture, etc.

Prior usage history and resulting surface conditions

SAE®

Friction and Wear Test Machines

Chase Machine – SAE Test J661a

FAST (Friction Assessment and Screening Test) Machine

- Block specimen, 6.35 mm^2, rubs on the periphery of a rotating ring at constant pressure

A pad of friction material loaded by air pressure against the inside surface of the 279.4 mm diameter drum

Inertial Dynamometer Machine

It use one or more shaft-mounted weights to store energy which is dissipated by the brake material during testing.

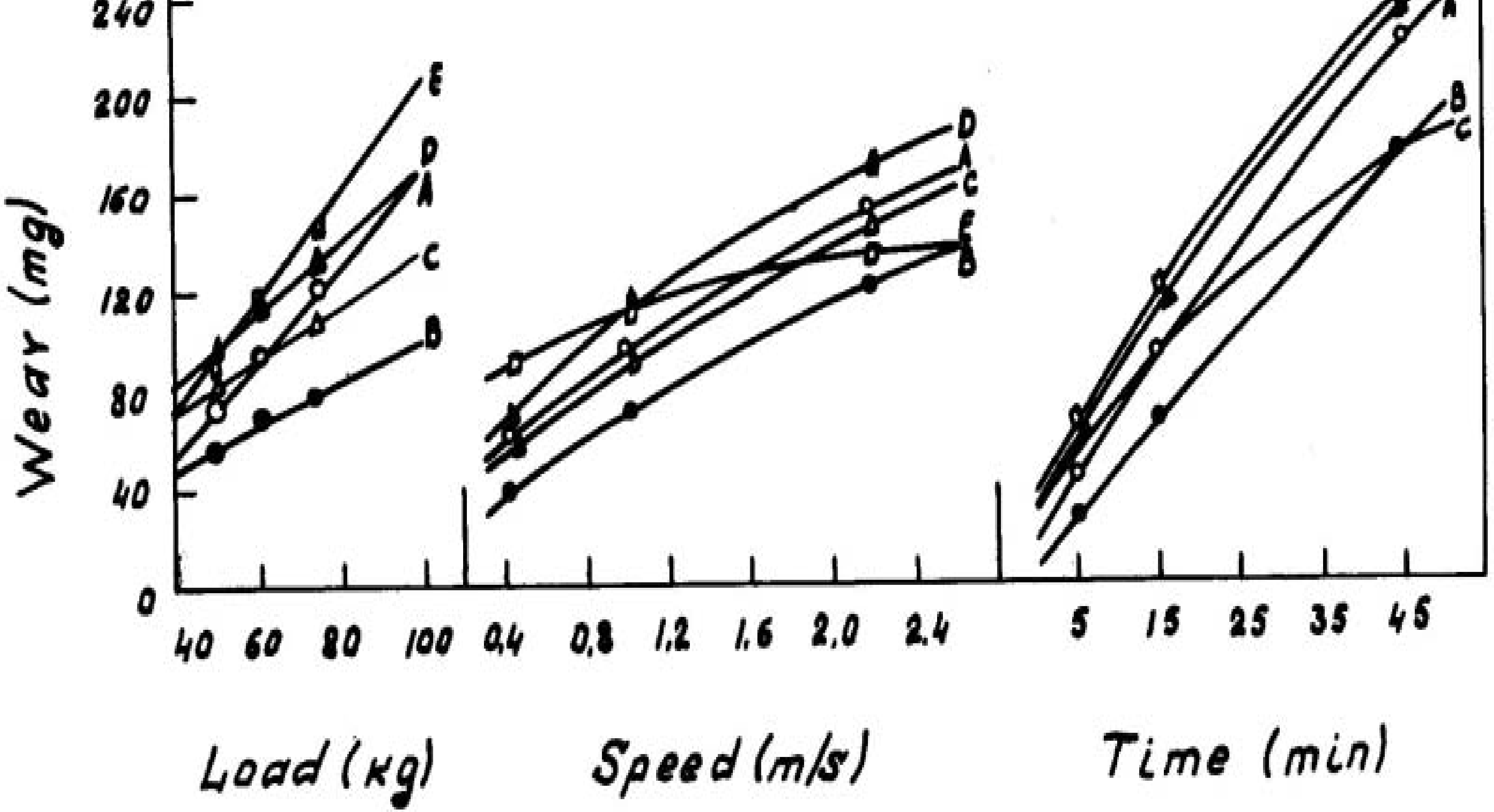
Machines vary in size from laboratory-scale to full-size units. FMVSS (Federal Motor Vehicle Safety Standard) tests for brake materials require the use of full-size inertial dynamometer)

Variation of Wear

- Inertial laboratory friction machine
- Variables: load, sliding speed, time, and counterface roughness
- Mating surface of Steel
- Sliding velocity 0.44 – 2.2 m/s, Load 61.2 kg on a surface area of 280 mm^2.

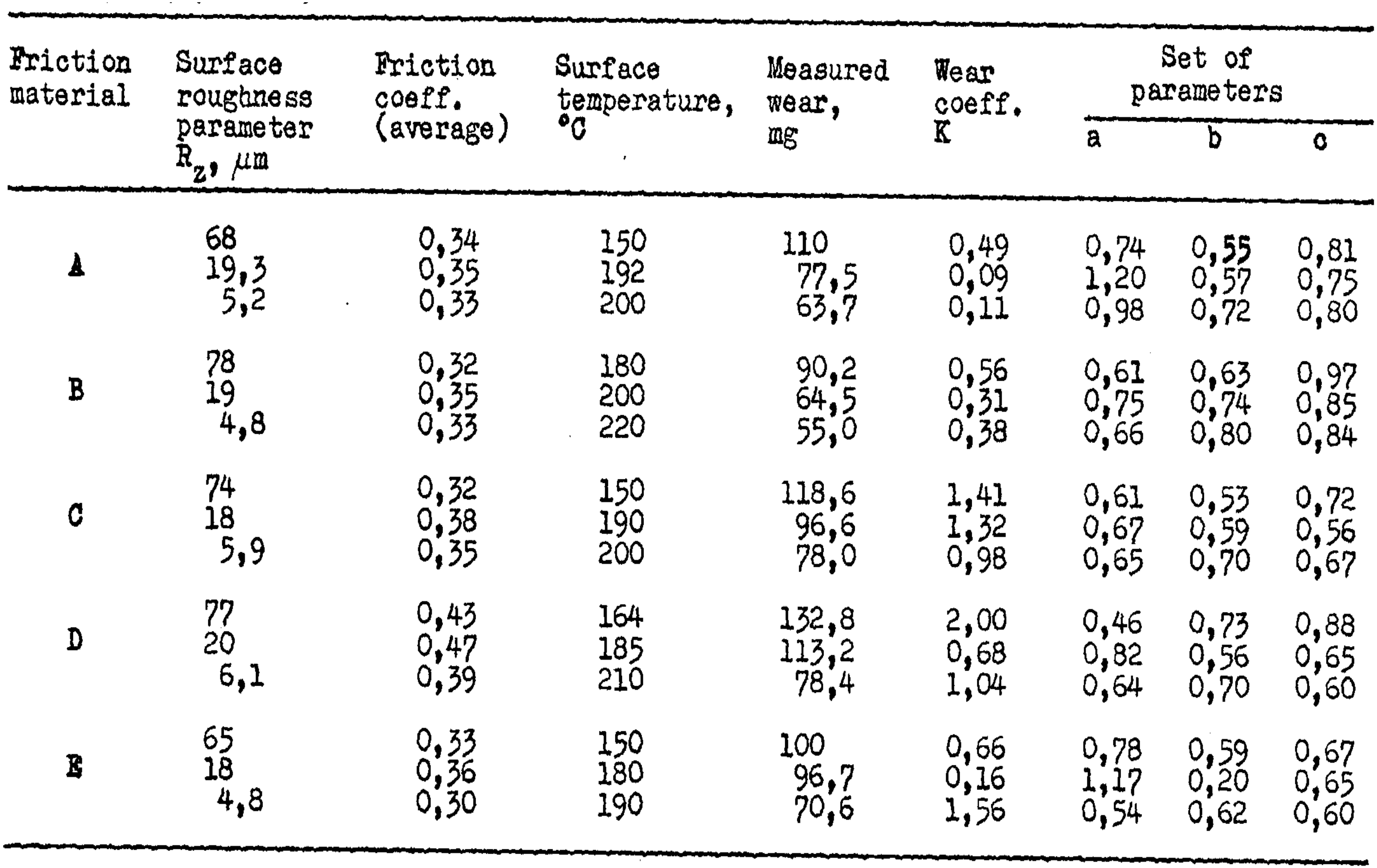
Materials A, B, C, D and E: asbestos-reinforced fiction materials Composition wt.%, bond material 15.00 – 27.71, fillers 69.55 – 81.77, accelerators 0.18 - 1.74, and vulcanizers 0.66 – 6.40.

