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**A Program to Calculate Deformation
Mechanism Maps Using an
HP-9821A Calculator**

W. A. Coghlan

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W. A. Coghlan

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A PROGRAM TO CALCULATE DEFORMATION MECHANISM MAPS
USING AN HP-9821A CALCULATOR

W. A. Coghlan

ABSTRACT

A program has been written to calculate Deformation Mechanism Maps using a Hewlett-Packard 9821A calculator. This report describes the equations which are used to represent the strain rate resulting from the five mechanisms considered. A listing of the program is given along with a complete description of how it performs the calculations. Step-by-step instructions are also provided along with the data required to calculate two example maps.

INTRODUCTION

In 1972 Ashby¹ introduced the idea of Deformation-Mechanism Maps (DMM). The basic idea is that several different mechanisms play a role in plastic deformation of materials and different mechanisms dominate different temperature-applied stress ranges. Constant values of the total steady-state strain rate resulting from all the mechanisms can be plotted as contours on a log stress versus homologous temperature, T/T_m , where T_m is the absolute melting temperature. Regions can be outlined on the plot which describe the region in temperature and stress where each deformation mechanism dominates. Although the plots have not found acceptance as ways to plot exact deformation data, the idea has found increasing use in planning research programs for material evaluation and choice. For this reason a program was written to plot these maps on our Hewlett-Packard 9821A desk-top computer. The numerical analysis used would be applicable to many other small computers. The report

¹M. F. Ashby, *Acta Met.* 20, 887-97 (1972).

that follows describes the equations Ashby suggested for DMMs and a numerical method for constructing the maps on a small computer. In addition, two deformation maps are shown along with the input parameters used for the construction. The HP-9821A programs and instructions for their use are given in Appendixes I and II.

EQUATIONS DESCRIBING THE PLASTIC DEFORMATION MECHANISMS CONSIDERED

Ashby¹ divided plastic deformation of materials into five separate components: defectless flow, dislocation glide, Nabarro-Herring creep, Coble creep, and dislocation creep. In this model the steady-state strain rate as a function of applied stress σ and temperature T from these mechanisms is described by the following equations

Defectless Flow:

$$\begin{aligned} \dot{\epsilon}_1 &= \infty & \frac{\sigma}{\mu} &\geq \frac{\sigma_{th}}{\mu} \\ \dot{\epsilon}_1 &= 0 & \frac{\sigma}{\mu} &< \frac{\sigma_{th}}{\mu} \end{aligned} \quad (1)$$

Dislocation Glide:

$$\begin{aligned} \dot{\epsilon}_2 &= \dot{\epsilon}_0 \exp \left(- \frac{\{s - \sigma\} b a}{kT} \right), & \frac{\sigma}{\mu} &\geq \frac{\sigma_0}{\mu(300 \text{ K})} \\ \dot{\epsilon}_2 &= 0 & \frac{\sigma}{\mu} &< \frac{\sigma_0}{\mu(300 \text{ K})} \end{aligned} \quad (2)$$

Diffusional Flow (Nabarro-Herring Creep and Coble Creep):

$$\dot{\epsilon}_{3,4} = \frac{14 \sigma \Omega D_V}{kT d^2} \left(1 + \frac{\pi \delta}{d} \frac{D_B}{D_V} \right) \quad (3)$$

Dislocation Creep:

$$\dot{\epsilon}_5 = A \frac{D_V \mu b}{kT} \left(\frac{\sigma}{\mu} \right)^n \quad (4)$$

where

- μ = shear modulus [$\mu(300\text{ K})$ is the value at 300 K]
- σ^{th} = theoretical tensile strength
- $\dot{\epsilon}_0$ = strain rate when $\sigma = s$
- $s \equiv \alpha \mu b \rho^{1/2}$ = flow stress at $T = 0$
- $\alpha \approx 1.75$ (Ashby neglected to tell us this value)
- b = magnitude of the Burgers vector
- ρ = dislocation density
- a = activation area
- σ_0 = the cutoff stress sometimes called athermal part of the flow stress
- k = Boltzmann's constant
- Ω = atomic volume
- D_V = self-diffusion coefficient
- d = grain diameter
- δ = grain boundary width
- D_B = grain boundary diffusion coefficient
- A = proportionality constant
- n = steady-state creep stress exponent.

