FRICTION AND WEAR AT SLIDING CERAMIC SURFACES

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CONTENT

INTRODUCTION

1. Ceramics as Engineering Materials

Ceramic ?

: 'material based on inorganic non-metallic compounds'

Oxygen, Carbon, Nitrogen with metal (Al, Si)

- cheap, plentiful and widespread element in the Earth

- dirt: ceramic

*** The Generic Ceramics**

GLASSES

GLASS	COMPOSITION	TYPICAL USES
Soda-lime glass	70 SiO_2,10 CaO,15Na_2O	Windows, Bottles
Borosilicate Glass	80SiO_2,15B_2O_3,5Na_2O	Pyrex; cooking and chemical glassware

Vitreous Ceramics

Ceramic	Typical Composition	Typical Uses
Porcelain	Clays	Electric insulator
China	(hydrous alumina-silicates)	Artware and
Pottery	$Al_2(SiO_5)(OH)_4$	Table ware, tiles
Brick		Construction, refractory uses

Forming - Dry - Firing

Characteristics: hard, long-life, light,
high service temperature

Weak at dynamic thermal and mechanical stress

Natural Ceramics

Ceramic	Typical Composition	Typical Uses
Lime stone (Marble)	Largely $CaCO_3$	
Sand stone	Largely SiO_2	Construction
Granite	Aluminium Silicates	
Ice	H_2O	Arctic Engineering: Off-shore Plant

durable: Pyramids 5000 ; Parthenon 2200 years old

high load-bearing capacity

TROUBLE: Inherent Brittleness

Cement and Concrete

Cement: mixture of a combination of lime (CaO), silica (SiO_2) and alumina (Al_2O_3) + water

Concrete: sand + stones + cement

High-performance Engineering Ceramics

Ceramic	Compositions	Typical Uses
Diamond	C	
Dense alumina	Al_2O_3	cutting tools, dies
Silicon Nitride	Si_3N_4	wear-resistant surfaces,
Silicon Carbide	SiC	bearings, medical implants,
Sialons	Si_2AlON_3	engine and turbine part,
Zirconia	ZrO_2	armours

Strength of a ceramic: hardness, toughness, surface/subsurface flaw size

APPLICATIONS

1. Ceramic Engine (PSZ, Silicon-Nitride, Alumina, SiC)

Target: increasing thermal efficiency of engine

- increase T_H (without water cooling)
- re-cycle T_L (using Turbocharger, turbocompound)

Requirement:

- good friction and wear resistance
- good thermal insulation
- durability
- economical

Limitations:

- low toughness (require $K_{1C} > 8.5$ MPa $m^{1/2}$)
- thermal expansion mismatch
- lubrication (gas lubrication?, new lubricant ?)

Example:

- Adiabatic Turbocompound Diesel Engine
  by CUMMINS ENGINES CO.

2. **Turbine Wheel (SiC, Silicon Nitride, Silica)**

requirements:

- good mechanical strength
- good chemical stability (anti-corrosion, anti-oxidation)
- low coefficient of thermal expansion
- light weight

Limitation:

- weak at erosion wear
- difficult to manufacture (HIP ?)

3. **Machining Tools (Alumina, WC, TiC, TiN, Si_3N_4, Diamond)**

- good mechanical strength
- good chemical stability

4. **Thermal Insulation (SiO_2 tile, Reinforced Carbon-Carbon)**

5. **Application to Bio-mechanical materials (Artificial bone, joint, tooth)**

6. **Application to Electrical Insulator (porcelains)**

7. **Application to Chemical components (Borosilicate glass)**

8. **Application to Magnetic materials (Ferrite; MO Fe_2O_3)**

9. **Application to Sensors (TiO_2, ZnO, Fe_2O_3, SnO, etc.)**

Requirements for Engineering Ceramics

- good mechanical strength: high hardness
  low density
  high toughness
  anti-wear and friction