Pogosian and Lambarian, Wear of Materials 1977, 547-551, ASME, NY.



Wear of asbestos-reinforced friction materials as a function of normal load, sliding speed, and time. 61.2 kg, 1.02 m/s, 15 min.

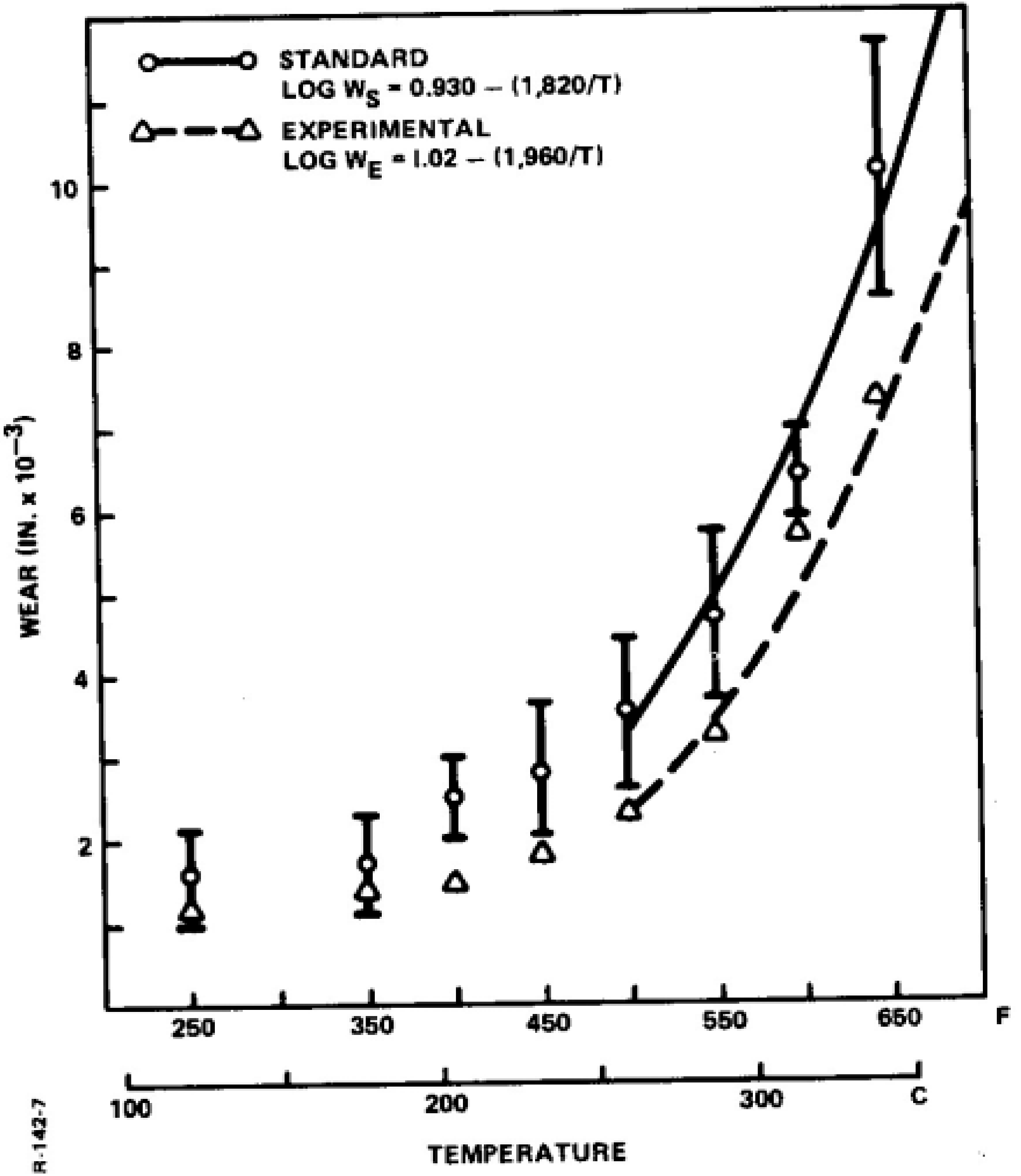
Wear and friction of asbestos-reinforced friction materials sliding against steel: load 61.2 kg, speed 1.02 m/s, time 15 min.



