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**A Computer Package for Calculating
Temperature Distributions in Machining
from Force, Shear Angle and
Contact Length Measurements**

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Abstract

A means of accurately calculating temperature distributions in cutting tools is an important part of a system of on-line temperature monitoring and hence, process control. The computer programs described use the finite element method to calculate steady-state temperature distributions in both workpiece and tool in orthogonal cutting. Realistic heat generation zones are used, consisting of primary deformation, tool-chip interface friction and secondary deformation.

The input required consists of the stress-strain and thermal properties of the work material, the thermal properties of the tool, the set cutting conditions and the measured values of cutting force, shear angle and contact length. An initial finite element mesh is automatically adjusted for different cutting conditions.

The method is illustrated by comparing temperature distributions for flat rake face tools with distributions for controlled contact tools under the same conditions.

1 Introduction

The use of a finite element method for calculating temperature distributions in the workpiece, chip and tool in orthogonal machining (Figure 1) was first described in 1974 by Tay, Stevenson and de Vahl Davis [1]. That program required as input not only the measured force components F_c and T_T , shear angle ϕ and contact length h , but also the strain, strain rate and velocity fields for the primary deformation zone (Figure 1). These fields were obtained experimentally, using quick-stop tests, with fine grids printed on the workpiece. The finite element mesh was based on the deformed grid for each case and adjusted manually as required. To calculate the heat generation rates at mesh points throughout the primary zone, the flow stress at these points was estimated as a function of strain, strain rate and temperature. In the absence of suitable data from conventional tests, machining test results were used as the source of the stress functions.

The original program has gradually been developed to increase its versatility, in particular its ability to handle a wide range of cutting conditions with little or no need for manual adjustment of the mesh. Another development trend has been in the use of flow stress data from high-speed torsion tests [2]. In this data, stress is a function of strain rate alone, and this is applied to machining on the assumption that the temperature rise in the material passing through the primary zone in machining will be equivalent to that in a torsion specimen subjected to the same strain rate. In fact, this is a simplification because the strain rate histories are different [3], but it is considered to be justified, considering the probable errors in torsion results and the machining strain rate field. Also, the torsion tests [2] show negligible strain hardening at the high strains pertaining to machining, suggesting the additional simplification of allowing the stress to be independent of strain.

Some of these developments were described by Stevenson, Wright and Chow [4] who also compared their calculated temperature distributions in the tool with the distributions obtained experimentally by etching the tool after the test. The agreement between these two methods was very good. Further developments made recently include the automatic generation of the finite element mesh in the primary zone and chip for different feed rates, rake angles and contact lengths, and the simplification of program modules and data file requirements. The program may now be more easily applied to a wide range of practical machining applications. It is still confined to the orthogonal case, but oblique machining conditions can usually be approximated by an orthogonal equivalent. This report describes the resulting system, and provides a guide to its use. An example of its application is given in which temperature distributions are compared for cutting with controlled contact and natural contact length cutting tools, both with a negative rake angle.

2 The Heat Transfer Model

The equation governing the heat transfer processes occurring during orthogonal machining is the steady, two-dimensional energy equation

$$\rho S \left[u \frac{dT}{dx} + v \frac{dT}{dy} \right] - k \left[\frac{d^2 T}{dx^2} + \frac{d^2 T}{dy^2} \right] = Q$$

where ρ , S , K and T are respectively the density, specific heat, thermal conductivity and temperature of the material concerned, Q is the heat generation rate per unit volume, x and y are cartesian co-ordinates, while u and v are the velocity components in the x and y directions, respectively. This

equation is to be solved for the region illustrated in Figure 2, subject to the boundary conditions shown there and further discussed below. The use of the finite element method for the numerical solution is described in Tay, Stevenson and Davis [1].

The external surfaces in contact with air are assumed to be adiabatic, i.e., heat losses to the surroundings by convection and radiation are assumed to be zero. Boundaries for the "downstream" end of the chip, and the exit of the work material from the solution region, were assumed to have zero temperature gradients. Positions for these boundaries were selected to ensure that this assumption was realistic.

Along the lower boundary between the primary zone and the workpiece, a temperature of "TROOM," usually the ambient temperature, is imposed. The value of TROOM could be increased above ambient if there tends to be a build-up in workpiece temperature from previous cuts. If the workpiece is deliberately pre-heated, TROOM would be made equal to the pre-heat temperature. A stress function applying to that starting temperature would then need to be applied.

An important feature of the present system is that the solution region in the tool is confined to the tool tip. In the original system, the mesh also extended throughout the cross-section of the toolholder, making mesh adjustment more complex. The present system requires that the conductance of heat from the tool tip to the tool shim (if any) and then to the toolholder be estimated. Most machining is done with disposable inserts which are clamped in place rather than brazed, so this modification allows the mesh to be more readily adapted to a practical set-up.

It is assumed that conductance takes place across the entire base of the tool tip, the rate of heat flow at a point on the base where the temperature is T being given by

$$Q = h_f(T - TSHANK)$$

where h_f is the contact conductance for the interface between the tool tip and its seating and TSHANK is the temperature of the supporting material immediately below the tool tip. TSHANK is assumed constant over the length of the tool base; it may be measured by a thermocouple during a test. Otherwise, a reasonable value to assume for conditions similar to the examples given here is $80^\circ C$. While these may seem to be rough approximations, the temperature distribution along the tool-chip interface is not greatly affected by them. For the present results, a value of conductance was obtained from the experimental results of Brunot and Buckland [5]. The conductance values for difference conditions vary with the finish of the surfaces and the clamping pressure. The value for a particular type of surface tends to a constant value as pressure is increased. It is this constant value for clean milled surfaces, viz. $0.00171 \text{ C.H.U./s.in}^2^\circ C$, which was used for the present results.

3 Mesh Generation

The finite element mesh used for the solution consists of quadrilaterals graded in size to suit the expected temperature gradients; a fine mesh being used in areas such as the tool tip where gradients will be high. The boundaries of the tool tip are established from the cross section of the actual tip to be used in the experiments. The basic mesh for the tip is established with a rake angle α of zero. As in previous programs, the 22 nodes making up the tool-chip contact length are shared by adjacent elements in the tool and chip. The total length taken up by these nodes, and their spacing, is adjusted

later to match the measured tool-chip contact length. The basic tool tip mesh used for the results described in this paper is shown in Appendix I.

The resulting co-ordinates of the nodes in the tool tip, the nodes in the workpiece below the primary zone (these need not be changed for different cutting conditions), and a set of base nodes on which the primary zone and chip will be built, are kept in a file which becomes an input to the Fortran program PRIMRY. PRIMRY, which is listed in Appendix II, adjusts the tool tip nodes, generates the nodes in the primary zone and chip and then calculates the distributions of strain, strain rate and velocity in the primary zone. The procedure is briefly described as follows:

a. **Adjustment of the tool-chip contact length.** Mesh point 538 on the rake face is moved to a distance from the tool edge equal to the total contact length. Points further away from the tool edge are moved a distance equal to that moved by 538, except for points making up the end face of the tool tip which are kept fixed. Points closer to the tool edge are moved by progressively smaller amounts to maintain the relative gradation of elements, except for points on the clearance face which are kept fixed.

The chip base nodes, which become separate from the tool beyond point 538, are gradually increased in spacing to a maximum of 0.01 inch.

b. **Rotation of the tool-tip.** The tool tip and chip base nodes are now rotated about the tool edge to give the required rake angle (Figure 3a). The basic tool mesh read in to PRIMRY has its origin at the tool edge. After rotation, the origin is shifted 0.05 inch to the left so that x-co-ordinates in the mesh will be positive.

c. **Generation of mesh in primary zone and chip.** This part of the mesh is based on a set of 5 equally spaced streamlines. The streamlines in machining have been found [6] to be well approximated by hyperbolae. Tay *et al.* [7] showed that an hyperbola of the form

$$y^2 \tan \alpha - xy = a \quad (1)$$

where the origin is at the intersection of the asymptotes with shear plane AB, gives a peak strain rate value on AB, as was found in the experiments. The constant "a" in equation (1) is given by

$$a = \frac{t_1^2}{16C^2 \sin^2 \varphi (\tan \alpha + \cot \varphi)} \quad (2)$$

where t_1 is the uncut chip thickness, φ the shear angle, α the rake angle (Figure 1) and C the constant in the empirical equation

$$\dot{\gamma}_{AB} = \frac{CV_S}{t_1} \quad (3)$$

where $\dot{\gamma}_{AB}$ is the shear strain rate on AB, i.e., the peak value along the streamline, and V_S is the shear velocity, given by

$$V_S = \frac{U \cos \alpha}{\cos(\varphi - \alpha)} \quad (4)$$

where U is the cutting speed.

The uncut chip thickness is divided into 5 layers of equal thickness by the streamlines. The first streamline forms the free surface, and it is positioned at a height t_1 above the cut surface. The

equivalent hyperbolae to equation (1), using x_0, y_0 as origin (the actual origin of the mesh co-ordinates) are given by

$$Ay^2 + Bx^2 + Cxy + Dy + Ex = 1 \quad (5)$$

where

$$A = \frac{\tan \alpha}{Z} ,$$

$$B = 0 ,$$

$$C = -\frac{1}{Z} ,$$

$$D = \frac{x_{AB} - 2 \tan \alpha y_{AB}}{Z} ,$$

and

$$E = \frac{Y_{AB}}{Z} ,$$

where

$$Z = a - \tan^2 \alpha y_{AB}^2 + x_{AB} y_{AB} ,$$

and (x_{AB}, y_{AB}) are the co-ordinates of the intersection of the asymptotes with AB (different for each streamline) as shown in Figure 1. With this procedure, each of the 5 streamlines will be identical in shape and have the same strain and strain rate distributions along them. If it were considered that the strain rates should be greater on streamlines closer to the tool edge, it would not be difficult to progressively increase the constant C for each streamline. However, there seems at present to be insufficient evidence to justify this.

Having established the coefficients of the equation of a streamline, mesh points along it are found from the intersection of the streamline with lines emanating from the base points, parallel to AB (Figure 3b). Each such point is found from the solution of a quadratic equation. This procedure gives 55 points along each streamline, 27 in the primary zone and 28 in the chip. The final boundary of the primary zone is rather arbitrarily positioned by the limit of 27 points, and the program could be slightly improved, at the cost of more complication, by terminating the primary zone only when the shear strain rate had dropped to some given low level. However, such a refinement would have little effect

on the variable of greatest concern, the maximum temperature at the tool-chip interface. A typical primary zone mesh, generated as described above, is shown in Appendix III.

4 Primary Zone Heat Generation

The heat generation rate at points throughout the primary deformation zone is given by

$$Q = \tau \dot{\gamma}$$

where τ is the plastic shear flow stress at the point and $\dot{\gamma}$ the shear strain rate at the point. τ may be determined as a function of the shear strain, shear strain rate and temperature at the point, but in the present application, as explained below, it is assumed to be a function of strain rate only.

Shear strain rate, shear strain and velocity distributions are found at each primary zone mesh point along the streamlines, using the following equations. These equations are based on the assumption that the maximum shear strain rate directions throughout the zone are parallel to AB.

$$\beta = \tan^{-1} \frac{dy}{dx}$$

$$\dot{\gamma} = \frac{d^2y}{dx^2} \cdot \frac{V_C \cos(\varphi - \alpha)}{(\sin \varphi + \cos \varphi \left(\frac{dy}{dx}\right))^3}$$

$$\gamma = \cot \varphi - \cot(\varphi + \beta)$$

$$V = V_C \frac{\cos(\varphi - \alpha)}{\sin(\varphi + \beta)} \quad (6)$$

where V_C is the chip velocity, and $\frac{dy}{dx}$ and $\frac{d^2y}{dx^2}$ are found from the equations of the streamline (equation (5)).

Strain rates, etc., cannot be determined in this way for the straight streamline which intersects the tool edge, yet the deformed grids in the quick-stop tests indicated substantial strain along this line. This is consistent with the plastic deformation remaining in the cut surface. In the present procedure, the tool-edge streamline is given the same distributions for strain rate, etc., as the one just above it, up to the tool edge. Beyond the tool edge, i.e., along the tool rake face, the primary strain rates on this streamline are made equal to zero, since it is in this region that secondary deformation takes over.