- good dimensional stability: low thermal expansion

- good thermal properties and chemical stability

Major problems in using ceramic

- inherent brittleness under tensile stress,
  impact load,
  thermal shock

- high coefficient of friction at dry sliding

New Aspects of Using Ceramic Machine Element

- from static contact to dynamic sliding/rolling contact

- application to high sliding velocity under dry contact

2. BASIC APPROACH TO THE SUBJECT

(1) Modelling of Surface Temperature due to Frictional Heating at Dry Sliding Contacts:

- Heat Flow Analysis under various contact geometry
- Modelling of Mechanical Contact Behaviour

  : at real asperity contact junction
  (contact area, number, interaction)
  'Flash Temperature'

  : at nominal contact area
  'Bulk Temperature'

- Modelling of Friction Coefficient

(2) Construction of Temperature Map (T-MAP 004)

(3) Experimental Measurement and Comparison Study

- direct temperature measurement
- experimental data from open literatures
  (thermocouples, Infra-red techniques)

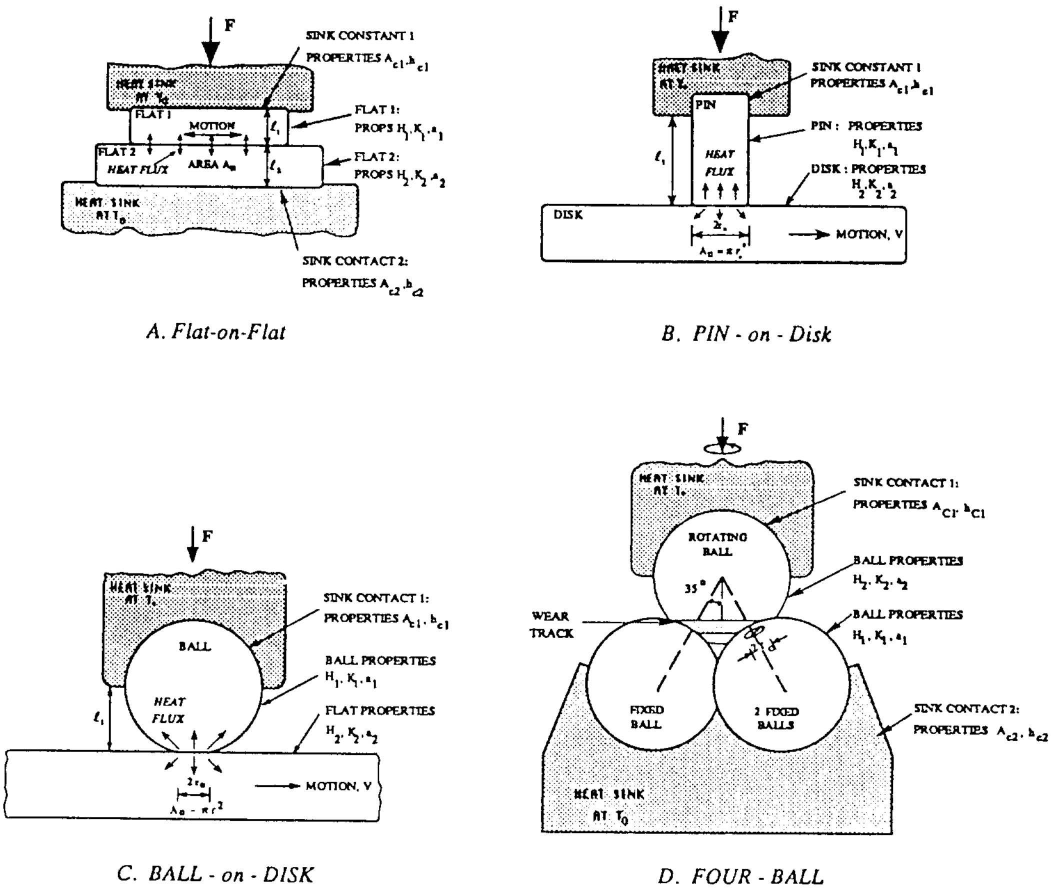
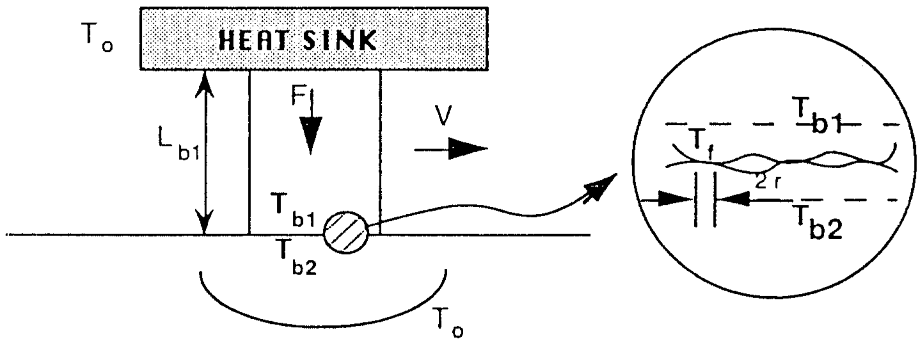