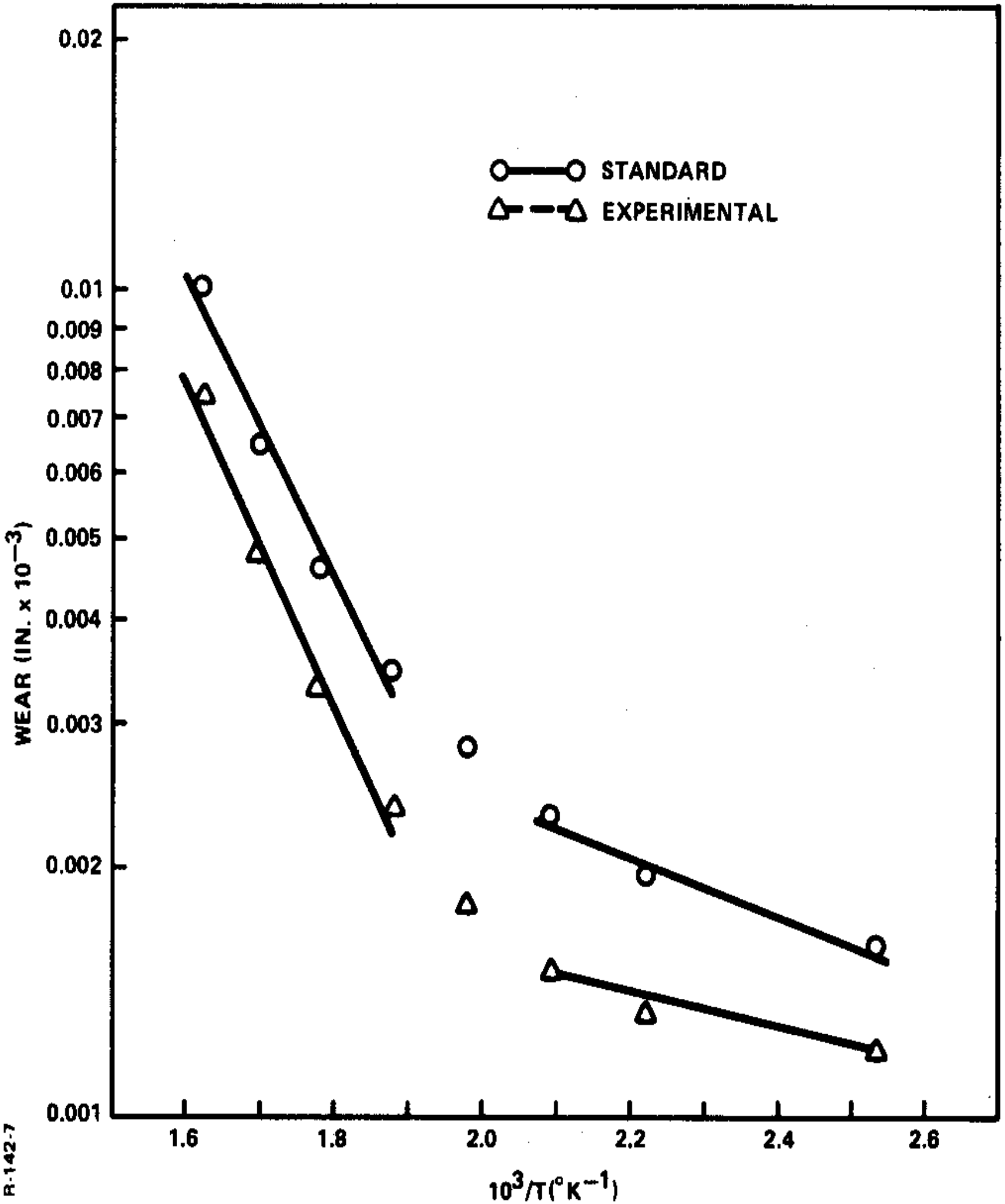
Friction material	Surface roughness parameter R_z, μm	Friction coeff. (average)	Surface temperature, °C	Measured wear, mg	Wear coeff. K	Set of parameters		
						a	b	c
A	68	0,34	150	110	0,49	0,74	0,55	0,81
	19,3	0,35	192	77,5	0,09	1,20	0,57	0,75
	5,2	0,33	200	63,7	0,11	0,98	0,72	0,80
B	78	0,32	180	90,2	0,56	0,61	0,63	0,97
	19	0,35	200	64,5	0,31	0,75	0,74	0,85
	4,8	0,33	220	55,0	0,38	0,66	0,80	0,84
C	74	0,32	150	118,6	1,41	0,61	0,53	0,72
	18	0,38	190	96,6	1,32	0,67	0,59	0,56
	5,9	0,35	200	78,0	0,98	0,65	0,70	0,67
D	77	0,43	164	132,8	2,00	0,46	0,73	0,88
	20	0,47	185	113,2	0,68	0,82	0,56	0,65
	6,1	0,39	210	78,4	1,04	0,64	0,70	0,60
E	65	0,33	150	100	0,66	0,78	0,59	0,67
	18	0,36	180	96,7	0,16	1,17	0,20	0,65
	4,8	0,30	190	70,6	1,56	0,54	0,62	0,60

Wear as a function of temperature for standard material (vol.%: phenolic binder 15, asbestos fiber 37.5, organic modifier and cashew 36.5, inorganic modifier 11) and experimental material (potassium titanate + asbestos fibers). Cast iron drum, sliding speed 7.6 m/s, load adjusted for a constant torque of 4.0 kgf-m.

L. Halberstadt, J. A. Mansfield and S. K. Rhee, Wear of Materials 1977, 560 – 568, ASME, NY



Semilog plots of wear as a function of reciprocal absolute temperature. Arrhenius plots (log W = A – B/T) gave activation energies of 6-10 kcal/mole which indicate thermal decomposition of the phenolic resin binder.

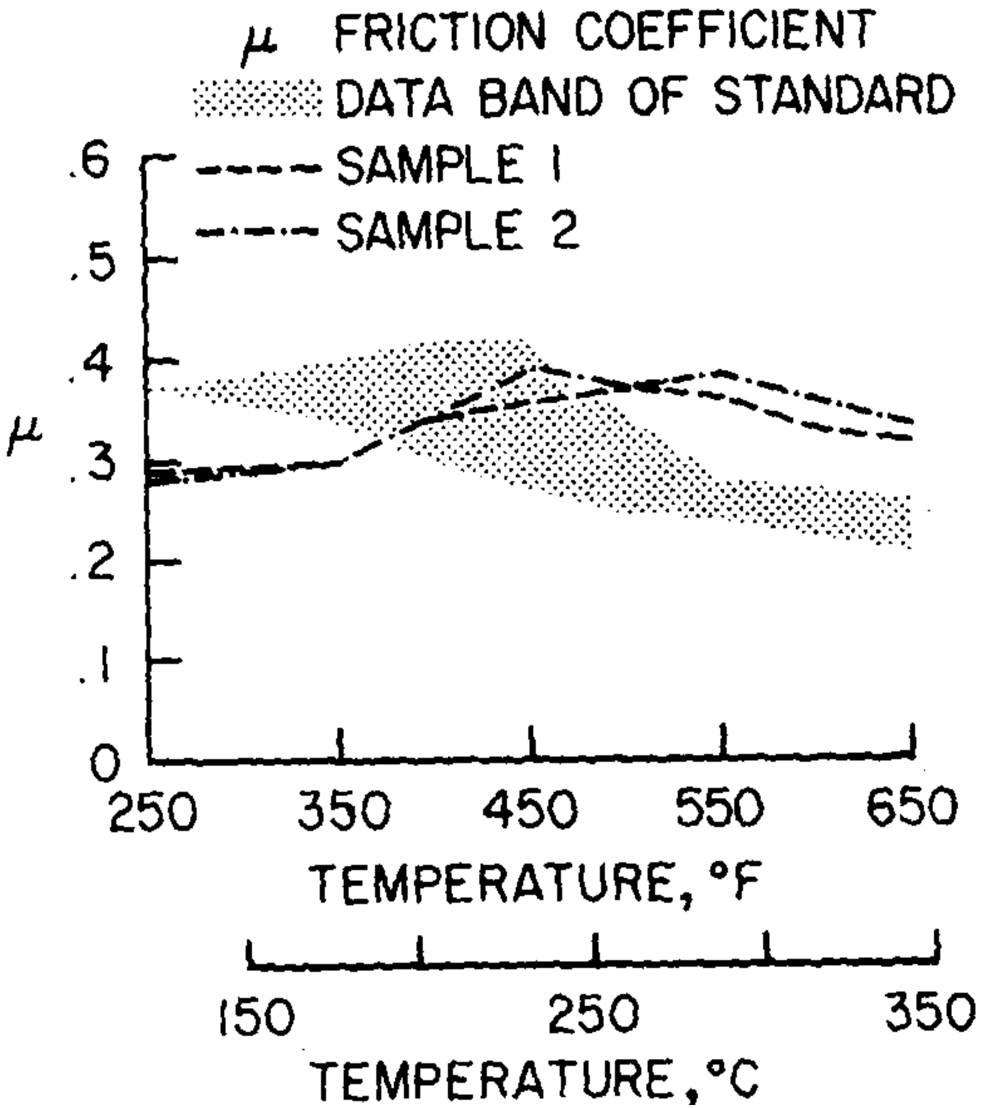


Wear mechanisms

Low temperature region – adhesive and abrasive wear, fatigue, delamination

High temperature region – thermally activated process because of the thermal degradation of phenolic resin binder which is pyrolized and oxidized and finally worn away as gases or other degradation products.

Oxidation was not the controlling mechanism because the activation energy is much lower than for oxidation (30 kcal/mole).



Coefficient of friction as a function of temperature for standard and experimental materials. Note potassium titanate promotes higher friction at high temperatures.