The flow stress τ is now found from a function of strain rate alone, where this function is derived from high speed torsion test results [2]. This is appropriate for a workpiece starting at room

temperature, as the torsion tests also did. The temperature history of material in the torsion and machining tests would be similar, so there is no need to include temperature in the stress function. This avoids the need for iteration to find the heat generation rates in the primary zone. The torsion tests on two low-carbon steels showed negligible strain hardening at the high strains applicable to machining, so the strain effect is considered negligible here. It may not be so for other materials, and the program has provision for inserting an appropriate value for the strain hardening exponent, n , in the power law equation:

$$\tau = \tau_1 \gamma^n .$$

The torsion test data is limited at present, and any bar of low-carbon steel will inevitably differ in strength from the steels so far tested, due to differences in composition and cold working. For this reason, the torsion data is used to give the strain rate sensitivity of the stress, while the stress magnitude is adjusted on the basis of the shear stress on the shear plane, calculated from the machining test itself [8].

5 Secondary Zone Heat Generation

The secondary zone heat generation rates are divided into two parts: Q_1 is the generation rate due to secondary plastic deformation, while Q_2 is the generation rate due to sliding friction along the tool-chip interface.

Secondary plastic deformation is confined to a relatively narrow zone of material adjacent to the tool-chip interface. This zone has been found to be approximately triangular in shape (Figure 1). Its length is usually readily measurable from the wear on the tool rake face after a test, being that part of the scar where abrasion is not evident. This "plastic contact length," shown as p in Figure 1, is usually close to half of the total contact length h , if the rake face length is sufficient to allow natural contact. In controlled contact tools, the total contact length may be so reduced that secondary plastic deformation takes place throughout its length, i.e.,

$$p = h .$$

The heat generation rate due to plastic deformation adjacent to the interface is given by

$$Q_1 = \tau_{INT} \dot{\gamma}_{INT} , \quad (7)$$

where

$$\tau_{INT} = \frac{2F}{w(p+h)} \quad (8)$$

and

$$\dot{\gamma}_{INT} = \frac{V_c}{\delta t_2} , \quad (9)$$

where F is the friction force, calculated from the measured force components F_C and F_T , using

$$F = F_C \sin \alpha + F_T \cos \alpha$$

and δt_2 is the maximum thickness of the secondary zone. δ , the proportion of chip width t_2 over which secondary deformation takes place, has been measured for a wide range of conditions when machining two low-carbon steels [9]. If that data is inadequate, a chip sample will need to be mounted, polished and etched for estimation of δ .

τ_{INT} in equation (7) is assumed to be constant throughout the secondary deformation zone. γ at the tool-chip interface is assumed to be constant along the plastic contact length and zero beyond it. γ is further assumed to decrease linearly from its interface value to zero along the secondary zone boundary within the chip.

Equation (8) is obtained from the assumption that the interface shear stress is equal to τ_{INT} over the plastic contact length and then drops linearly to zero at the end of the total contact length. Equation (9) is based on examination of a limited number of quick-stop results in which the further deformation of the grids in the secondary zone could be measured.

The heat generation rate along the tool-chip interface due to friction is given by

$$Q_2 = \tau_{INT} V_x$$

where V_x is the velocity parallel to the rake face of chip material at a distance x from the tool edge. Again on the basis of quick-stop results, it is assumed that V_x starts at $V_C/3$ at the tool edge and accelerates uniformly to the chip velocity V_C at the end of the plastic contact length, beyond which it remains constant at V_C .

It will be evident from the above description of heat sources that contact length measurement is an important part of the procedure. However, in the absence of such measurement, an approximation to the total contact length may be calculated [7].

6 Arrangement of Program and Data Files

The system used for the present results is illustrated in Figure 4. Individual users are likely to modify this arrangement to suit their application and computer system.

The Fortran program, PRIMARY, is run first, using a basic mesh from a file such as XYBASE and data in the file PRIMD as input. Output from PRIMARY consists of the file RESULT, which contains a listing of the calculated strain and strain rate distributions for printing if required, the file UVEDOT which contains the strain, strain rate and velocity distributions for reading in to the next program, FINELT, and the file XYTSTN which contains the generated mesh for Test N, also to be read in to FINELT.

FINELT, the main finite element program, is listed in Appendix IV. Apart from UVEDOT and XYTSTN, it also requires as input the data file FINREV. FINELT is an iterative procedure which usually converges to a sufficiently accurate solution (2% maximum relative error) within 5 iterations. If it does converge (and there is something wrong if it does not), it will produce a final listing of temperatures at all nodes, TRESUL. It will also produce a file, CALC26, for the Calcomp plotter for plotting the isothermals.

The finite element mesh may also be plotted using the Fortran program MESHPL, shown in Figure 4. Since mesh plotting takes around 7 minutes of plotter time, it should not be done as a matter of course, but only when there is some need to check the mesh. MESHPL is listed in Appendix V. Data files for the example experiments are given in Appendix VI.

- NFE:** the number of element sides forming the tool-chip interface, i.e., the maximum value of i in $NFLUX(i,j)$.
- LH:** the number of elements in the vector H. The value of H is calculated in the subroutine BANWTH, but a maximum expected value of LH is given as MAXH in the parameter statement of FINELT for dimensioning H.
- IQTL:** the number of primary zone nodes at which the heat generation due to primary deformation is calculated.
- NXI:** the number of points on a streamline.
- NYI:** the number of streamlines.
- NITL1 and NITL2:** the numbers of the two primary zone elements sharing the tool point node, the former just ahead of the shear place and the latter just past it.
- NXBTI:** the number of points on streamline 6 up to the tool edge.
- NELSLI (i):** the numbers of the 27 elements along the free surface of the primary zone.
- NUVQ(i,j):** the node numbers for elements in the primary zone, using the system where points are numbered consecutively along streamlines, starting with the one at the free surface.

Variables Possibly Needing to be Changed for Each Test

- CHIP:** the identifying name for the test being analysed.
- NSTEEL:** the code name for the work material being machined, e.g., 1080.
- ITST:** the number of the starting iteration, normally 1, but if previous iterations are to be resumed, a value greater than 1 should be given.
- ITMAX:** the maximum iteration number. If ITST is 1, putting ITMAX at 7 should suffice to prevent the use of excessive computer time if the program happens not to converge.
- RERROR:** the criterion for stopping the iterations; if set to 2%, then the program stops when the greatest relative change in temperature among all points from one iteration to the next is 2% or less.
- U, T1, T2, ALPHA, FT, FC>CL, W, TROOM, TSHANK, DT2 and PCL:**
the machining test data* all defined in the source program, including their units.
- DCN:** the density of the work material at 50°C, in lb/cu. in,
- €P:** the specific heat of the work material at 50°C, in C.H.U. (centigrade heat units)/lb.

- WCOND: the conductivity of the work material at 50°C, in C.H.U./s.in. °C.
- TCOND: the tool tip conductivity at 22°C in C.H.U./s.in. °C.
- NDATA: the number of values in the arrays giving the variation of the thermal properties with temperature, starting at 0°C, in 50° steps.
- DENCPS(i): the array giving the products of work material density and specific heat for NDATA temperature steps.
- CONDS(i): the array giving the conductivity of the work material for NDATA temperature steps.
- HINTF: the conductance between the tool tip and tool base in C.H.IL/s.in.² °C.

8 Some Results

To demonstrate its applicability to practical machining conditions, the package was applied to some experimental results in which commercial disposable insert tools, supplied by the Kennametal Company, were used. Two types of coated-insert were used: Kenloc SNMA-432, which has a flat rake surface, and Kentrol SNMM-432, which has a land around its edge giving a controlled tool-chip contact length of 0.01 inch. Both inserts were 0.5 inch square and 3/16 inch thick, and were of KC850 grade. A low-carbon free-cutting steel bar was turned, with the tool set to cut orthogonally (side cutting-edge angle = 0). Force components F_T and F_c were measured with a Kistler dynamometer, chip thickness with a micrometer and contact lengths from the wear scar on the tool, using a Nikon Shadowgraph projector. The other cutting conditions and the test results are given in Table 8-1.

Isothermal plots obtained with the package for the above tests are given in Figure 5 a-f. The plots in Figure 5 show the areas of most interest, viz., the primary and secondary zones and the hottest segment of the tool tip. A typical plot for the remainder of the tool tip is given in Figure 6. The maximum interface temperatures for each of the tests are listed in Table 8-2.

As might be expected, where the controlled contact was much less than the natural contact at a particular feed, the shear angle was increased and the force components decreased. It turned out that the reduction of contact length also decreased the interface temperature in these cases, substantially so in the case of the 0.008 inch feed. With the smallest feed, there was little change in shear angle and force and the temperature turned out to be higher for the controlled contact case. Apparently* the contact length was not sufficiently reduced in this case to have a significant effect

Experimental results for comparison are sparse. Spur and Beyer [10] used a radiation detection technique to measure tool temperature distributions and gave an example for controlled contact tools. A higher carbon steel was machined, and the cutting speed was higher (80 in./s). With a feed rate of 0.01 inch, the natural contact length was 0.041 inch, and the maximum temperature was found to be 790°C. When the contact length was reduced to 0.017 inch using a controlled contact tool, the maximum temperature decreased to 726°C, a similar reduction to that found in the present results.

Table 1: Summary of Experimental Results

In all cases: $\alpha = -5$
 $U = 60 \text{ in./s}$
 $W = 0.200 \text{ in.}$
 $T_{ROOM} = 25.0^\circ\text{C}$

Test No.	Tip	t_1 inch	t_2 inch	ϕ deg.	Total C.L. h, inch	Plastic C.L. p, inch	F_T lb.	F_C lb.
T1	Kenloc	0.0104	0.029	19.11	0.035	0.019	331.6	522.7
T2	Kentrol	0.0104	0.022	24.34	0.010	0.010	196.7	420.4
T3	Kenloc	0.0080	0.021	20.17	0.027	0.016	219.2	382.2
T4	Kentrol	0.0080	0.015	26.92	0.010	0.010	114.7	305.7
T5	Kenloc	0.0052	0.013	21.06	0.018	0.011	140.5	250.7
T6	Kentrol	0.0052	0.013	21.06	0.010	0.010	134.9	243.9

Table 2: Maximum Interface Temperatures

Test No.	Feed t_1 , inch	Contact Length, h, inch	Maximum Interface Temp., $^\circ\text{C}$
T1	0.0104	0.035	721
T2	0.0104	0.010	676
T3	0.0080	0.027	594
T4	0.0080	0.010	496
T5	0.0052	0.018	517
T6	0.0052	0.010	557

9 Concluding Remarks

The package can now handle the full range of rake angles, feeds, shear angles and contact lengths likely to be encountered in practice. Some development of automatic mesh generation in the tool tip, for the full range of tool tip sizes, would be a desirable further development. A study of the sensitivity of the results to mesh size would also be desirable. Probably the mesh could be made substantially coarser with little loss in accuracy. This would speed up execution of the program and possibly even allow its use on a microcomputer.