Ashby defends his choice for these four equations in his first paper,¹ and then makes a number of modifications, primarily for $\dot{\epsilon}_2$, in future papers he published with a number of co-authors.²⁻⁴ It is useful to mention here that the methods for determining the DMM described below do not depend on the form of these equations. Other choices can be made with minor changes in the programs.

²H. J. Frost and M. F. Ashby, Final report on ONR Contract N00014-67-A-0298-0200, Harvard University, Boston (1973).

³F. N. Crossman and M. F. Ashby, *Acta Met.* 23, 425-40 (1975).

⁴H. J. Frost and M. F. Ashby, *Deformation-Mechanisms Maps for Pure Iron, Two Austenitic Stainless Steels and a Low-Alloy Ferritic Steel*, a preprint written July 1975.

NUMERICAL TECHNIQUES USED

Numerical techniques were developed to determine the boundary between regions where various mechanisms dominate and then to find the contours describing constant total steady-state strain rate. First the boundaries describing the dominant mechanisms will be found. In this model the region of defectless flow includes all stresses above σ^{th}/μ . Since the strain rate is considered infinite in this region, there are no boundaries to calculate between this region and the others. This leaves three possible boundaries to calculate: (1) the boundary between dislocation glide and diffusional flow where $\dot{\epsilon}_2 = \dot{\epsilon}_{3,4}$, (2) the boundary between dislocation glide and dislocation creep where $\dot{\epsilon}_2 = \dot{\epsilon}_5$, and (3) the boundary between dislocation creep and diffusion flow where $\dot{\epsilon}_{3,4} = \dot{\epsilon}_5$. The equations for boundaries (1) and (2) are transcendental equations (5) and (6) in stress and temperature using the simplifying definitions $C(T) \equiv \frac{\mu}{KT}$ and $F(T) \equiv \frac{14\Omega D_V}{d^2} \left(1 + \frac{\pi\delta}{d} \frac{D_B}{D_V} \right)$

$$\dot{\epsilon}_0 \exp - \left[\left(b_p^{1/2} - \frac{\sigma}{\mu} \right) abC(T) \right] - C(T)F(T) \frac{\sigma}{\mu} = 0 \quad (5)$$

$$\dot{\epsilon}_0 \exp - \left[\left(b_p^{1/2} - \frac{\sigma}{\mu} \right) abC(T) \right] - AD_V C(T) b \left(\frac{\sigma}{\mu} \right)^n = 0 \quad (6)$$

The last boundary can be found explicitly, and is given by

$$\frac{\sigma}{\mu} = \left[\frac{F(T)}{AD_V b} \right]^{1/(n-1)} \quad (7)$$

The $\frac{\sigma}{\mu}$ values that satisfy Eq. (5) are found for each of 50 temperatures by starting with $\frac{\sigma}{\mu}$ greater than the boundary and evaluating expression (5). The value of $\frac{\sigma}{\mu}$ is then reduced by 1/50 of the total range of that parameter and expression (5) is evaluated again. This process of decreasing $\frac{\sigma}{\mu}$ is continued until expression (5) equals zero or changes sign, indicating a solution is located between the last two values. A final value is found by linear interpolation of the $\log \frac{\sigma}{\mu}$ values. The process is repeated for expression (6).

A similar process is used to calculate the constant strain rate contours. Fifty points on the contours are calculated from high temperature to low temperature. The stress is incremented in equal steps from low to high, and the strain rate minus the particular value being considered is calculated. When this function changes sign, a linear interpolation (on the $\log \frac{\sigma}{\mu}$ axis) is used to find the zero value indicating the contour. The process is simplified by the fact that the contour curves are monotonic functions and that the search for the next point on the contour can begin with the final values of stress used for the previous point.