Glass and Carbon Short-Fiber Reinforced Friction Materials

Material Composition:

CFRFM: by Vol.%, Carbon Fiber 34.5, Steel fiber 2.3, cashew-modified phenolic resin 34.0, phenolic particles 21.67, $BaSO_4$ 7.6

CGRFM – material reinforced with glass fibers

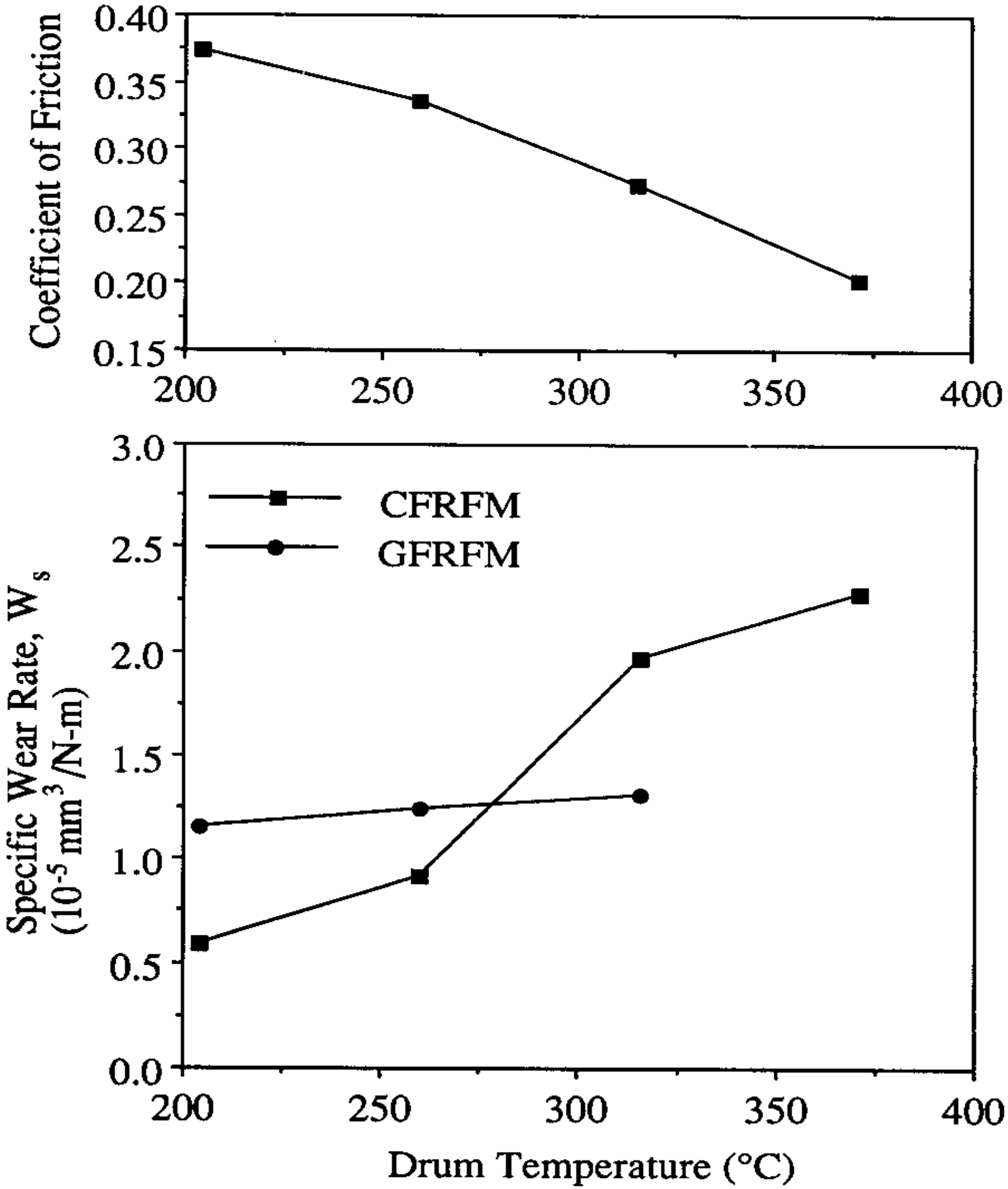
Chase machine with cast iron drum 280 mm diameter rotating at 800 rpm

Thermal damage and pitting observed at high temperatures: fiber thinning and pullout at low speeds and temperatures

Fade and Recovery phenomena

Gopal et al., Wear 181-183, (1995) 913-921.

Effect of temperature on specific wear rate and friction at P=669 N, V = 5.8 m/s



Synergistic Effects of Aramid Pulp and Potassium Titanate Whiskers

Friction material composition Vol.% : Phenolic resin 20, Barite 45, MoS_2 5, Aramid pulp and potassium titanate used in different proportions

Materials designated as AP-0, AP-0.25, AP-0.75, etc. (the number indicates the vol.% ratio of aramid in the total of aramid and potassium titanate)