Figure 4.1. The Four Configurations for which the Temperatures Calculation are performed.

5. Pin-on-Disk Sliding Contact.



$$k_1\left(\frac{T_{b1}-T_0}{L_{b1}}\right)+k_2\left(\frac{T_{b2}-T_0}{L_{b2}}\right)=\frac{\mu F V}{A_n}$$

$$\therefore \quad T_b = T_o + \frac{\mu F V}{A_n}\left(\frac{1}{\dfrac{K_1}{L_{b1}}+\dfrac{K_2\sqrt{\pi}}{r_o \tan^{-1}\left(\dfrac{2\pi a_2}{r_o V}\right)}}\right)$$

Friction Coefficient μ

μ = f(F, V, roughness, contamination, etc.)

abrasive + plowing + adhesive + etc.....

using a semi-empirical relationship, let's assume;

$\mu = \mu_o$ (V < Vc : Velocity for asperity melting)

$$\mu = \mu_o \exp - \left\{ \frac{\log \frac{V}{V_c}}{\log C_1} \left(1 - C_2 \log \tilde{F}\right) \right\}$$

for steel $C_1 = 250$, $C_2 = 0.33$ using a least square fit

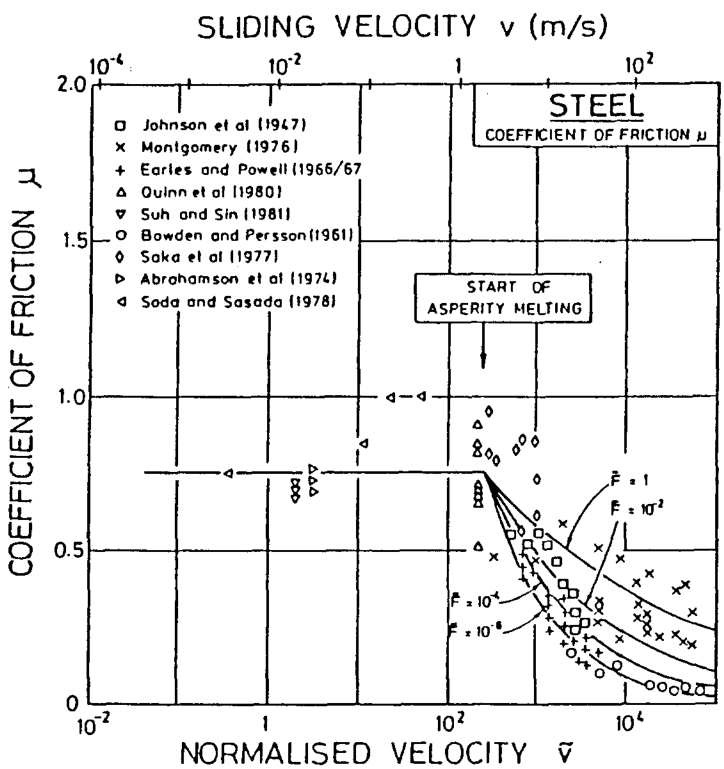
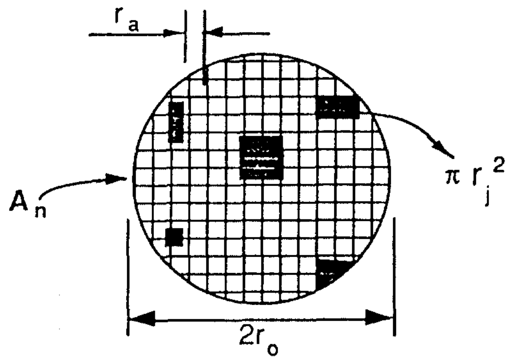