DEFORMATION MECHANISM MAPS FOR PURE ALUMINUM AND FOR AISI 316 STAINLESS STEEL

Ashby calculated many examples of DMMs and gives much of the information needed to reproduce them. Table 1 gives the data used to calculate two examples in Figs. 1 and 2 which agreed with the plots published by Ashby⁵ and Frost and Ashby.⁴ The method used to determine the constants for Ashby's plots will be given following the table.

Eighteen parameters are needed to calculate the DMM, including choosing 0.039μ for the theoretical strength. Several of these parameters are available from a variety of sources. The melting temperature, shear modulus, and its temperature dependence, the magnitude of the Burgers vector, the atomic volume, and the five constants describing self- and boundary-diffusion can be found for many materials in the literature with the exception that the grain boundary width is chosen to be $2b$. Another somewhat arbitrary choice Ashby made was to choose the melting temperature for pure iron to determine the homologous temperature for stainless steel. Three other parameters, d , A , and n , are given values in the references cited. In addition, the dislocation density given for aluminum of $4 \times 10^8 \text{ cm}^{-2}$ results in the value of 1.75 for α in the definition for s in Eq. (2). The same value for α to get the $T = 0 \text{ K}$ values of the dislocation glide boundary on Ashby's DMM gives a

⁵M. F. Ashby, *Acta Met.* 20, 887-97 (1972).

Table 1. Data Required to Calculate DMMs

Text Symbol	Pure Aluminum	AISI 316	Units	Computer Symbol
T_m	933	1810	K	TM
μ (300 K)	2.54 E11	8.10 E11	dynes/cm ²	mu(300)
$\frac{1}{\mu} \frac{d\mu}{dT} = \frac{d\ln\mu}{dT}$	-5.40 E4	-4.70 E4	K ⁻¹	D LN(mu)/DT
$\dot{\epsilon}_0$	1. E6	1. E6	s ⁻¹	EPS0
σ_0	1.57 E9	5.43 E9	dynes/cm ²	S0
ρ	4 E10	6.1 E10	cm ⁻²	RHO
b	2.86 E8	2.58 E8	cm	B
a	4.1 E14	3.3 E14	cm ²	ACT A
Ω	1.660 E23	1.210 E23	cm ³	AT VOL
d	3.2 E3	2.0 E2	cm	GR DIAM
δ	5.72 E8	5.16 E8	cm	GB W
D_0 (self-diffusion)	0.035	0.37	cm ² /s	D0 SD
Q (self-diffusion)	28.8	66.8	kcal/mole	Q SD
D_0^b (boundary)	0.01	3.876	cm ² /s	D0 B
Q^b (boundary)	14.4	40.0	kcal/mole	Q B
A	3.4 E6	1.0 E10	s ⁻¹	A
n	4.4	6.9		N

dislocation density for AISI 316 stainless steel of 6.1 E10 cm⁻². These choices leave three remaining constants that Ashby does not give values for directly, σ_0 , $\dot{\epsilon}_0$, and a. These three constants are all needed to describe dislocation glide, which is the mechanism Ashby admits is least well understood. The form of Eq. (2) is such that the DMMs are not strongly changed by the choice of these values, so $\dot{\epsilon}_0 = 1.E6$ and $a = 50 b^2$

Fig. 1. DMMs for Pure Aluminum with a Grain Size of 32 μm .

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Fig. 2. DMMs for AISI 316 Stainless Steel with a Grain Size of 200 μm .

were chosen arbitrarily and σ_0 was chosen to get the high-temperature limit of the dislocation glide regions.

In the four references cited, Ashby and his co-workers used a variety of conventions for choosing units for the parameters and also for recording stress and strain. We have chosen to stay with Ashby's first choice of normalizing the tensile stress by the shear modulus and to plot contours of constant tensile strain rate. Shear stress values⁵ can be found by dividing the tensile stress by $\sqrt{3}$ and shear strain rate can be found by multiplying the tensile strain rate by $\sqrt{3}$.