Pad and disk type of test used

Kim et al., Wear, 2001, Vol. 251, pp. 1484 – 1491

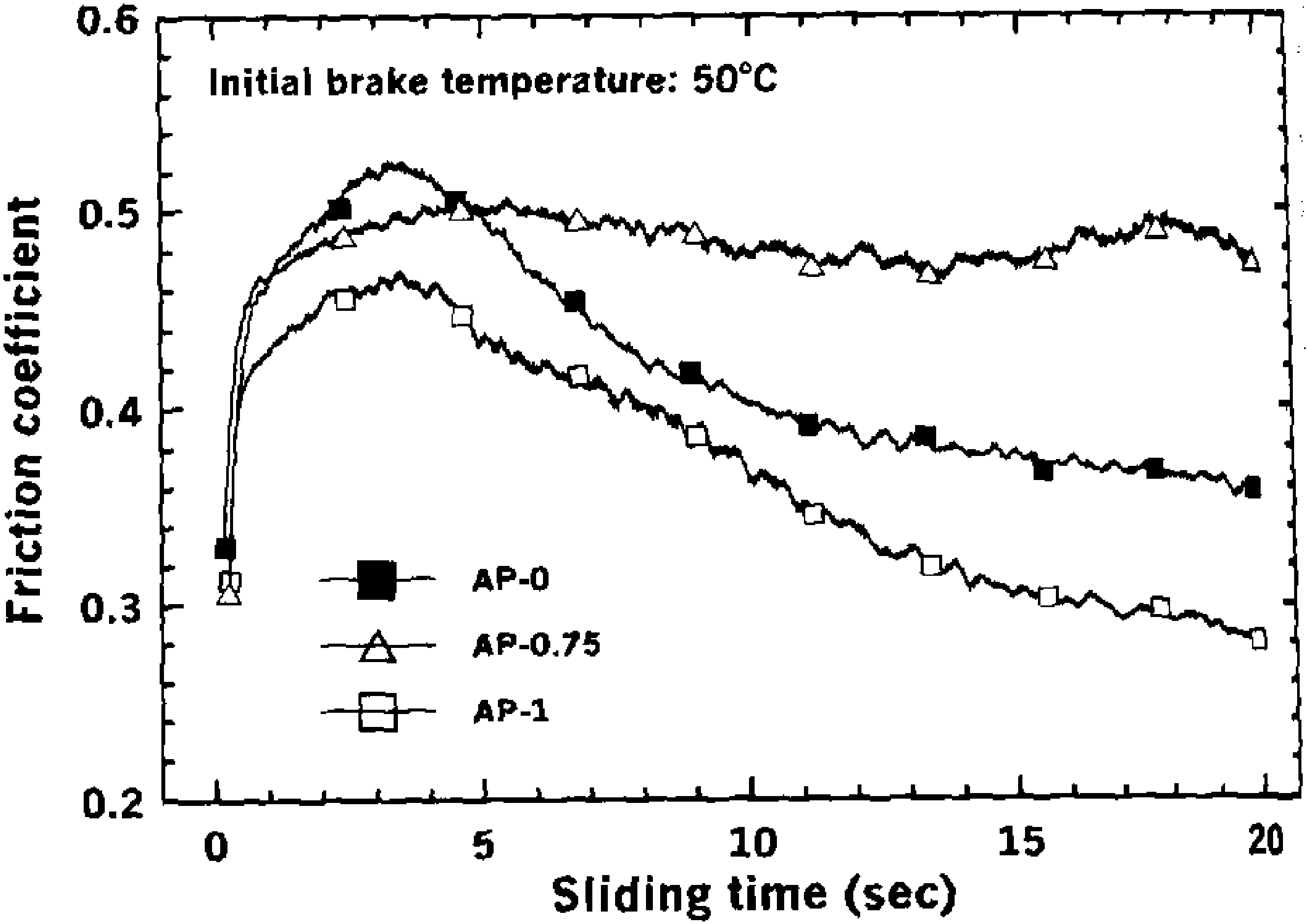
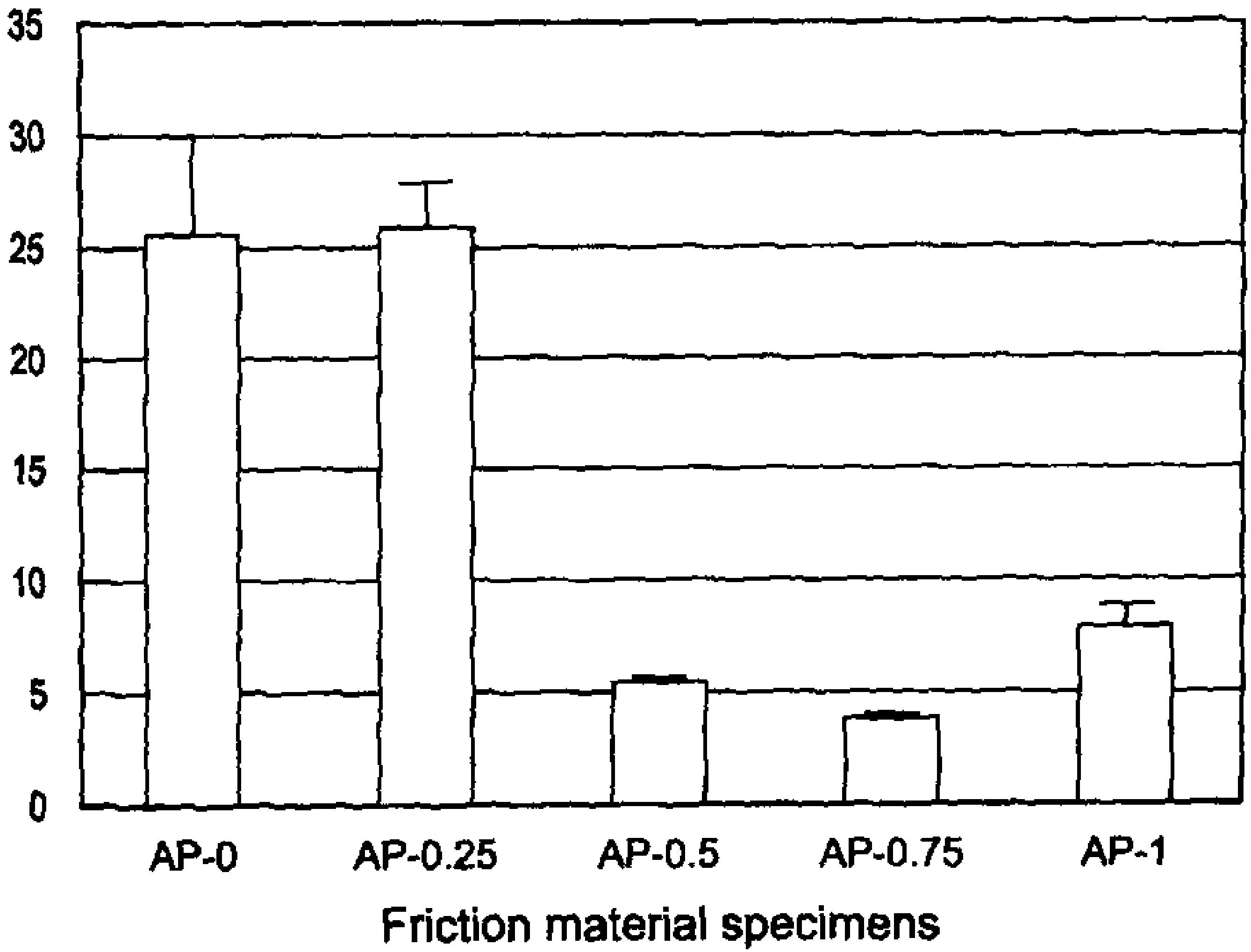


Fig. 3. The change of friction coefficient as a function of sliding tim for friction materials AP-0, AP-0.75, and AP-1 (speed: 4 m/s, pressure 1 MPa).



Specific wear rate (x10^{-5} mm^3/Nm) of friction materials. Sliding conditions: 5 m/s, 1.4 MPa, 100° C, 2.5 km distance.

Comparison of Aluminum-Matrix Composites with Cast Iron

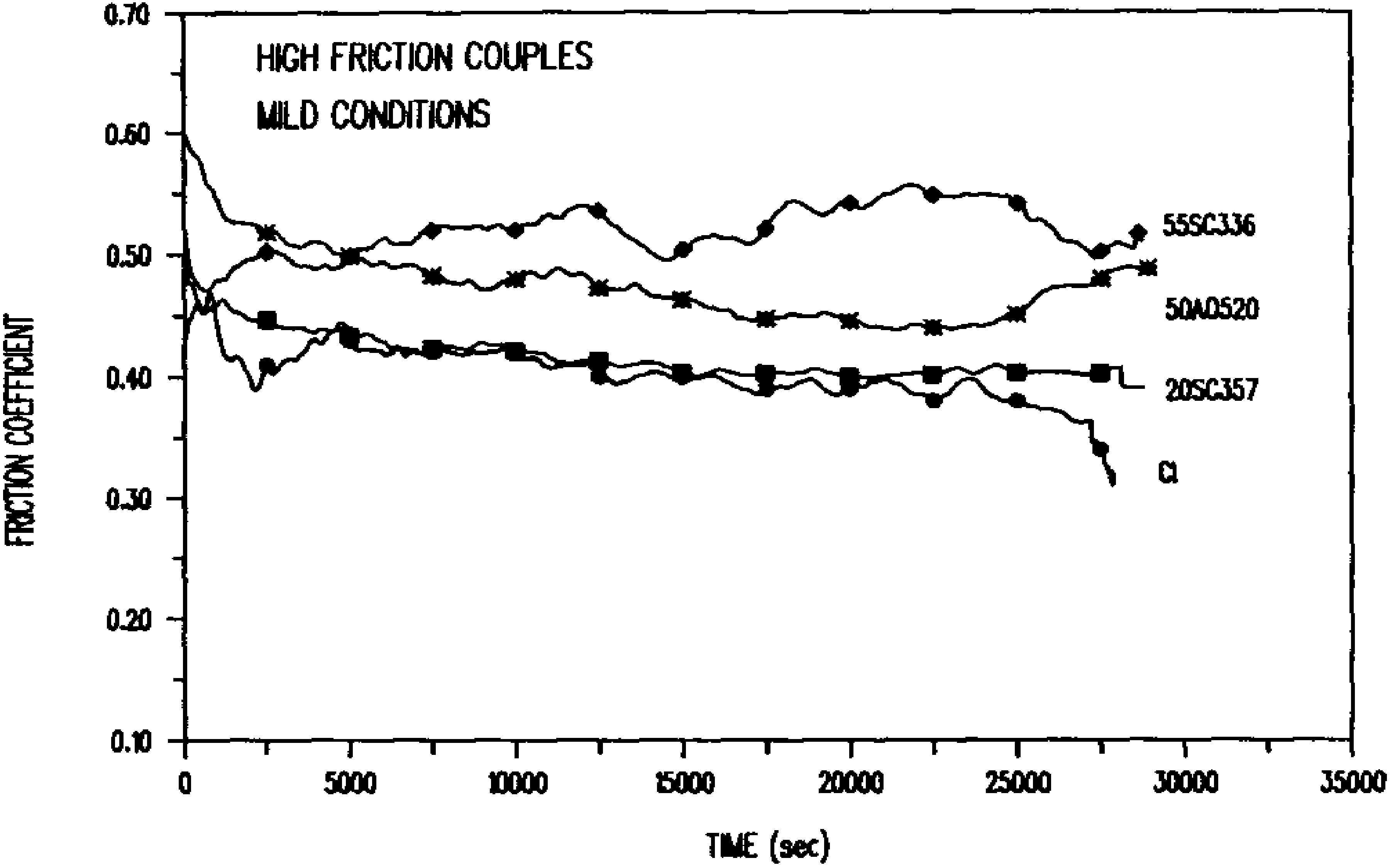
Block-on-ring test: Mild -1.5 m/s, 0.4 MPa, Severe - 1.5 m/s, 1.3 MPa