Figure 2. The equation for the coefficient of friction (equation 11) valuated for μ_o = 0.75, C_1 = 500 and C_2 = 0.3, compared with experimental data. Asperity melting starts at v_o = 2 m/s.

Asperity Junction Radius, $r_j = f(F,\mu)$



Asperity Contact in a nominal contact area

$$dN_j = \left(1-\eta\frac{N}{N_t}\right)dN = \left(\frac{r_o}{r_a}\right)^2\left(1-\eta\frac{A_r}{A_n}\right)d\left(\frac{A_r}{A_n}\right)$$

$$N_j = \left(\frac{r_o}{r_a}\right)^2\frac{\tilde{F}}{\tilde{F}_s}\left(1-\frac{\tilde{F}}{\tilde{F}_s}\right)+\frac{\tilde{F}}{\tilde{F}_s}$$

by M.F.Ashby and his colleges

$\pi r r_j^2 N_j = A_r$ *and* $\frac{A_r}{A_n} = \frac{F}{F_s}$ *for ideal plastic contacts*

$$\frac{r_j}{r_o} = \left[\frac{1}{\left(\frac{r_o}{r_a}\right)^2\left(1-\frac{F}{F_s}\right)+1}\right]^{1/2}$$

where r_a : radius of a single isolated asperity

r_j : radius of a contact junction ($r_a < r_j < r_o$)

r_o : radius of a nominal contact area

TABLE 4.1 : BULK SURFACE TEMPERATURE EQUATIONS

$$T_b - T_o = \frac{\mu F v}{A_n}\left[\frac{1}{\frac{k_1}{\ell_{1b}} + \frac{k_2}{\ell_{2b}}}\right]$$

Configuration 1 : Flat on Flat

$$\ell_{1b} = \ell_1 + \frac{A_n k_1}{A_{c1} h_{c1}} = L_1 r_o$$

$$\ell_{2b} = \ell_2 + \frac{A_n k_2}{A_{c2} h_{c2}} = L_2 r_o$$

Configuration 2 : Pin on Disk

$$\ell_{1b} = \ell_1 + \frac{A_n k_1}{A_{c1} h_{c1}} = L_1 r_o$$

$$\ell_{2b} = \frac{r_o}{\sqrt{\pi}} \tan^{-1}\left[\frac{0.9\pi a_2}{r_o v}\right]^{1/2} = L_2 r_o$$

Configuration 3 : Ball on Flat

$$\ell_{1b} = \frac{\pi^{1/2} r_o}{2} + \frac{A_n k_1}{A_{c1} h_{c1}} = L_1 r_o$$

$$\ell_{2b} = \frac{r_o}{\sqrt{\pi}} \tan^{-1}\left[\frac{0.9\pi a_2}{r_o v}\right]^{1/2} = L_2 r_o$$

Configuration 4 : Four Balls

$$\ell_{1b} = \frac{r_o}{\sqrt{\pi}} \tan^{-1}\left[\frac{0.9\pi a_2}{r_o v}\right]^{1/2} + \frac{3 r_o^2}{R} = L_1 r_o$$

$$\ell_{2b} = \frac{\pi^{1/2} r_o}{2} = L_2 r_o$$

TABLE 4.2 : FLASH SURFACE TEMPERATURE EQUATIONS

$$T_f - T_b' = \frac{\mu F v}{A_r}\left[\frac{1}{\frac{k_1}{\ell_{1f}} + \frac{k_2}{\ell_{2f}}}\right]$$