The DMM plotted in Figs. 1 and 2 agree with those plotted by Ashby. This agreement tests the program and makes it possible to use parameters for other materials to obtain their DMM. The two appendixes following give the programs for the Hewlett-Packard 9821A computer and also the instructions for using it.

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APPENDIX I

HP 9821A Programs to Calculate DMMs

This appendix described a series of HP 9821A programs for calculating and plotting deformation DMMs. It consists of two parts: first, a list of the variables and flags used with identifying storage registers and the purpose of the flags; second, a program listing with the various parts described.

List of Variables Used in DMM Programs

A $\left\{ \begin{array}{l} \text{used in file 2 for initial stress for } \dot{\epsilon}_2 = \dot{\epsilon}_{3,4} \text{ boundary and} \\ \text{log strain rate} \\ \text{used in file 3 for strain rate contour value.} \end{array} \right.$

B $\left\{ \begin{array}{l} \text{used in file 2 for initial stress for } \dot{\epsilon}_2 = \dot{\epsilon}_5 \text{ boundary} \\ \text{used in file 3 for function to zero to set contour values.} \end{array} \right.$

C $\left\{ \begin{array}{l} \text{used in file 3 to bracket contour value between B and C} \\ \text{used in file 4 for log } (\dot{\epsilon}_2 + \dot{\epsilon}_{3,4} + \dot{\epsilon}_5) \end{array} \right.$

x - Current value of T/T_m

y - Current value of σ/μ

z - Temporary storage

R0 - T_m - melting temperature

R1 - T_1/T_m , where T_1 is minimum temperature to be plotted

R2 - T_2/T_m , where T_2 is maximum temperature to be plotted

R3 - σ_1/μ , where σ_1 is minimum stress to be plotted

R4 - σ_2/μ , where σ_2 is maximum stress to be plotted

R5 - μ (300 K), the shear modulus at 300 K

R6 - $\dot{\epsilon}_0$, pre-exponential constant for $\dot{\epsilon}_2$

R7 - ρ , dislocation density

R8 - b , magnitude of the Burgers vector

R9 - a , activation area for dislocation glide

R10 - Ω , atomic volume

R11 - d , grain diameter

R12 - δ , grain boundary width

- R13 - D_0 , pre-exponential for self-diffusion
 R14 - Q , activation energy for self-diffusion
 R15 - D_0^b , pre-exponential for boundary diffusion
 R16 - Q^b , activation energy for boundary diffusion
 R17 - A , proportionality constant for $\dot{\epsilon}_5$
 R18 - n , creep stress exponent
 R19 - $C(T) = \frac{\mu}{kT}$
 R20 - $F(T) = 14 \Omega D_V \left\{ 1 + \frac{\pi \delta D_B}{d n_V} \right\} / d^2$
 R21 - $\dot{\epsilon}_2$, deformation rate from dislocation glide
 R22 - $\dot{\epsilon}_{3,4}$, deformation rate from diffusional flow
 R23 - $\dot{\epsilon}_5$, deformation rate from dislocation creep
 R24 - $\Delta x = (T_2/T_m - T_1/T_m)/50$, homologous temperature step length
 R25 - $\Delta y = \left(\frac{\sigma_2}{\sigma_1} \right)^{1/50}$, normalized stress step length
 R26 - σ_0/μ (300 K)
 R27 - μ , shear modulus at temperature
 R28 - D_V , self-diffusion coefficient
 R29 - D_B , boundary diffusion coefficient
 R30 - $\frac{1}{\mu} \frac{d\mu}{dT}$, temperature coefficient of the shear modulus
 R31 - σ_0 , the dislocation glide cutoff stress

Flags

- 0 - Set in file 2 to eliminate boundary calculations during plotting; set in file 4 to start program over.
 1 - Set in file 1 to eliminate the defectless flow line; set in file 2 to eliminate $\dot{\epsilon}_2 = \dot{\epsilon}_{3,4}$; set in file 3 to plot a set of contours differing by factors of 10.
 2 - Set in file 2 to eliminate the $\dot{\epsilon}_2 = \dot{\epsilon}_5$ boundary.
 13 - Used in file 3 to not draw new axes; used in file 4 to set default values of stress fraction increment = 10 and initial $\sigma/\mu = \sigma_1/\mu$.
 14 - Set in files 1, 2, 3, and 4 to eliminate overflow and underflow in calculations.