Ring materials – particulate reinforced aluminum composites

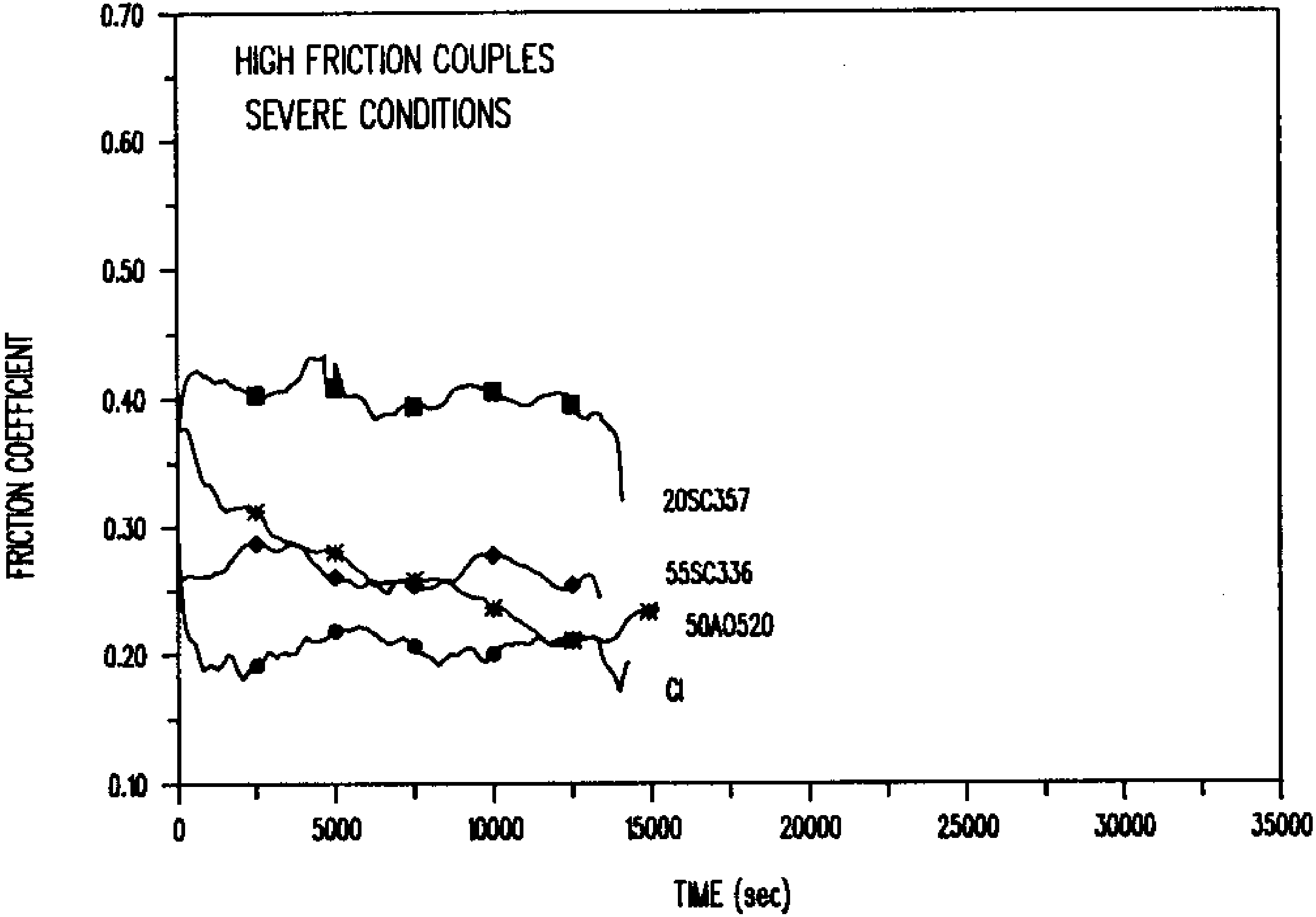
20% SiC-357Al (20SC357)
60% SiC-336Al (55SC336)
50% Al_2O_3-520Al (50AO520)
Pearlitic gray cast iron

Block material: friction material with non-asbestos reinforcement, friction modifiers, phenolic binder (NAO)