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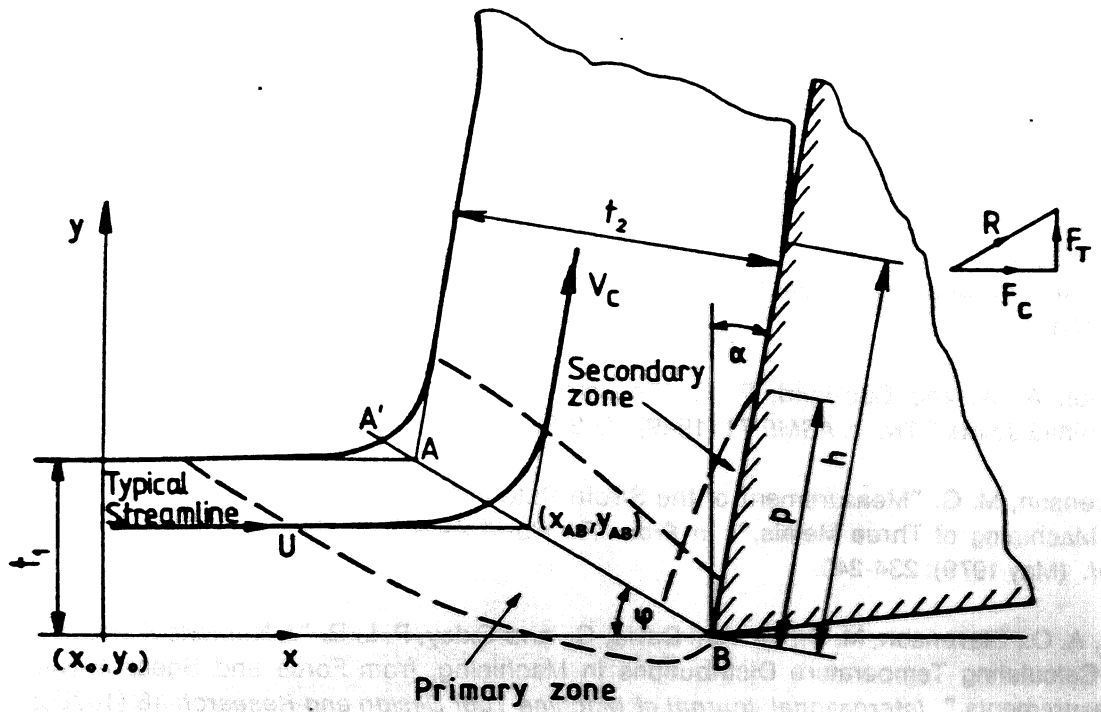


Figure 1: Typical cross-section of deformation zones in steady-state orthogonal machining

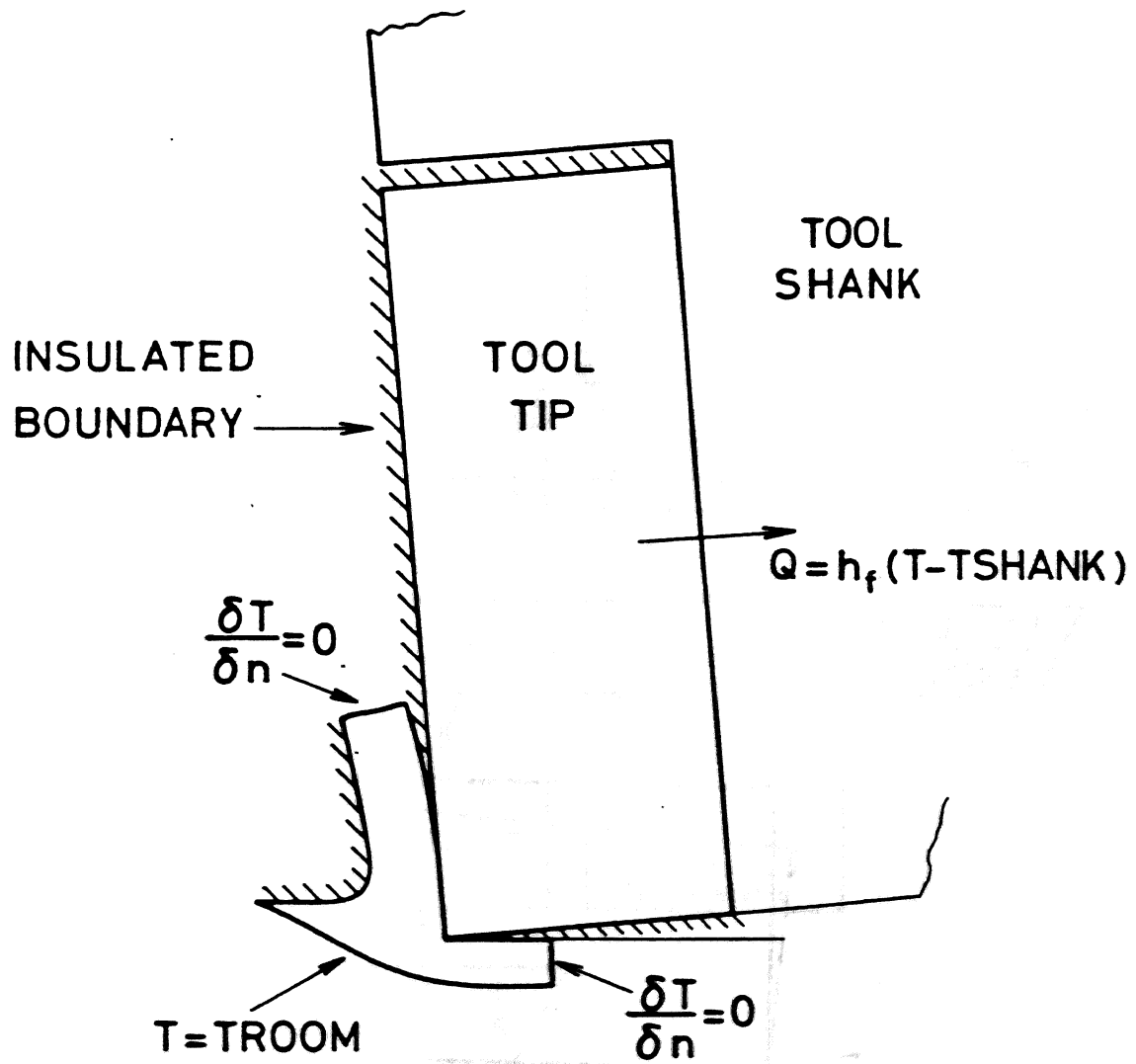


Figure 2: Boundary conditions for the finite element model

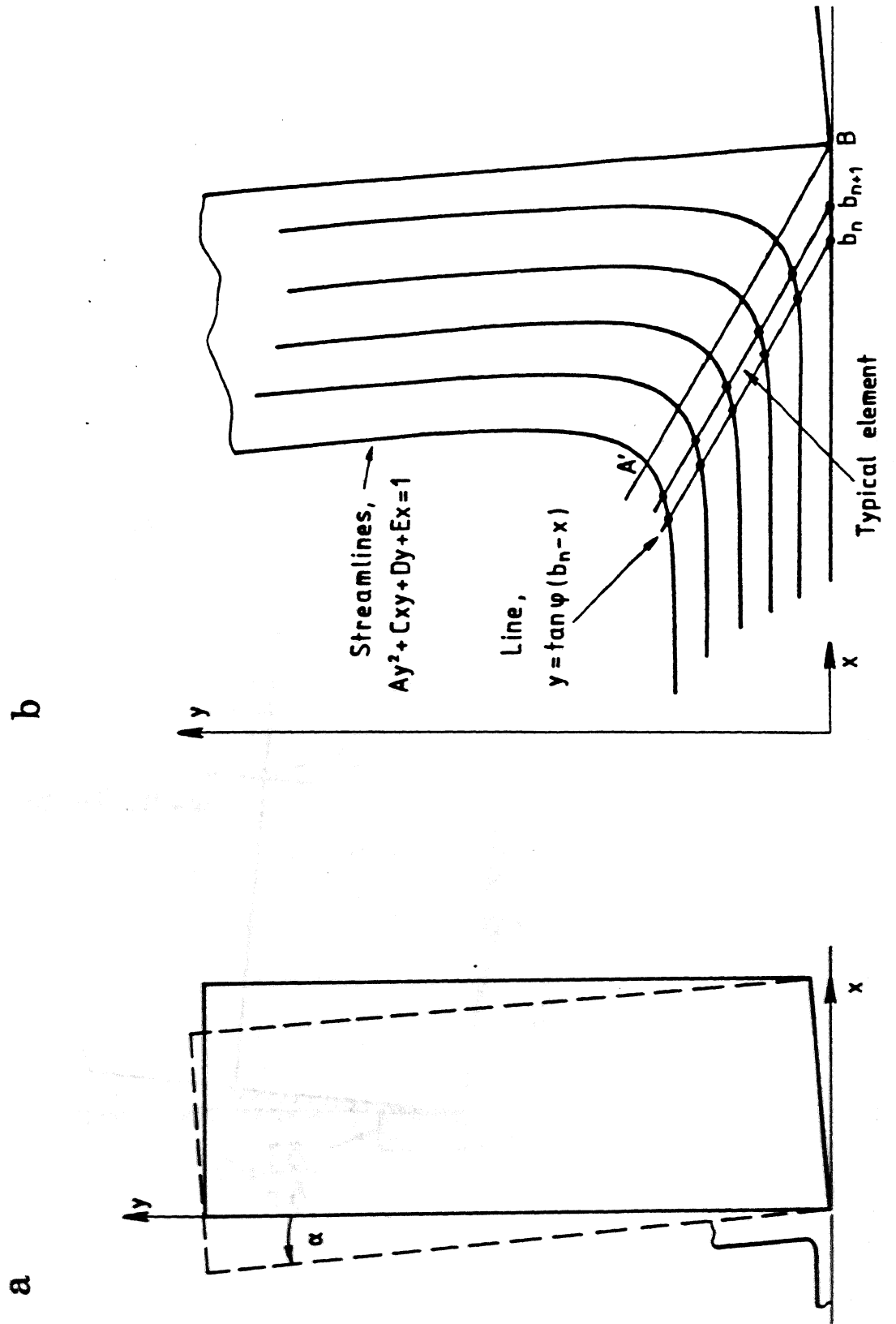


Figure 3: Steps in the mesh generation; (a) rotation of tool tip about its edge to form α , and (b) formation of mesh points in primary zone and chip.