File 1 -- Data Input

```

0: ENT "T1/TM", R1,"T2/TM", R2, "TM",RD; (R2-R1)/→R24; SFG 14|—
1: PRT "T1/TM, T2/TM, TM = ",R1, R2, R0|—
2: ENT "ST1/MU", R3; PRT "ST1/MU =", R3; ENT "ST2/MU", R4|—
3: PRT "ST2/MU =", R4; ENT "MU(300K)", R5; PRT "MU =", R5|—
4: ENT "D LN(MU)/DT", R30; PRT "D LN(MU)/DT =", R30|—
5: ENT "ESP0", R6; PRT "EPS0 =", R6; ENT "S0", R31; R31/R5→R26|—
6: PRT "S0 =", R31; ENT "RHO", R7; PRT "RHO =", R7; ENT "B", R8|—
7: PRT "B =", R8; ENT "ACT A", R9; PRT "ACT A =", R9|—
8: ENT "AT VOL", R10|—
9: PRT "AT VOL =", R10; ENT "GR DIAM", R11|—
10: PRT "GR DIAM =", R11; ENT "GB W", R12|—
11: PRT "GB W =", R12; ENT "D0 SD", R13|—
12: PRT "D0 SD =", R13; ENT "Q SD", R14; PRT "Q SD =", R14|—
13: ENT "D0 B", R15; PRT "D0 B =", R15; ENT "Q B", R16|—
14: PRT "Q B =", R16|—
15: ENT "A", R17; PRT "A =", R17; ENT "N", R18|—

16: PRT "N =", R18; SCL R1, R2, LOG R3, LOG R4|—
17: AXE R1, LOG R3, .1,1; AXE R2, LOG R4, .1,1|—

18: 10+((LOG R4-LOG R3)/5E1)→R25;R1→X|—
19: LN (πR12R15/R11R13)→Z|—

20: PRT "E3-E4 X=", -(R14-R16)/1.987E-3 R0Z; IF FLG 1; GTO 23|—

21: PLT X, LOG .039; X + R24→X|—
22: IF X ≤ R2; PLT X, LOG .039; X + R24→X; PEN; GTO 21|—

23: CFG 1; GTO SCR; LDF 2|—
24: END|—

```

^aStatements 0 through 15 are used to input data to the storage registers.

^bInitializes plotter and draws axes.

^cCalculates and prints $\bar{T}/\bar{T}_m$ value for boundary between Nabarro-Herring creep and Coble creep.

^dPlots defectless flow boundary.

File 2 - Calculates Boundaries between Regions

```

0: ENT "SET FLAGS", Z; R2→X; SFG 14├─
1: X→R24→X; PEN ; CLL FD├─
2: 1.75 R25 R8√R7 →A→B→Z; IF FLG 1; GTO 4├─
3: FC (A,R20,1)→Y→Z; PLT X, LOG Y; PEN├─
4: IF FLG 2; GTO 6├─
5: FC (B,R17R28R8, R18)→Y→Z; PLT X, LOG Y; PEN├─
6: (R20/R17R28R8)+(1/(R18-1))→Y; IF Y > 1.75R8√R7; GTO 8├─
7: IF Z>Y, PLT X, LOG Y; PEN├─
8: IF (FLG 0=0) (X>R1); GTO 1├─
9: CFG 1; CFG 2; CFG 14; GTO SCR; LDF 3├─
10: END├─