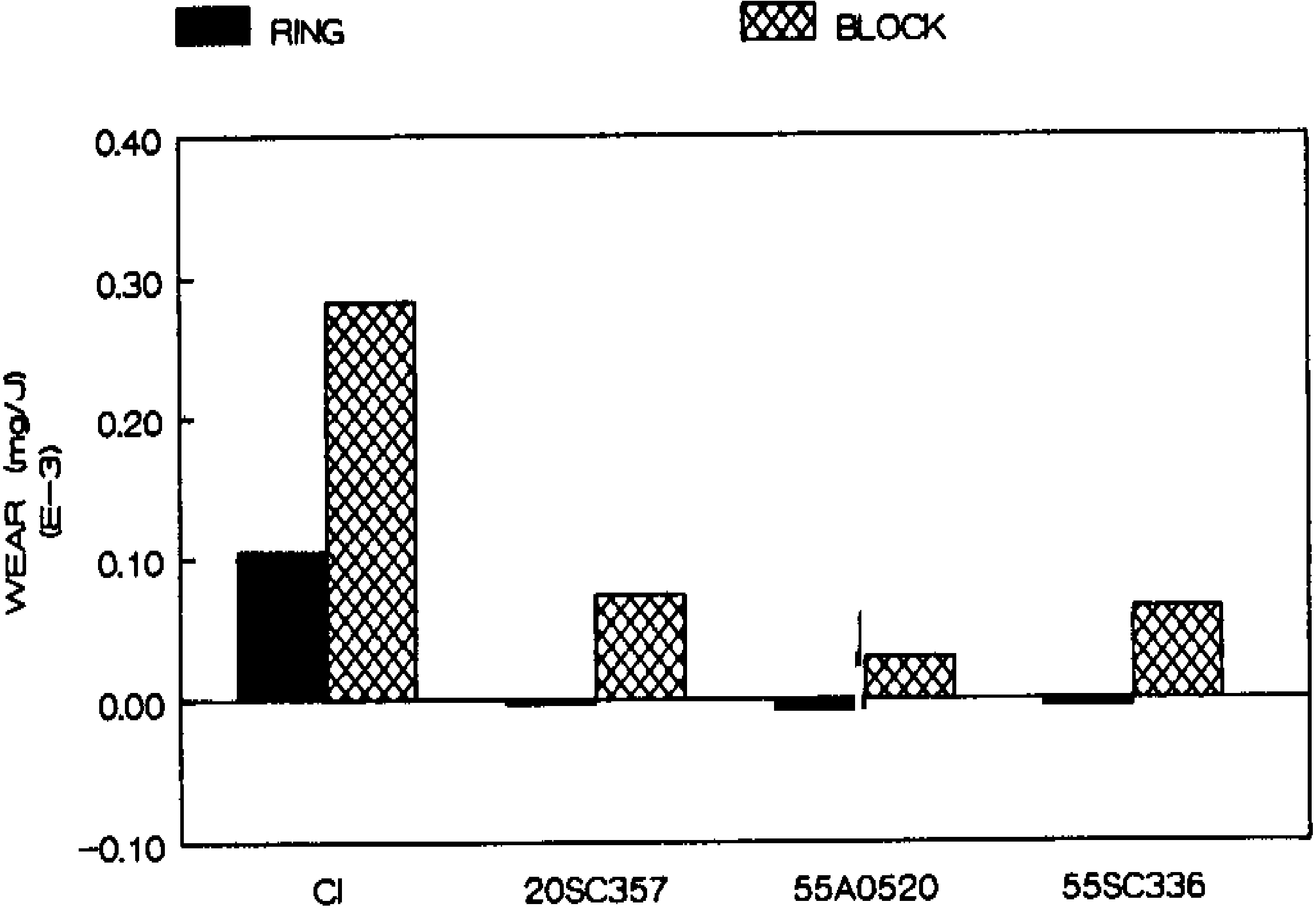
Shaw et al., Wear of Materials, ASME 1991, pp. 167-175.



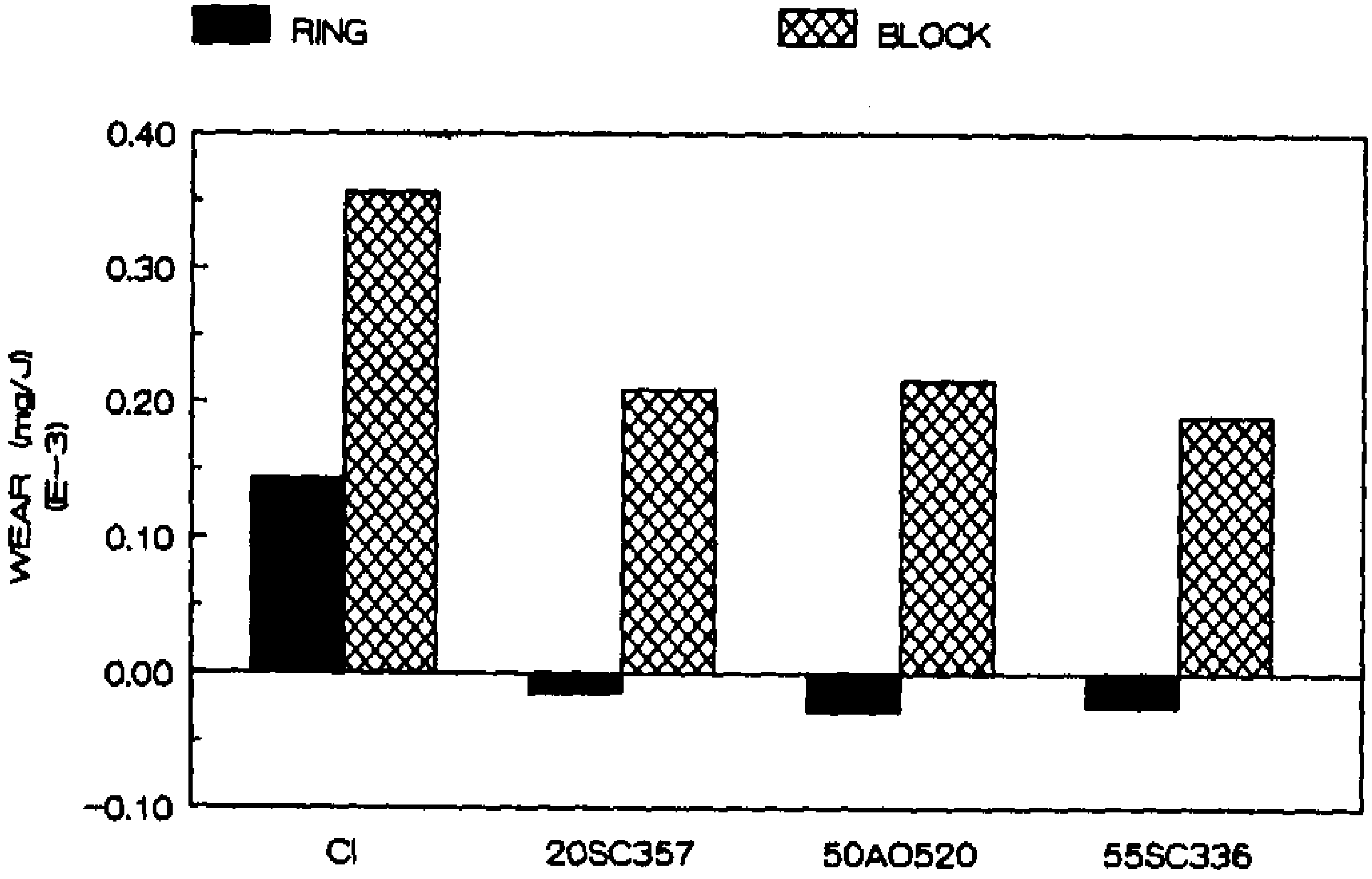
Friction coefficient as a function of time for NAO friction material sliding against Al-composite ring under mild conditions.



Friction coefficient as a function of time for NAO friction material sliding against Al-composite ring under severe conditions.



Wear normalized by energy for NAO friction material sliding against Al composite ring under mild conditions.



Wear normalized by energy expended for NAO friction material sliding against Al composite ring under severe conditions.