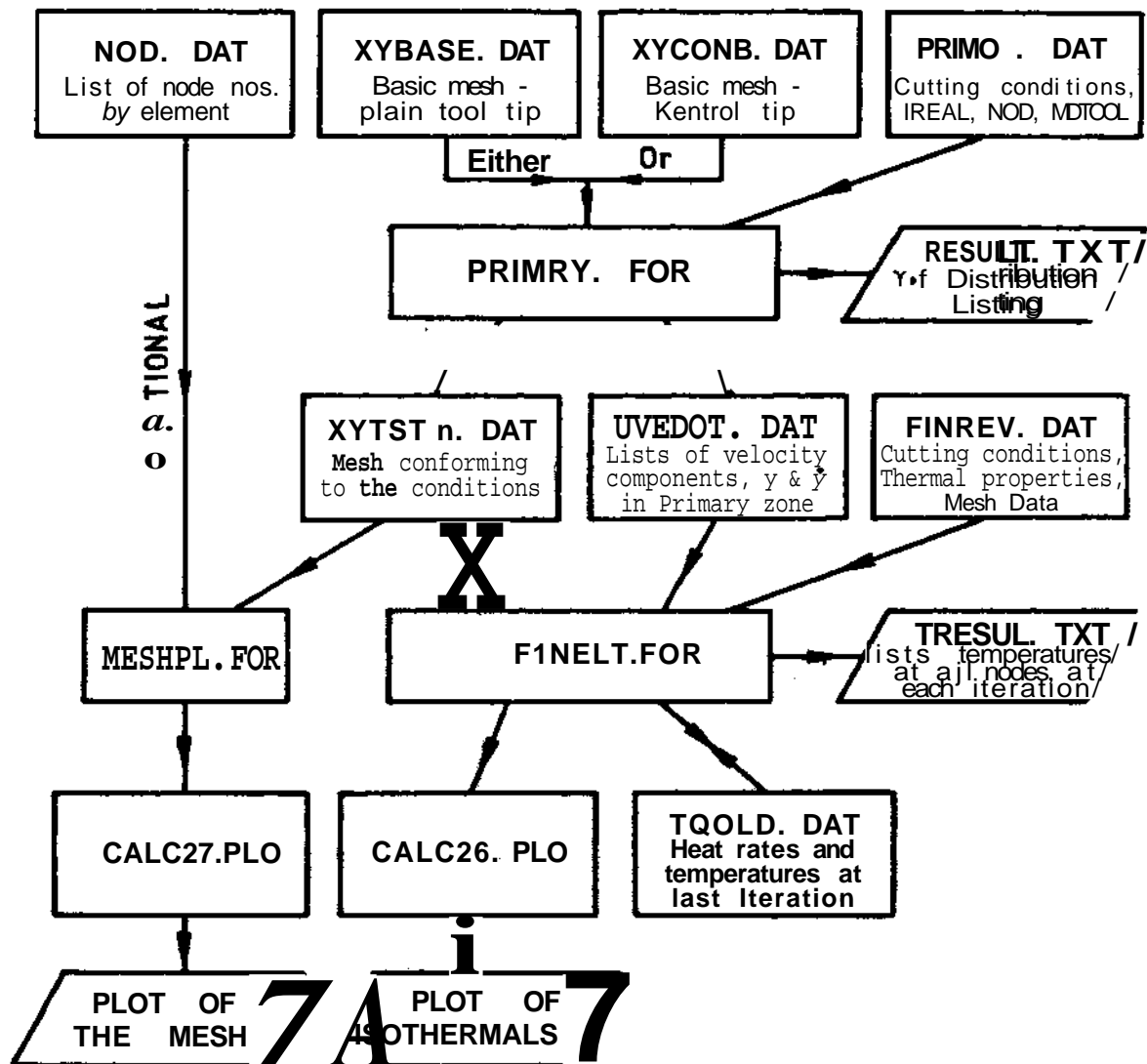


Figure 4: Arrangement of the program modules

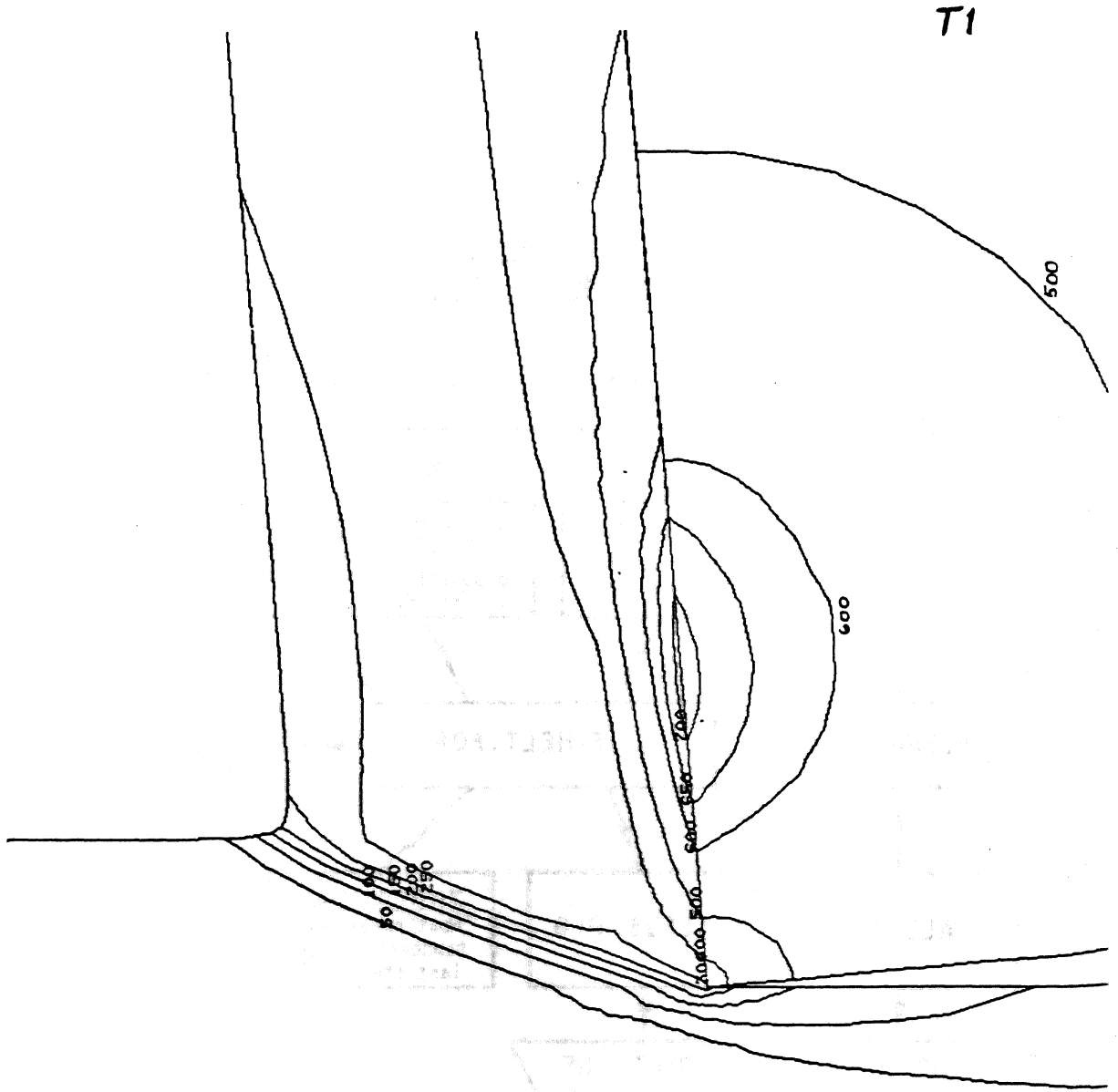
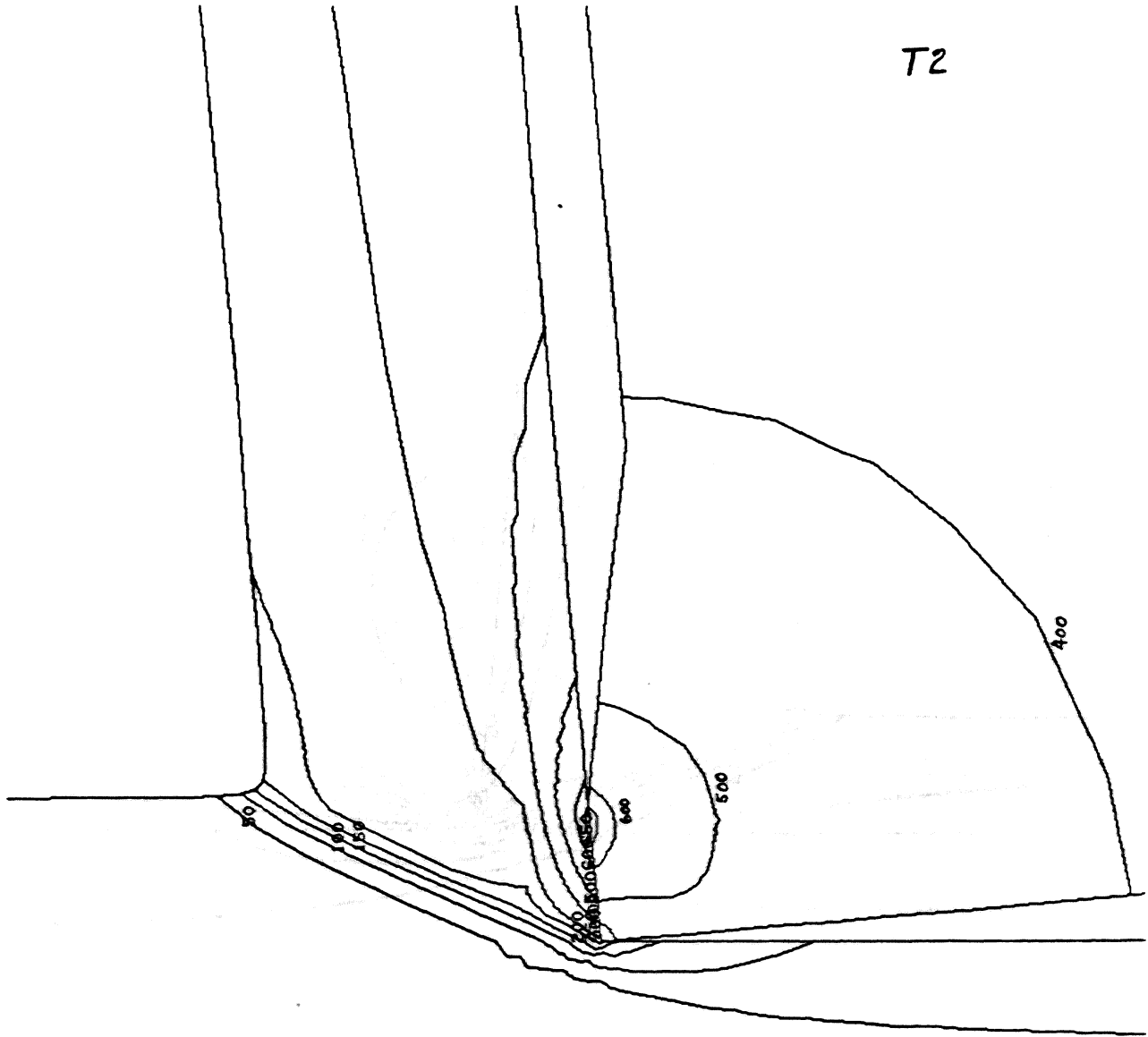
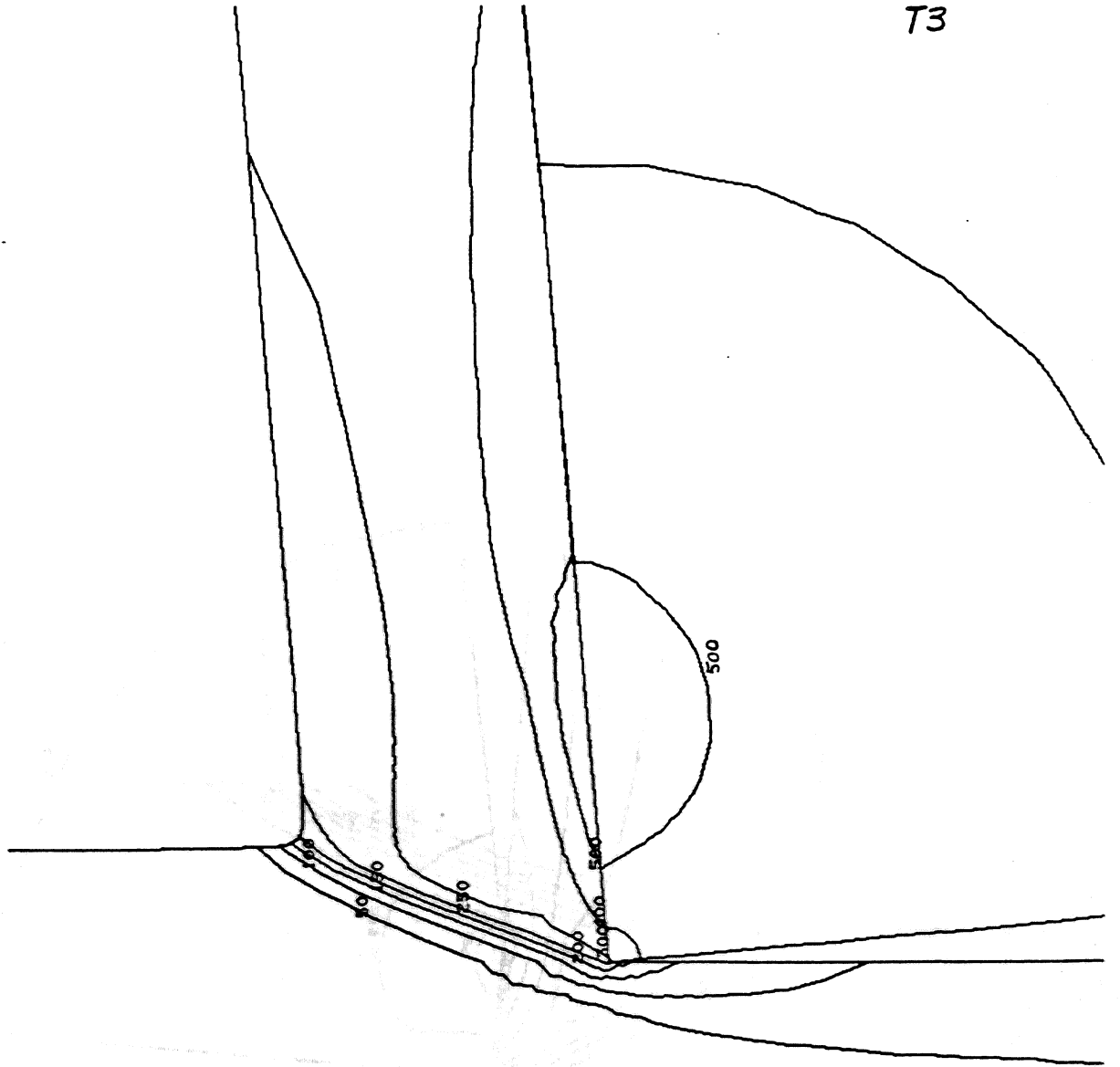
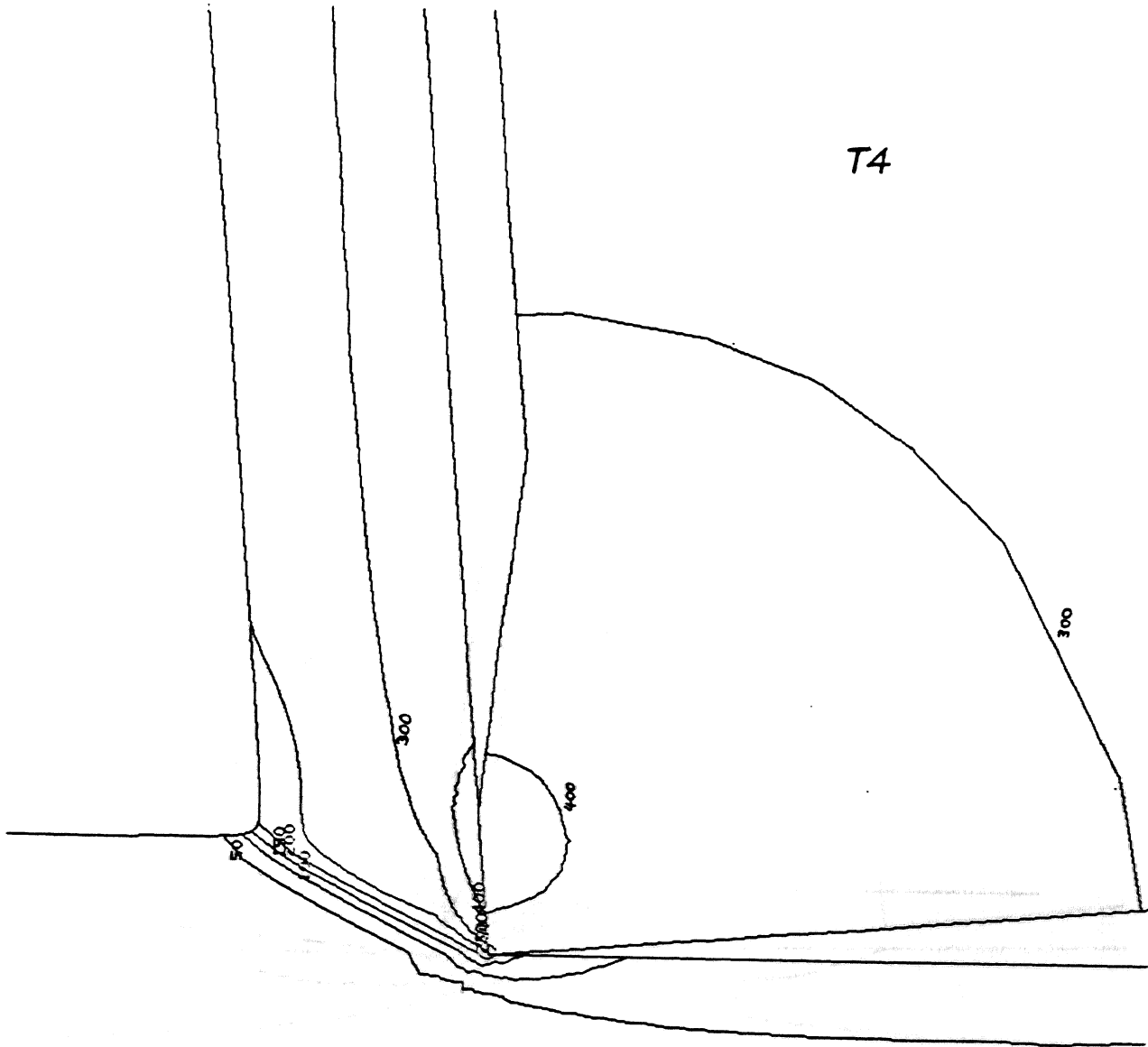