```

┌─ a
 └─
 ┌─ b
 └─
 ┌─ c
 └─
 ┌─ d
 └─
 ┌─ e
 └─

SUBROUTINE FC

```

0: -R19P2P1+P3→Z; IF R26 ≤ P1 ; Z + R6 EXP (-R19R8R9 (1.75R8√R7-P1))
  →Z├─
1: P1/R25→P1; -R19P2P1+P3→Y├─
2: IF R26 ≤ P1; Y + R6 EXP (-R19R8R9 (1.75R8√R7-P1))→Y
3: IF ZY ≤ 0; GTO 6├─
4: IF P1 ≤ R3; 10→F; GTO 7├─
5: Y→Z; GTO 1├─
6: P1R25+(Y/(Y-Z))→F├─
7: END├─

```

┌─ f
 └─

^aIncrements X and calculates the current values of μ , σ_0/μ , D , D_R , $C(T)$, and $F(T)$.

^bFinds and plots $\dot{\epsilon}_2 = \dot{\epsilon}_{3,4}$ boundary.

^cFinds and plots $\dot{\epsilon}_2 = \dot{\epsilon}_5$ boundary.

^dFinds and plots $\dot{\epsilon}_{3,4} = \dot{\epsilon}_5$ boundary.

^eReturns to 1 for new value of T/T_m .

^fSubroutine to find boundary points for $\dot{\epsilon}_2 = \dot{\epsilon}_{3,4}$ and $\dot{\epsilon}_2 = \dot{\epsilon}_5$ boundaries by searching for zero of proper functions and then interpolating.

SUBROUTINE FD

```

Ø: R5EXP (R3Ø (XRØ-3ØØ))→R27; R31/R5 →R26|
1: R13EXP (-R14/1.987E-3XRØ)→R28|
2: R15EXP (-R16/1.987E-3XRØ)→R29|
3: 14R1ØR28(1 + πR12R29/R11R28)/R11R11→R2Ø|
4: R27/RØX1.38E-16→R19; RET|
5: END|

```

a

File 3 - Calculation of Contour Lines

```

Ø: ENT "NEW PAPER=1",A; SFG 14; IF FLG 13; PEN; GTO 2|
1: AXE R1, LOG R3, .1, 1; AXE R2, LOG R4, .1,1|

```

b

```

2: ENT "STRAIN RATE", A;R2→X;R3→Y; LOG A→A; CLL FD|

```

c

```

3: FC Z→A→B; IF B > Ø; GTO 9|

```

```

4: YR25→Y; FC Z→A→C|

```

```

5: IF BC ≤ Ø; GTO 8|

```

```

6: IF Y ≤ .Ø39; C→B; GTO 4|

```

```

7: R3→Y; BEL; GTO 9|

```

```

8: PLT X, LOG Y-CLOG R25/(C-B); IF FLG Ø; CFG Ø; PEN; GTO 12|

```

d

```

9: Y/R25→Y; X→R24→X; IF X ≤ R1; PEN; GTO 12|

```

```

10: CLL FD|

```

```

11: GTO 3|

```

```

12: PRT "STRAIN RATE", TN + A; IF FLG 1; A+1→A; R2→X; R3→Y; CLL FD|

```

e

^aSubroutine to find current value of μ , σ_0/μ , D , D_B , $C(T)$, $F(T)$ used in files 2, 3, and 4.

^bInitialized plotter if new paper is desired for constant strain rate contours.

^cInitial strain rate entered. Calculates current values of temperature dependent parameters.

^dFinds and plots a point on a contour for each T/T_m .

^eIncrements and plots strain rate if desired.

```

13: IF FLG 1(A ≤ 0); GTO 3|
14: GTO 2|
15: END|

```

SUBROUTINE FC

```

0: 1E-99→R21|
1: IF R26 ≤ Y; R6 EXP (-R19R8R9 (1.75 R8√R7-Y))→R21|
2: R19R20Y→R22|
3: R19R17R28R8Y+R18→R23|
4: LOG (R21+R22+R23)→F|
5: END|