Transfer Film Studies

Friction material: % by volume

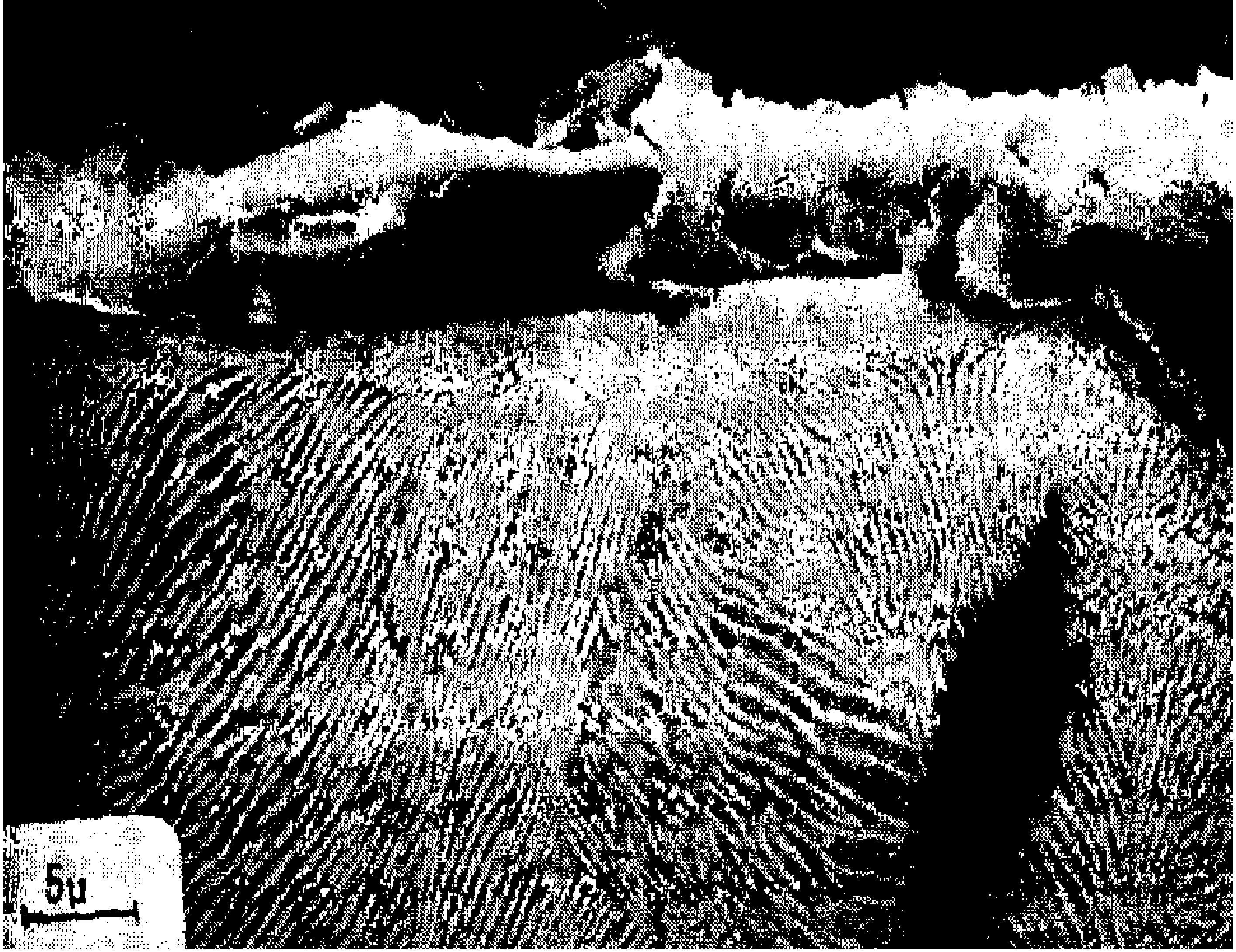
Asbestos 53.3%, organic friction modifier 21.2%, inorganic friction modifier 0.5%, phenolic resin 25%

Cast iron drum finished to 1.5μ rms, rubbing surface diameter 280 mm

Running conditions: 90 kg load, 300 rpm, 150° C temperature, rubbing surface area 25 mm x 25 mm

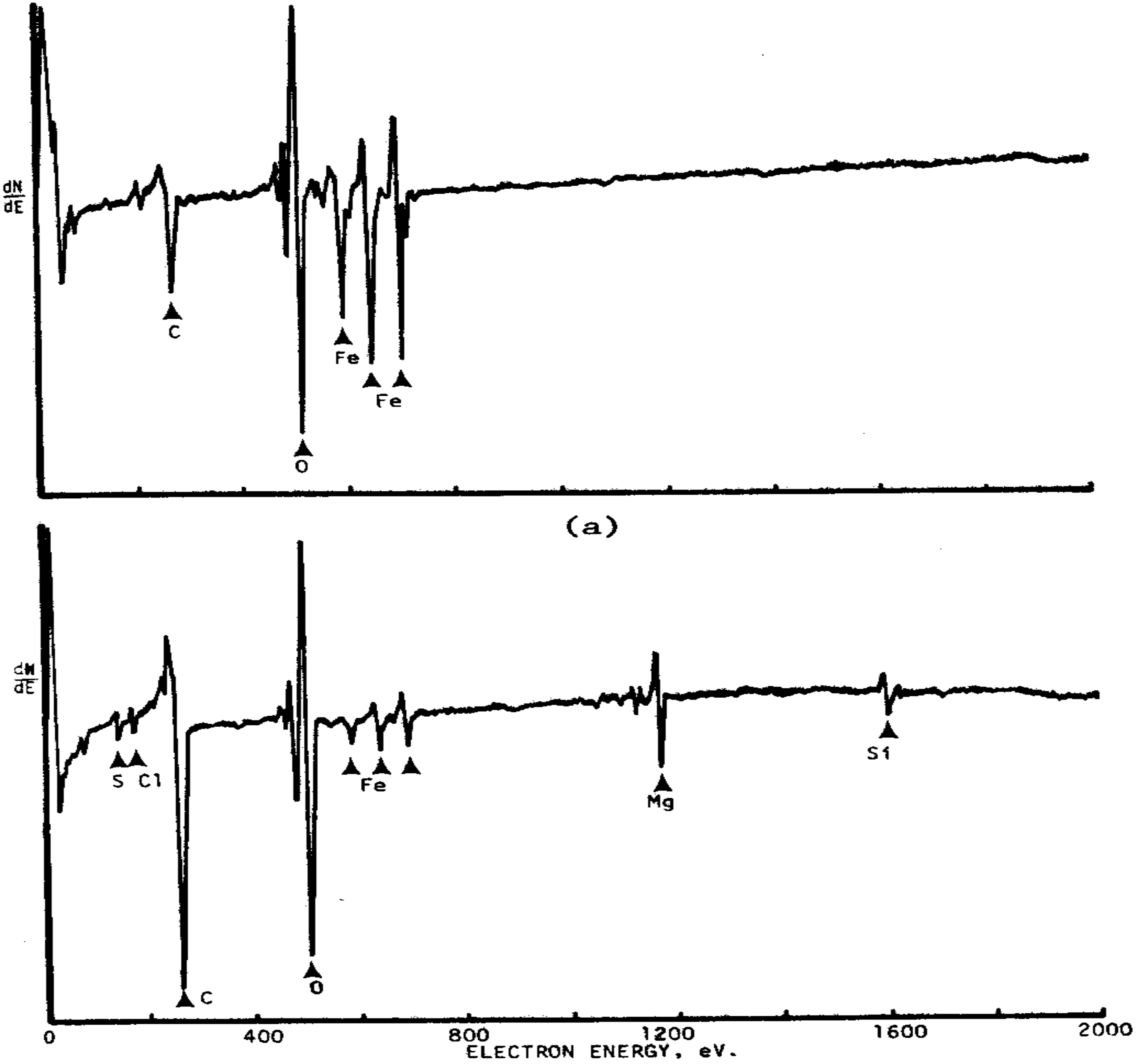
Chase machine, two 20 min break-in periods followed by two 10-min low temperature periods and two 10-min high temperature periods

Liu et al., Wear of Materials, 1979, pp. 595-600.



SEM micrograph of the cross-section of cast iron drum. It shows transfer film and deformed cementite platelets in the cast iron subsurface structure.

Scanning Auger Microscopy results. Upper diagram for non-friction location and lower diagram for transfer film. Elements in lower diagram indicate higher C, lower Fe, and the presence of Mg, Si, S and Cl from friction **material.**



Concluding Remarks

The friction and wear behaviors of brake materials are very complex because of variable speeds and loads, dissipation of energy and temperature rise.

Fade and recovery phenomena make friction variable.

There are too many constituents in the friction materials to make their behavior predictable.

The coefficient of friction decreases with the increase in temperature – fade.

The wear mechanisms relevant to friction materials are fatigue, delamination, abrasion, degradation, fiber thinning, fiber pull-out, etc.

Wear increases with the increase in temperature.

Transfer film of friction material is formed on the metallic surface. It helps to stabilize friction and reduces wear.