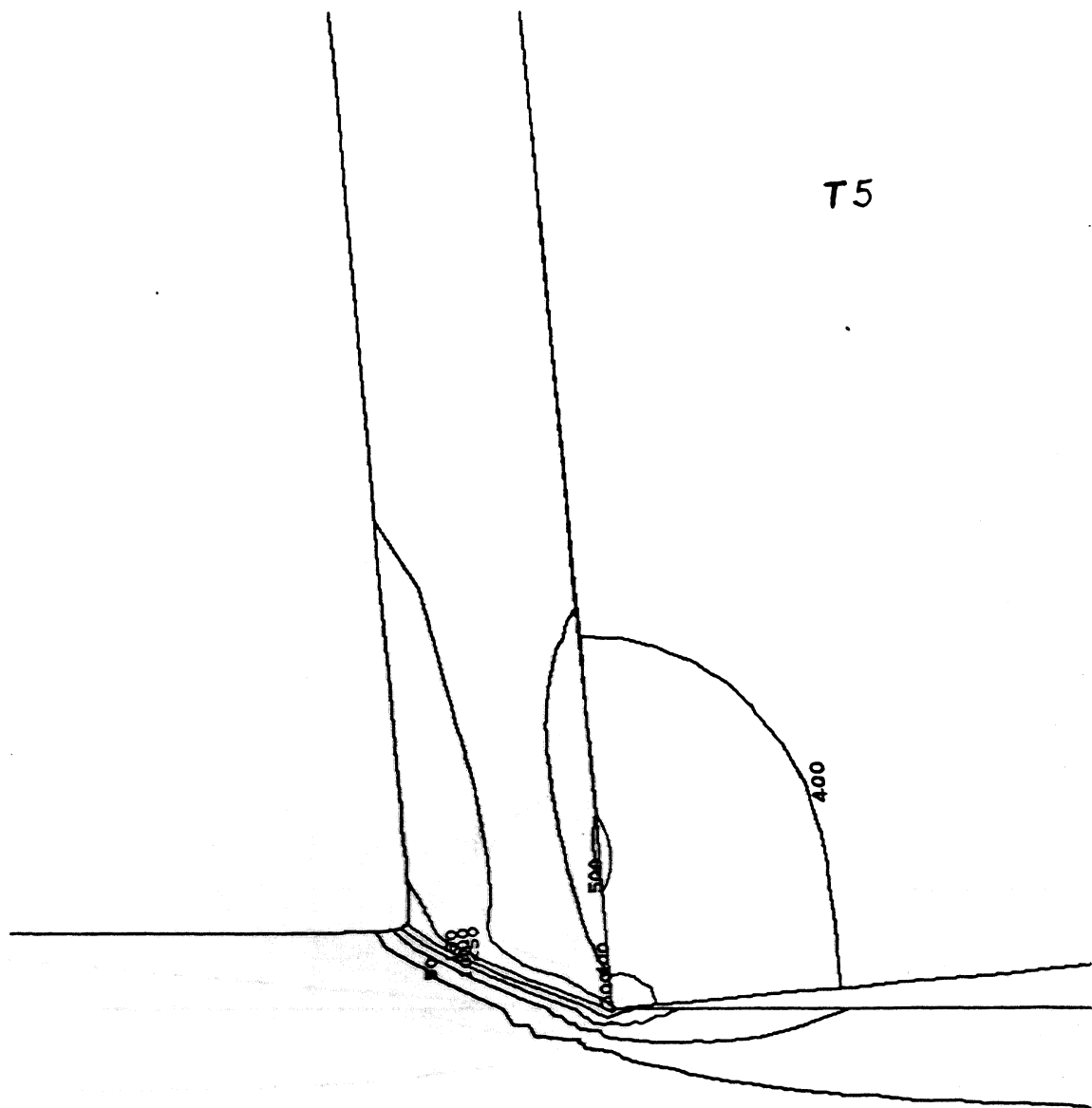
Figure 5: Isothermal plots for the experiments. Isothermal values are 50, 100, 150, 200, 250, 300, 400, 500, 600, 650, 700, 750.