For all configurations

$$T_b' = T_b - \frac{A_r}{A_n}\left(T_b - T_o\right)$$

$$\frac{A_r}{A_n} = \frac{F}{F_s}$$

$$\ell_{1f} = \frac{r_j}{\sqrt{\pi}}\tan^{-1}\left[\frac{0.9 n_1\, \pi a_1}{r_j v}\right]^{1/2} \left(\approx \frac{\pi^{1/2}}{2} r_j \quad \text{when v small}\right)$$

$$\ell_{2f} = \frac{r_j}{\sqrt{\pi}}\tan^{-1}\left[\frac{0.9 n_2\, \pi a_2}{r_j v}\right]^{1/2} \left(\approx \frac{\pi^{1/2}}{2} r_j \quad \text{when v small}\right)$$

with

$$r_j = r_o\left\{\left(1 - \frac{F}{F_s}\right)\left[\frac{r_o}{r_a}\right]^2 + 1\right\}^{-1/2}$$

$$F_s = \frac{A_n H_o}{\sqrt{1 + 12\mu^2}}$$

H_o = Least of (H_1, H_2)

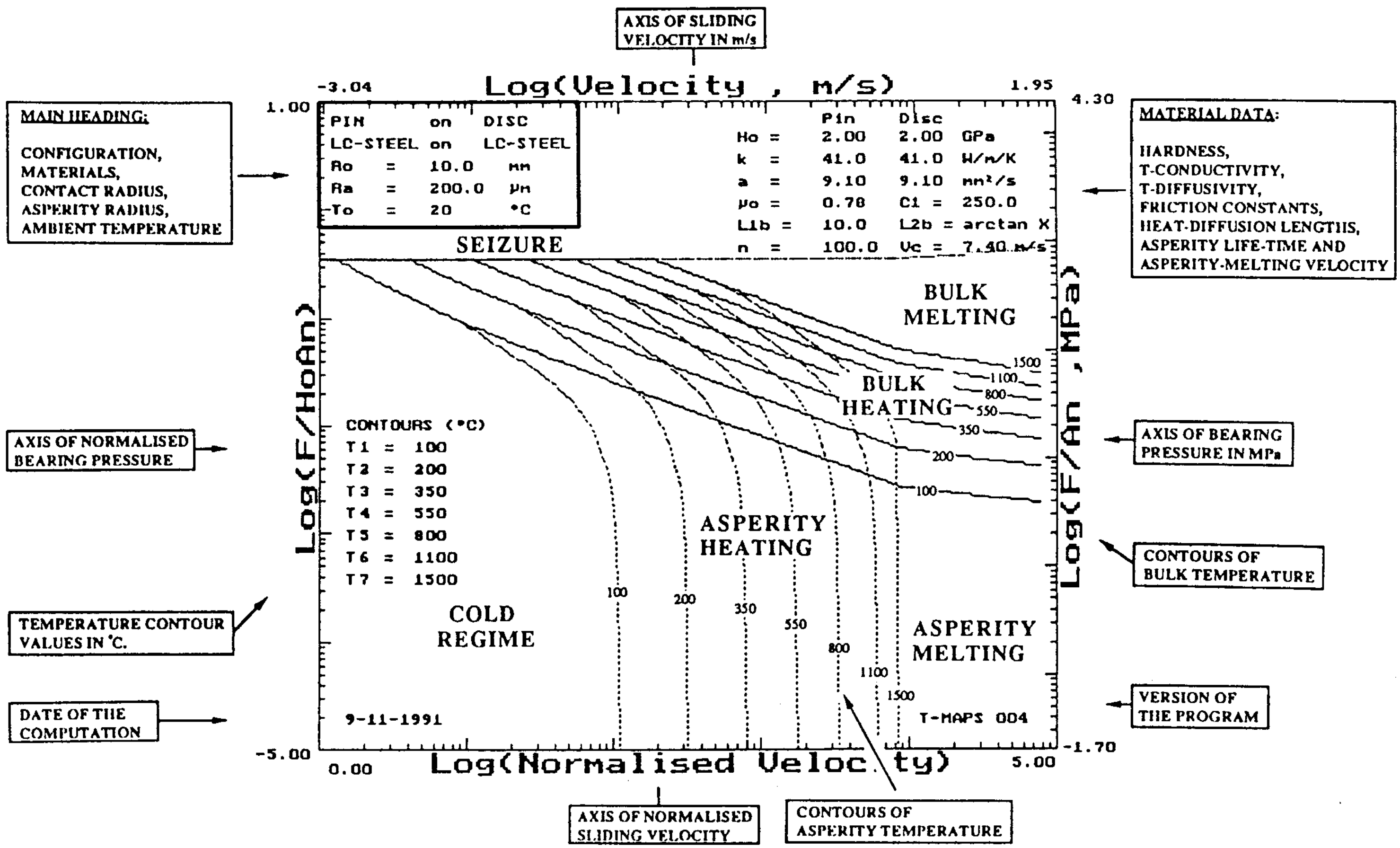


Figure 4.3. A Temperature Map for a Low-Carbon Steel Pin Sliding on a Disk of the Same Material, identifies in the Features of the Map.

3. Applications to Several Practical Friction and Wear Process

(1) **Friction Welding**

(2) **Friction Cutting**

(3) **Striking a Match**

(4) **Curling**

(5) **Head-Crash Damage to Magnetic Storage-Disks**

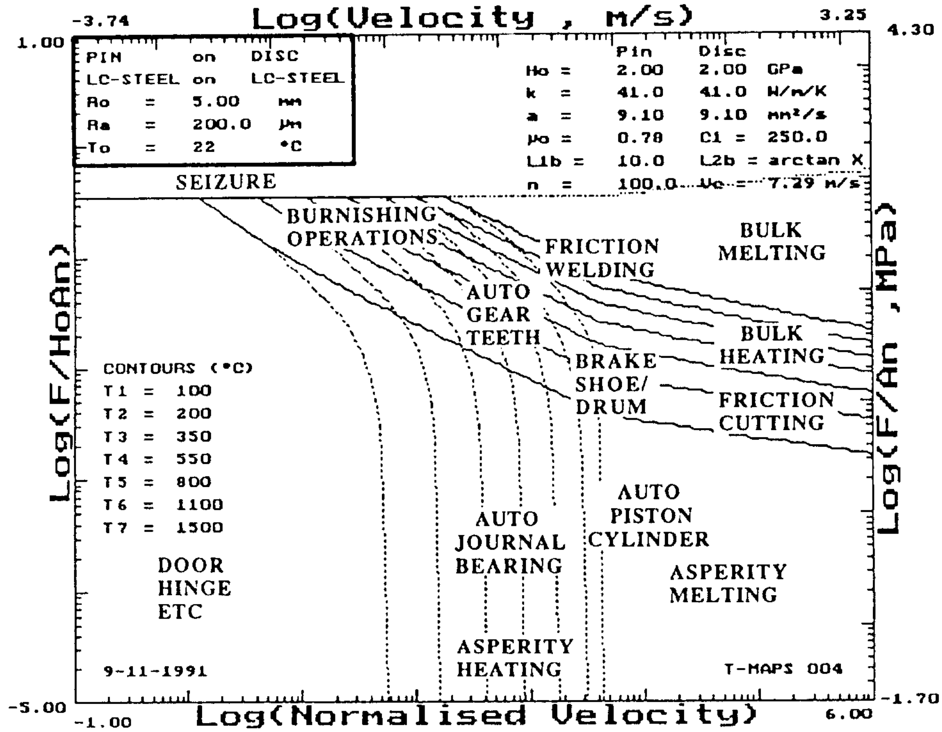


Figure 6.1. The Temperature Map with the Conditions of a Number of Applications Plotted on it.