```

] a

File 4 - Calculates and Prints $\dot{\epsilon}_2$, $\dot{\epsilon}_{3,4}$, and $\dot{\epsilon}_5$ and Their Total for a Series of Stress Values and a Given Temperature

```

0: ENT "STRESS FRC INC", Z; IF FLG 13; 10→Z|
1: ENT "INIT ST/MU", Y; IF FLG 13; R3→Y|
2: ENT "T/TM", X; PRT "T/TM =", X; SPC 2; STF 14|
3: IF FLG 0; CFG 0; GTO 0|
4: PRT "ST/MU", Y; CLL FD|
5: FC C→C; PRT "E2", R21|
6: PRT "E3,4", R22; PRT "E5", R23; PRT "E TOT", 10+C; SPC 3|
7: IF Z=0; GTO 1|
8: YZ→Y; IF Y > R4; GTO 1|
9: GTO 3|
10: END|

```

^aSubroutine to calculate $\dot{\epsilon}_2$, $\dot{\epsilon}_{3,4}$, $\dot{\epsilon}_5$ and the log of the total for current values of X and Y used in Files 3 and 4.

APPENDIX II

Instructions for Using HP 9821A Programs to Calculate DMM

As described in Appendix I, there are four programs located on the first four files of a cassette tape. The following will discuss how to use each of these programs in turn. The first file contains the program that aids the user in storing the data to the proper storage registers and in initializing the plotter. The following instructions assume the calculator and plotter are turned on, the cassette tape is in place, a piece of paper is placed on the plotter, and the lower left and upper right corners of the plot are set. In the following instructions, all commands from the calculator are written in capital, underlined letters. RP is used to abbreviate the RUN PROGRAM command and EX is used to represent the EXECUTE command. STF and CLF are entered by pressing the "SET/CLEAR FLAG N" key.

1. GTO SCRATCH; LDF 1 EX.
2. After the tape is run and the calculator is ready for another command, END RP.
3. Type the data requested on the display and RP. If the defectless flow line is not wanted, type STF 1 EX any time before "N" is entered.
4. When all the data have been entered, the plotter will draw the outline of the plot and the theoretical strength line, and the printer will print $E3-E4 = X.XXXEXX$, where the X's represent a floating point number which is the homologous temperature separating the Nabarro-Herring and the Coble creep regions. The computer will automatically load the next program.
5. After the next program is loaded, type RP. The computer will display "SET FLAGS." At this time type STF 1 EX if the dislocation glide-dislocation creep boundary is not wanted, and type STF 2 EX if the dislocation glide-diffusion creep boundary is not wanted. Type RP to resume the calculation and the computer will draw the boundaries separating the dominant mechanisms. If the boundaries have gone far enough, pressing the STF button during execution will cause the next

program to be loaded. In any case, the next program will be loaded after all the boundaries are completed.

6. After the program is loaded, type RP and the computer will display "NEW PAPER=1." If the contours are wanted on an overlay, the paper can be changed and 1 RP typed. The pen may be changed if the contours are wanted in another color. If the contours are to be drawn on the same plot, simply type RP.

7. The computer will display "STRAIN RATE." If only a single contour is desired, type that value and type RP. If a series of strain rates separated by a factor of 10 are desired, type SFG 1 EX and enter the smallest value desired. Type RP. The calculator will draw contours until STOP is pressed or until a strain rate of 1 s^{-1} is exceeded. Individual contours can be stopped by depressing STF during executions.

8. If another DMM is desired with only minor changes in the data, press STOP and return to Step 1. As the data are entered if no change is desired, simply press RP. You need to only enter values that have changed.

This completes the instructions for obtaining DMM, but there is one additional feature available to the user. If STOP GTO SCRATCH; LDF 4 EX is typed after a DMM has been plotted, the computer will load a program to evaluate the various strain rates at requested temperatures and stresses. The computer will calculate and print the various strain rates and the total as a function of stress. Typing END RP will cause the calculator to display "STRESS FRC INC." "STRESS FRC INC" is requesting the fractional change in stress between each point. The computer will then request "INAT ST/MU" and the T/T. The default values, STRESS FRC INC = 10 and INIT ST/MU = ST1/MU, are available if RP is typed and no data are entered. Pressing the STF key during execution will send the program back to the beginning and a request for a new STRESS FRC INC.

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