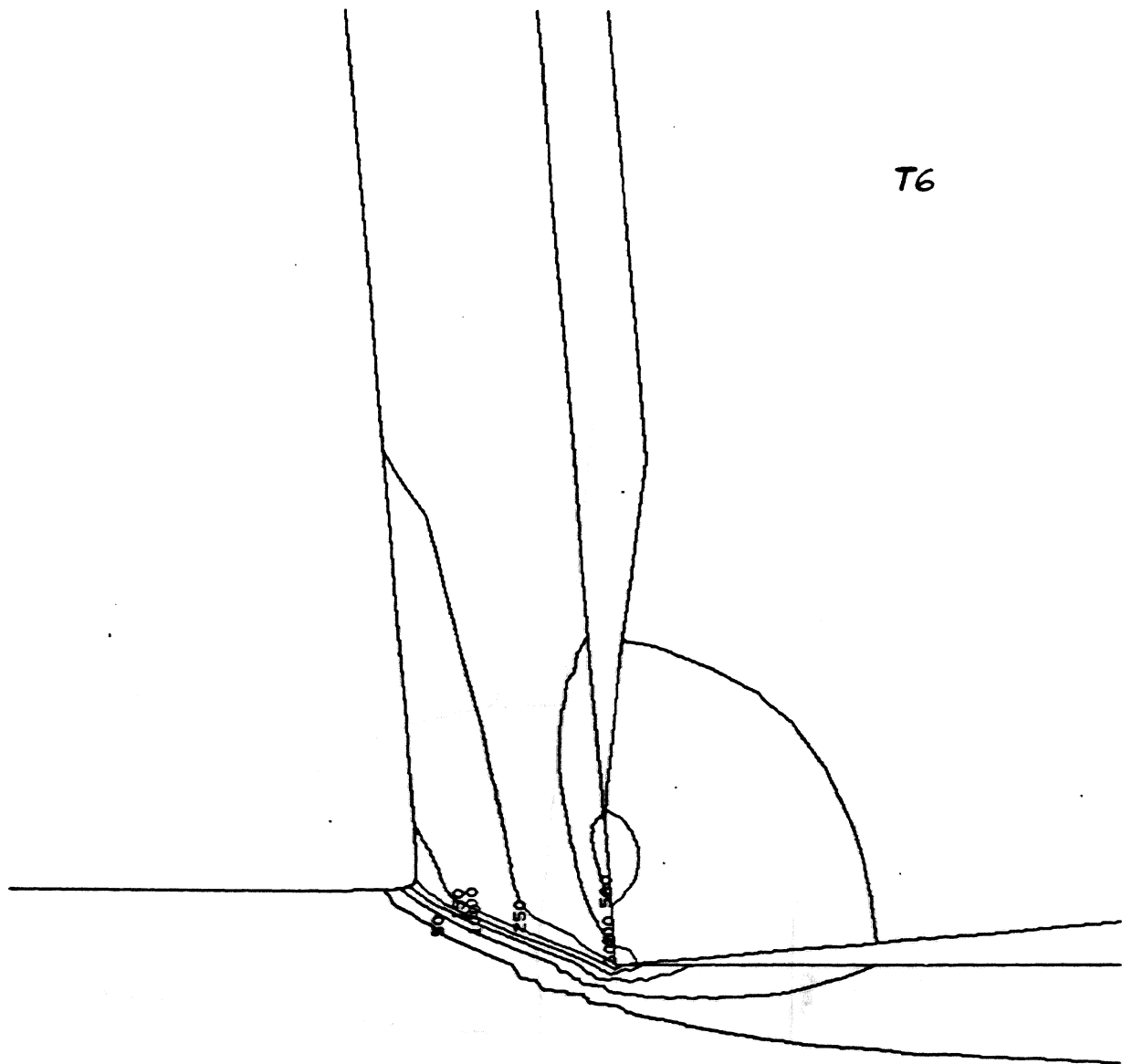


T3









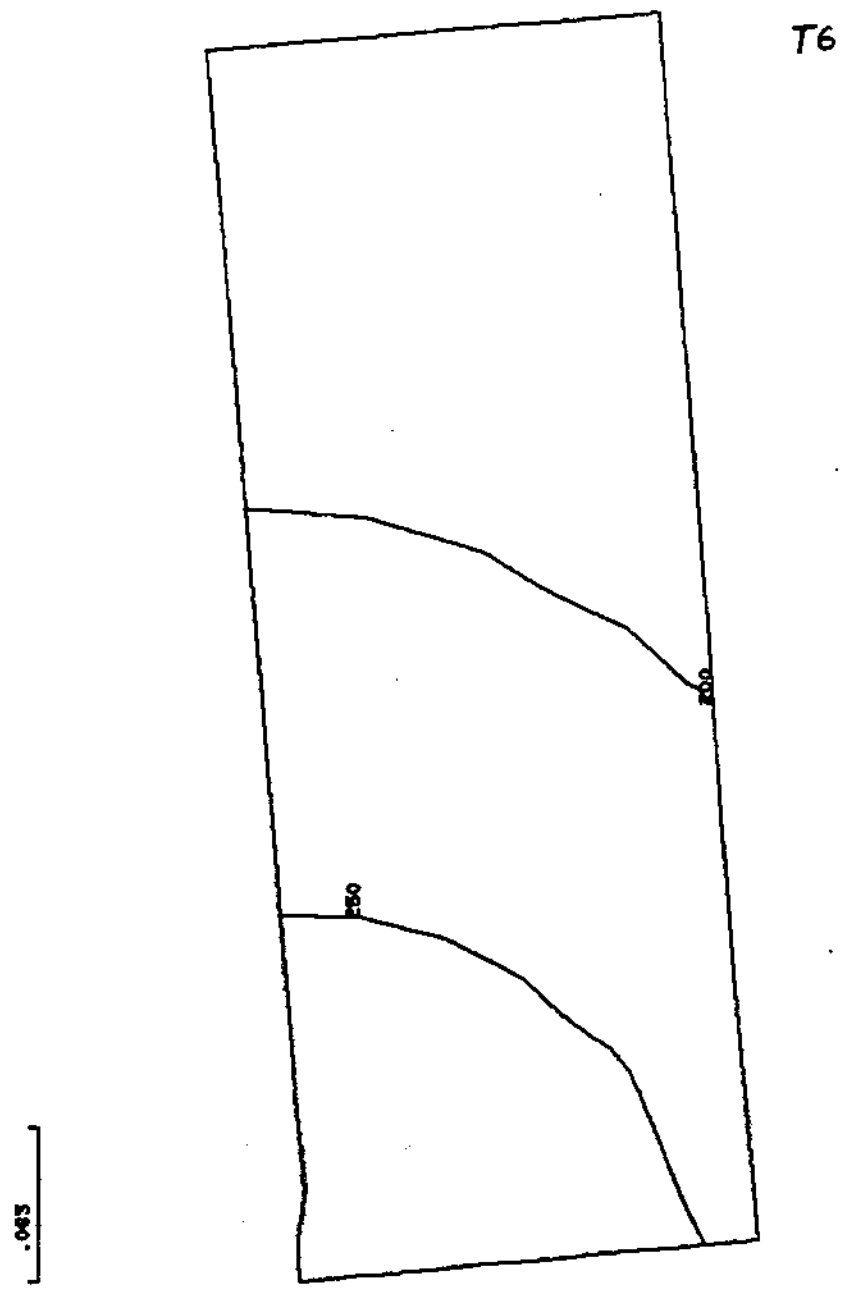
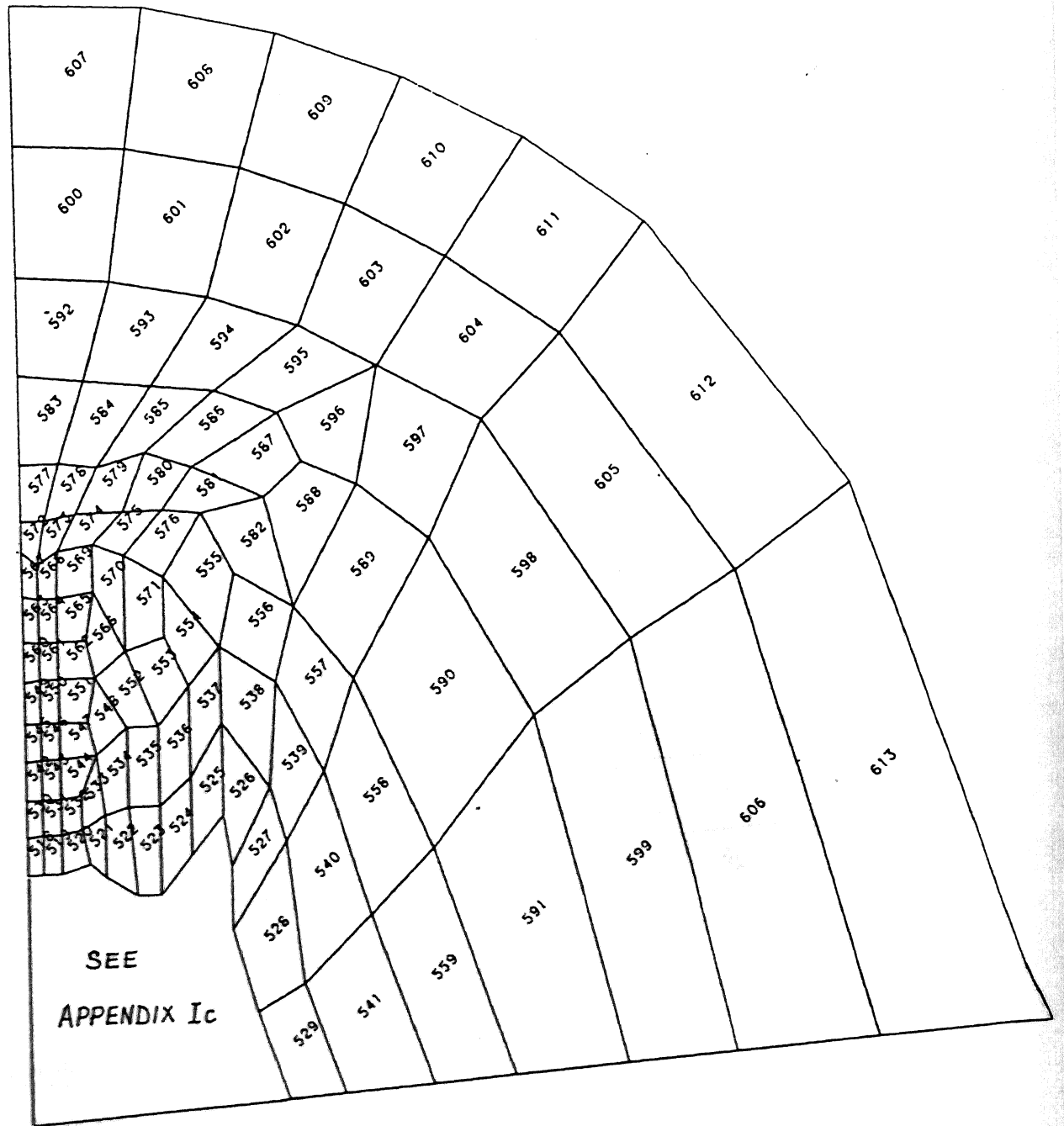


Figure 6: Typical isothermal plot for the remainder of the tool tip (isothermals already shown in the finer detail plot are omitted)

APPENDICES



APPENDIX Ib


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00100      PROGRAM PRIMRY
00200      C
00300      C   PRIMRY TAKES AS INPUT A BASIC MESH FOR ALPHA=0, AND THE MEASURED
00400      C   CONDITIONS. IT PUTS OUT FOR FURTHER PROCESSING BY PROGRAM FINELT
00500      C   A MESH GENERATED FOR THE GIVEN ALPHA, PHI, T1 AND CONTACT LENGTH.
00600      C   IT ALSO PRODUCES FILES OF SHEAR STRAIN, SHEAR STRAIN RATE AND
00700      C   VELOCITY FOR POINTS THROUGHOUT THE PRIMARY ZONE.
00800      C
00900      DIMENSION X(769,2),NOD(679,4),IREAL(343),NFI XD(31),NDTOOL(271)
01000      DIMENSION UV(175,2),GAMMA(175),GAMMAD(175)
01100      DOUBLE PRECISION ACONST,ZED,CAPFA,ABLE,BAKER,CHARLY,
01200      & ALPHA,PHI,SPHI,CPHI,TPHI,SALPHA,CALPHA,TALPHA,SQARG,
01300      & XAB,YAB,XB,YB,SSPACE,T1,ALF,COL,DAN,ERN
01400      DATA NFI XD/187,220,252,282,307,332,356,380,402,420,440,460,482,
01500      & 506,528,550,573,594,611,626,639,651,663,675,689,705,723,724,
01600      & 725,726,727/
01700      C   THE FIRST 26 POINTS OF NFI XD ARE THE CLEARANCE FACE NODES OF THE
01800      C   TOOL(NOT TO BE ROTATED). THE LAST 5 ARE THE END FACE NODES.
01900      OPEN(UNIT=7,DEVICE='DSK',FILE='XYINPT.DAT')
02000      OPEN(UNIT=5,DEVICE='DSK',FILE='PRIMD.DAT')
02100      OPEN(UNIT=3,DEVICE='DSK',FILE='RESULT.TXT')
02200      OPEN(UNIT=20,DEVICE='DSK',FILE='UVEDOT.DAT')
02300      OPEN(UNIT=8,DEVICE='DSK',FILE='XYTEST.DAT')
02400      C   XYTEST.DAT WILL BE THE NEW MESH PRODUCED BY THIS PROGRAM FOR USE
02500      C   BY FINELT. XYINPT.DAT IS A BASIC MESH WITH ALPHA=0.0 AND THE ORIGIN
02600      C   AT THE TOOL EDGE. THE APPROPRIATE FILE IS COPIED TO XYINPT.DAT
02700      C   BEFORE RUNNING THIS PROGRAM. NOTE THAT THIS PROGRAM SHIFTS THE
02800      C   ORIGIN 0.05 IN. TO THE LEFT, MAKING NEARLY ALL X POSITIVE.
02900      READ(7,16) ((X(I,J),J=1,2),I=1,769)

03000      16 FORMAT(8F10.6)
03100      READ(5,5)ALPHA,T1,U,T2,CL,CCONST
03200      5 FORMAT(8F10.6)
03300      ALPHR=ALPHA*0.017453293
03400      TPHI=T1/T2*COS(ALPHR)/(1.-T1/T2*SIN(ALPHR))
03500      PHIR=ATAN(TPHI)
03600      PHI=PHIR/0.0174533
03700      C
03800      C   ALPHA IS THE RAKE ANGLE(DEG.), T1 THE FEED(INCH), U THE CUTTING
03900      C   SPEED(IN./SEC.), T2 IS THE CHIP THICKNESS(INCH), CL THE TOOL-CHIP
04000      C   CONTACT LENGTH(INCH) AND CCONST IS THE CONSTANT IN THE EQUATION:
04100      C   GAMMADOT(MAX)=C*VS/T1.
04200      C
04300      WRITE(3,5)ALPHA,T1,U,PHI,CL,CCONST
04400      READ(5,10) (IREAL(I),I=1,343)

04500      WRITE(3,10) (IREAL(I),I=1,343)
04600      10 FORMAT(20I4)
04700      C   IREAL IS A LIST OF NODE NUMBERS ALONG STREAMLINES, TO THE END
04800      C   OF THE CHIP. THE FIRST STREAMLINE IS AT THE FREE SURFACE.
04900      C   THERE ARE 55 POINTS ON EACH STREAMLINE. THE LAST 13 POINTS IN
05000      C   THIS LIST ARE JUST BELOW THE TOOL EDGE STREAMLINE.
05100      READ(5,12) ((NOD(I,J),J=1,4),I=1,679)
05200      READ(5,12) (NDTOOL(I),I=1,271)
05300      12 FORMAT(16I5)
05400      C   NDTOOL IS A LIST OF ALL NODES IN THE TOOL.
05500      SPHI=SIN(PHIR)
05600      CPHI=COS(PHIR)
05700      COTPHI=CPHI/SPHI
05800      SALPHA=SIN(ALPHR)