4. Friction and Wear Tests of Brittle Solids

(Thermo-mechanical Wear)

- Test of Soda-lime Glass
- Test on Rosin
- Test of Alumina (two sorts of alumina of different grain size)

5. THEORETICAL MODELLING OF CERAMIC WEAR

- Wear by Brittle Fracture
- Wear by Thermo-mechanical Fracture
- Wear by Bulk Heating
- Wear by Bulk Melting

TARGETS:

- to specify dominant wear mechanisms under a wide ranges of operating conditions
- to describe and to qualify wear mechanism transition behaviour
- to get a prediction power to quantify wear-rate of each dominant wear regime if possible

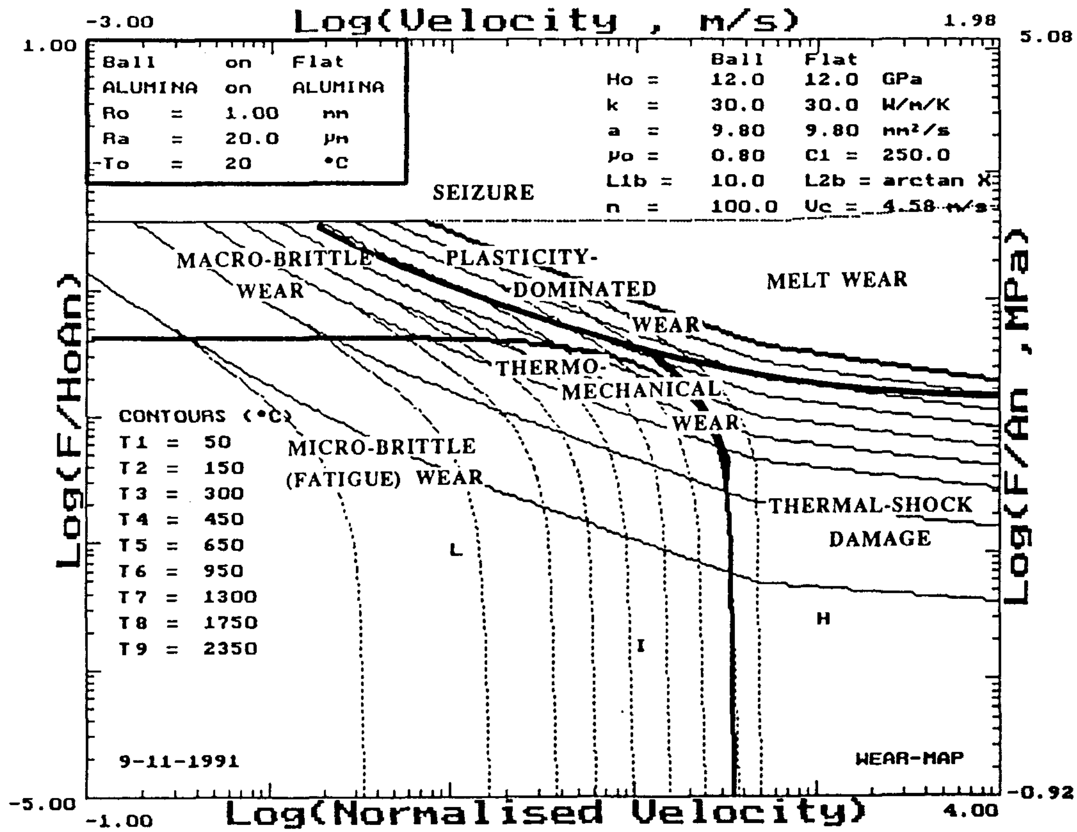


Figure 7.24. Wear mechanism map for alumina ball sliding on alumina disk (based on Figure 7.23), showing characteristic wear-transition boundaries of Macro-Brittle wear, of Micro-Brittle (Fatigue) wear, of Thermo-Mechanical wear, of Thermal-Shock damage, of Plasticity-dominated wear and of Melt wear.