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05900      CALPHA=COS(ALPHR)
06000      TALPHA=SALPHA/CALPHA
06100      CONST=U*TPHI*(1.+TPHI*TPHI)

06200  C  •CONST1 IS USED IN THE EQUATION FOR SHEAR STRAIN RATE LATER.
06300      PMA=PHIR-ALPHR
06400      VC=U*SPHI/COS(PMA)
06500      ACONST=T1*T1/(16.*CCONST**2*SPHI**2*(TALPHA + COTPHI))
06600  C  •ACONST1 IS USED LATER IN THE CALCULATION OF STREAMLINE COEFFICIENTS.
06700  C*1
06800  C  THE FOLLOWING SEGMENT ADJUSTS THE CONTACT LENGTH IN THE MESH, I.E.
06900  C  THE DISTANCE FROM THE TOOL EDGE TO POINT 538 ON THE TOOL FACE.
07000  C  OTHER POINTS THROUGHOUT THE TOOL ARE ADJUSTED TO RETAIN A SIMILAR
07100  C  MESH GRADATION. CLEARANCE & END FACE NODES ARE NOT DISTURBED.
07200      CLOLD=X(538,2)
07300      CLDIFF=CL-CLOLD
07400      DO 25 L=2,271
07500          M=NDTOOL(L)
07600          DO 22 N=1,31
07700              IF(NFIXD(N).EQ.M) GO TO 25
07800          22 CONTINUE
07900          IF(X(M,2) .GT.CLOLD) GO TO 24
08000          X(M,2)=X(M,2) + (X(M,2)/CLOLD)**1.1 * CLDIFF
08100          GO TO 25
08200          24 X(M,2)=X(M,2) + CLDIFF
08300          25 CONTINUE
08400  C  ALSO SHIFT THE CHIP BASE NODES BEYOND POINT 538. THE GAP BETWEEN
08500  C  NODES IS INCREASED 30% AT A TIME UNTIL IT REACHES 0.01, WHERE
08600  C  IT STAYS.
08700      GAP=X(538,2)-X(537,2)
08800      GSUM=0.0
08900      DO 26 K=313,330
09000          GAP=GAP*1.3
09100          IF(GAP.GT.0.01) GAP=0.01
09200          GSUM=GSUM + GAP
09300          J=IREAL(K)
09400          X(J,2)=CL + GSUM
09500          26 CONTINUE
09600  C*****
09700  C  THE FOLLOWING SEGMENT ROTATES THE TOOL AND CHIP BASE NODES TO SUIT
09800  C  THE GIVEN RAKE ANGLE, KEEPING THE CLEARANCE FACE FIXED.
09900      DO 35 K=2,271
10000          J=NDTOOL(K)
10100          DO 30 L=1,26
10200              IF(NFIXD(L).EQ.J) GO TO 35
10300          30 CONTINUE
10400          X(J,1)=XOLD *CALPHA+X(J,2)*SALPHA
10500          X(J,2)=X(J,2)*CAXJ>HA-XOLD> *SALPHA
10600          35 CONTINUE
10700  C  ROTATION OF CHIP BASE MODES BEYOND THE CONTACT LENGTH:
10800      DO 50 K=313,330
10900          J=IREAL(K)
11000          X(J,1)=X(J,1)*CALPHA+X(J,2)*SALPHA
11100          X(J,2)*X(J,2)*CALPHA-X(J,1)*SALPHA
11200          50 C30HTIMDE
11300          60 CONTINUE
11400  C  LOW SHIFT THE ORIGIN TO MAKE X VALUES POSITIVE:
11500      DO 70 I=1,769
11600          X(I,1)*X(I,1) + 0.0500000
11700          70 CONTINUE

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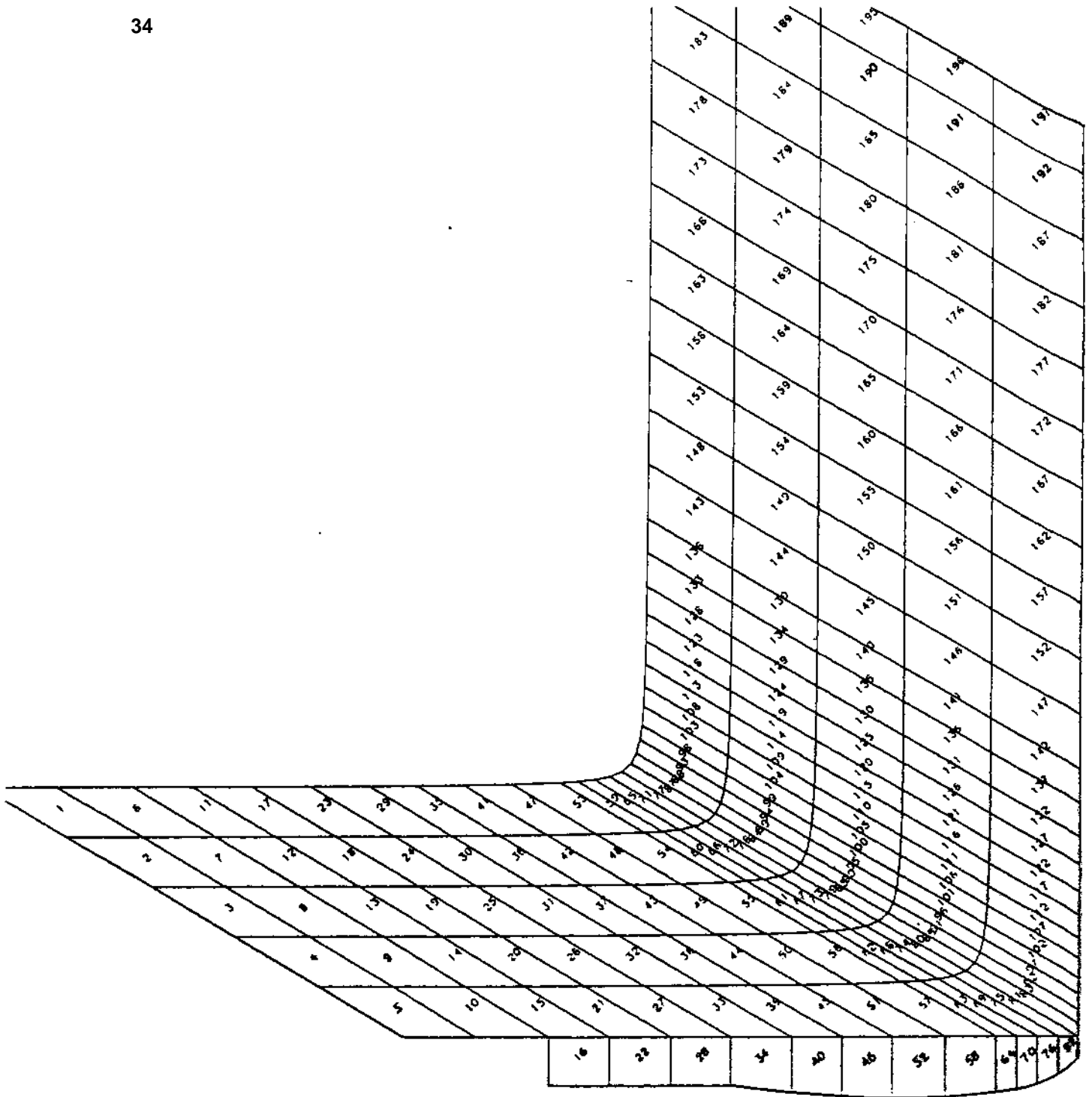
11800 C*****
11900 C THIS SEGMENT BUILDS UP THE PRIMARY ZONE AND CHIP MESH FROM THE BASE
12000 C COORDINATES, VIZ. IREAL(276 TO 330). FIRST THE STREAMLINE EQUATION
12100 C IS FOUND AND THEN ITS INTERSECTIONS WITH LINES EMANATING FROM THE
12200 C BASE NODES, PARALLEL TO THE SHEAR PLANE. WE START WITH THE STREAMLINE
12300 C AT THE FREE SURFACE, WHICH IS PLACED AT A DISTANCE ABOVE THE CUT
12400 C SURFACE EQUAL TO THE FEED, T1. THE SPACING BETWEEN THE STREAMLINES
12500 C IS MADE EQUAL TO T1/5. 55 POINTS ARE DETERMINED ON EACH STREAMLINE.
12600 C
12700     SSPACE=T1/5.
12800     INDEX=0
12900     DO 100 NSLINE=1,5
13000     NPRIM=0
13100     YAB=SSPACE*(6-NSLINE)
13200     XAB=X(156,1)-YAB/TPHI
13300 C XAB AND YAB ARE THE POINTS ON THE SHEAR PLANE WHERE THE ASYMTOTES
13400 C OF THE HYPERBOLIC STREAMLINE INTERSECT.
13500 C THE COEFFICIENTS OF THE HYPERBOLA,  $A*Y*Y+B*X*X+C*X*Y+D*Y+E*X=1$ ,
13600 C ARE FOUND AS FOLLOWS:
13700     ZED=ACONST-TALPHA*YAB**2+XAB*YAB
13800     ALF=TALPHA/ZED
13900     BOB=0.
14000     COL=-1./ZED
14100     DAN=(XAB-2.*TALPHA*YAB)/ZED
14200     ERN=YAB/ZED
14300     WRITE(3,250)NSLINE
14400     250 FORMAT(/' THE COEFFICIENTS FOR STREAMLINE',I3,' ARE:')
14500     WRITE(3,260)ALF,BOB,COL,DAN,ERN
14600     260 FORMAT(/' A =',E15.5,' B =',E15.5,' C =',E15.5,' D ='
14700     & ',E15.5,' E =',E15.5)
14800     WRITE(3,280)
14900     280 FORMAT(//' INDEX NPOINT',7X,'X',11X,'Y',9X,'BETA',7X,'GAMMA',
15000     & 5X,'GAMMADOT')
15100 C FINDING THE MESH POINTS ALONG THE STREAMLINE:
15200     DO 150 I=1,55
15300     INDEX=INDEX+1
15400     NPRIM=NPRIM+1
15500     NBASE=IREAL(275+I)
15600     XB=X(NBASE,1)
15700     YB=X(NBASE,2)
15800     CAPP=TPHI*XB+YB
15900 C THE COEFFICIENTS OF THE QUADRATIC WHOSE SOLN. GIVES THE MESH POINT:
16000     ABLE=ALF-COL/TPHI
16100     BAKER=COL*CAPP/TPHI +DAN - ERN/TPHI
16200     CHARLY=ERN*CAPP/TPHI-1
16300 C GIVING THE SOLUTION:
16400     SQARG=BAKER**2-4.*ABLE*CHARLY
16500     IF(SQARG.LT.0.0) GO TO 99
16600     YY=(-BAKER+SQRT(SQARG))/(2.*ABLE)
16700     XX=(CAPP-YY)/TPHI
16800 C MAKING THE SOLUTION A MESH POINT:
16900     NPOINT=IREAL(INDEX)
17000     X(NPOINT,1)=XX
17100     X(NPOINT,2)=YY
17200 C*****
17300 C THE FOLLOWING CALCULATIONS FOR SHEAR STRAIN, SHEAR STRAIN RATE AND
17400 C VELOCITY ARE ONLY DONE FOR THE PRIMARY ZONE, VIZ. THE FIRST 27 POINTS
17500 C OF EACH STREAMLINE.
17600     IF(NPRIM.GT.27) GO TO 150
17700     J=J+1 .

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17800 DD=2.*ALF*YY + COL*XX + DAN
17900 SLP=- (2.*BOB*XX + COL*YY + ERN)/DD
18000 YDD=-2.*(ALF*SLP*SLP + COL*SLP + BOB)/DD
18100 BETA=ATAN(SLP)
18200 PPA=PHIR+BETA
18300 COTPPA=COS(PPA)/SIN(PPA)
18400 GAMMA(J)=COTPHI-COTPPA
18500 GAMMAD(J)=YDD*CONST/(TPHI+SLP)**3
18600 BETAD=BETA/0.01745329
18700 WRITE(3,450)INDEX,NPOINT,XX,YY,BETAD,GAMMA(J),GAMMAD(J)
18800 450 FORMAT(I7,I8,2X,F10.6,3X,F10.6,3X,F7.3,3X,F8.3,3X,F9.1)
18900 UV(J,1)=VC*COS(PMA)*COS(BETA)/SIN(PPA)
19000 UV(J,2)=VC*COS(PMA)*SIN(BETA)/SIN(PPA)
19100 150 CONTINUE
19200 100 CONTINUE
19300 C THE TOOL EDGE STREAMLINE, UP TO THE TOOL EDGE, IS NOW GIVEN STRAIN,
19400 C STRAIN RATE & VELOCITY DISTRIBUTIONS OF THE STREAMLINE ABOVE IT.
19500 DO 600 J=136,150
19600 K=(J-27)
19700 GAMMA(J)=GAMMA(K)
19800 GAMMAD(J)=GAMMAD(K)
19900 UV(J,1)=UV(K,1)
20000 UV(J,2)=UV(K,2)
20100 600 CONTINUE
20200 DO 650 J=151,162
20300 UV(J,1)=VC*SALPHA
20400 UV(J,2)=VC*CALPHA
20500 GAMMAD(J)=0.0
20600 GAMMA(J)=SIN(PMA)/COS(PMA) + COTPHI
20700 650 CONTINUE
20800 DO 700 J=163,175
20900 UV(J,1)=U
21000 UV(J,2)=0.0
21100 GAMMA(J)=0.0
21200 GAMMAD(J)=0.0
21300 700 CONTINUE
21400 C*****
21500 WRITE(20,900)((UV(I,J),J=1,2),I=1,175)
21600 WRITE(20,900)(GAMMA(I),GAMMAD(I),I=1,175)
21700 WRITE(8,16)((X(I,J),J=1,2),I=1,769)
21800 900 FORMAT(2E20.7)
21900 GO TO 999
22000 99 WRITE(3,400)
22100 400 FORMAT('/' NEGATIVE ARGUMENT IN SQUARE ROOT!')
22200 999 CONTINUE
22300 STOP
22400 END

```



APPENDIX IE

GENERATED PRIMAL XONE

MESH


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01100      IF(DT2.EQ.0.0) DT2=0.05*T2
01120      IF(PCL.EQ.0.0) PCL=CL/2.
01140      WRITE(3,14)U,T1,PHI,ALPHA,FT,FC,CL,W,TROOM,TSHANK,VC,DT2,PCL
01160      14 FORMAT(///' *****'/' CUTTING CONDITIONS:'/' *****

01180      &*****'//T26' WORK VELOCITY, U =',F10.4,' IN/SEC'
01200      & //T26,' FEED RATE, T1 =',F10.4,' INCH/REV.'
01220      & //T26,' SHEAR ANGLE, PHI =',F10.4,' DEGREES'
01240      & //T26,' RAKE ANGLE, ALPHA =',F10.4,' DEGREES'
01260      & //T26,' FEED FORCE, FT =',F10.4,' LBS.'
01280      & //T26,' CUTTING FORCE, FC =',F10.4,' LBS.'
01300      & //T26,' CONTACT LENGTH, CL =',F10.4,' INCH'
01320      & //T26,' WIDTH OF CHIP, W =',F10.4,' INCH'
01340      & //T26,' ROOM TEMP., TROOM =',F10.4,' DEGREES'
01360      & //T26,' TOOL SHANK TEMP.,TSHANK ='F8.2,' DEG.C'
01380      & //T26,' CHIP VELOCITY, VC =',F10.4,' INCH/SEC.'
01400      & //T26,' SEC.ZONE THICKN., DT2 =',F10.4,' INCH'
01420      & //T26,' PLASTIC CONTACT, PCL =',F10.4,' INCH')
01440      READ(1,8) DEN,CP,WCOND,TCOND
01460      WRITE(3,13) DEN,CP,WCOND,TCOND
01480      READ(1,1) NDATA

01500      READ(1,8) (DENCPS(I),I=1,NDATA)

01520      WRITE(3,8) (DENCPS(I),I=1,NDATA)

01540      READ(1,8) (CONDS(I),I=1,NDATA)

01560      WRITE(3,8) (CONDS(I),I=1,NDATA)

01580      8 FORMAT(4E20.7)
01600      13 FORMAT(///// ' *****'/' MATERIAL THERMAL PROP
01620      &ERTIES:'/' *****'
01640      & //T26,' WORK DENSITY AT 50C =',E20.7,' LB/CU.IN.'
01660      & //T26,' WORK SPECIFIC HEAT AT 50C =',E20.7,' CHU/LB'
01680      & //T26,' WORK CONDUCTIVITY AT 50C =',E20.7,' CHU/SEC.IN.DEG.C'
01700      & //T26,' TOOL TIP CONDUCTIVITY AT 22C =',E20.7,' CHU/SEC.IN.DEG.C'
01720      & //' WORK PROPERTY VARIATION WITH TEMPERATURE, 50 DEG.C STEPS:'/'
01740      &' FIRST SET:PRODUCT OF DENSITY & SPEC.HT.;SECOND:CONDUCTIVITY'//)
01760      C
01780      C      READING MESH PARAMETERS
01800      C
01820      READ (1,1) NPOIN,NELEM,NPR1,NENDR1,NENDR2,NENDR3,NENDR4,NBOUN,

01840      &IHC,IHW,IHT
01860      WRITE(3,15) NPOIN,NELEM,NPR1,NENDR1,NENDR2,NENDR3,NENDR4,NBOUN,

01880      &IHC,IHW,IHT
01900      READ (1,1) IQTL,NX1,NY1,NITL1,NITL2,NXBT1

01920      WRITE(3,1) IQTL,NX1,NY1,NITL1,NITL2,NXBT1

01940      READ(1,1) IHST,IHEND

01960      WRITE(3,1) IHST,IHEND

01980      C      IHST & IHEND IDENTIFY THE FIRST & LAST NODES OF TOOL-TO-SHANK
02000      C      CONTACT IN THE MATRIX (NHCWT).
02020      READ (1,8) HINTF

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02040      WRITE(3,8)  HINTF

02060      C      HINTF IS THE TOOL TO SHANK CONDUCTANCE IN CHU/S. SQ.IN. DEG.C
02080      15 FORMAT(///f *****•/• MESH PARAMETERS:1/1 *****
02100      f****<>//T26,• NPOIN =fI10//T26,1 NELEM =•,I10//T26,f NPR1  =',110

02120      &//T26,1 NENDR1=r,I10//T26,f NENDR2=',I10//T26,• NENDR3=f,I10//T26,

02140      &' NENDR4=',I10//T26r' NBOUN =f,I10//T26,f IHC  =f,I10//T26,f IHW

02160      & =1fI10//T26rf IHT  <f,I10/)
02180

      IHCWT=IHC+IHW+IHT

02200

      IHCW=IHC+IHW

02220

02240      C      IHCW2=IHCW+1
02260      C      CALCULATION OF SHEAR STRESS ON AB & ANY RESULTING CORRECTION
02280      C      REQUIRED FOR THE STRESS FUNCTION.
02300      C
02320      GAMDOT=4.67*U*COS (ALPHR) / (T1*COS (PHIR-ALPHR) )
02340      ALMINA=ATAN(FT/FC)
02360      THETA=PHIR+ALMINA
02380      RESUL=SQRT(FC*FC +FT*FT)
02400      ZEE=1. + 1./(4-4.67*SIN(PHIR)*(TAN(ALPHR)+1./TAN(PHIR)))
02420      TAUAB=RESUL*COS (THETA) *SIN (PHIR) / (T1*V*2EE)
02440      CALL      STRESS ( GAMTOT, NSTEEL9,TAU)
02460      DELTAU=TAUAB-TAU
02480      WRITE (3,10)TAU,TAUAB
02500      10 FORMAT(///f CALCULATED SHEAR STRESS <fF10.2f      SHEAR STRESS ON
02520      &AB =fF10.2,•      (PSI)•//)
02540      C

02560      C      CALCULATING GAUSSIAN CO-ORDINATES

02580      C

02600      READ(lf1)  (HPE(I)fI=1f3 )

02620      READ(lr1)  NGP

02640      READ(lf8)  (XGAU(I)fI=1,NGP), (WTC(I)#J=1fNGP)

02660      DO 30 I=1-,NGP

02680      XDUM=XGAU(I)

02700      DO 30 J=1,NGP

02720      WTG(I,J)= WTC(I)*WTC(J)

02740      XEG(I,J,2)= fiUH

02760      XEG(J,I,1) * XDUM
02780      30 CX>NTINUE
02800      WRITE(3,22)  (((XEG(I,J,K),J>1,KGP),I=1,NGP),K=1,2)

02820      22 FORMAT(3E20.7 )

02840      WRITE (3r23)  NGP,(XGAU(I),I=1,MGP),(WTC(I),1=1,NGP )

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02860      23 FORMAT(///' NGP   =',I10//' XGAU(I)=' ,3E20.7//' WTC(I) =' ,3E20.7/)

02880      C

02900      C      READING NODE NUMBERS, BOUNDARY NODES, PRIMARY ZONE STRAINS,
02920      C      STRAIN RATES & VELOCITIES AND NODE COORDINATES.
02940      C

02960      READ(1,920) (NELSL1(I),I=1,NX1)

02980      READ(1,920) ((NOD(I,J),J=1,4),I=1,NELEM )
03000      READ(1,920) (NKNOW(I),I=1,NBOUN)

03020      READ(1,920) ((NHCWT(I,J),J=1,2),I=1,IHCWT )

03040      READ(1,920) ((NFLUX(I,J),J=1,2),I=1,NFE )

03060      READ(1,920) ((NUVQ(I,J),J=1,4),I=1,NENDR1 )

03080      READ(20,970) ((UV(I,J),J=1,2),I=1,NPR1)
03100      READ(20,970) (GAMMA(I),GAMMAD(I),I=1,NPR1)
03120      READ(7,950) ((X(I,J),J=1,2),I=1,NPOIN )

03140      900 FORMAT(10I8)
03160      920 FORMAT(16I5)
03180      950 FORMAT(8F10.6)
03200      970 FORMAT(2E20.7)
03220      C

03240      CALL BANWTH(NELEM,NPOIN,NTYPE,NPE,NOD,ND,NBANR,LH,NBANL)
03260      C
03280      IF(LH.LE.MAXH) GO TO 40

03300      WRITE (3,610) LH

03320      610 FORMAT(//' CHECK LH=',I10)
03340      STOP

03360      40 CONTINUE

03380      WRITE (3,611) LH

03400      611 FORMAT(//' LENGTH OF ARRAY H, LH = ',I10)
03420      F=FT*COS(ALPHR)+FC*SIN(ALPHR)
03440      QC= F*VC/16800./CL/W
03460      QCL= QC*CL

03480      QTOT= FC*U/W/16800. - QCL
03500      WRITE (3,614)QCL,QC,QTOT

03520      614 FORMAT(//' QCL=',E20.8,5X,' QC=',E20.8,5X,' QTOT=',E20.8)

03540      C

03560      C      CALCULATING COORDINATES OF THE SECONDARY ZONE (ASSUMED TRIANGULAR)
03580      C

03600      NY=NY1-1

```



```

03620 C BY-PASS THIS SEGMENT IF SECONDARY DEFORMATION IS NEGLIGIBLE.
03640 IF(DT2.LT.0.0001) GO TO 840

03660 C CALCULATE NFHALF, THE NUMBER OF NODES FROM THE TOOL EDGE
03680 C WHERE PLASTIC CONTACT FINISHES.
03720 YPCL=PCL*COS(ALPHR)
03740 C IF THE PLASTIC CONTACT LENGTH HAS NOT BEEN MEASURED, A VALUE
03760 C OF 0.0 SHOULD BE GIVEN FOR IT IN THE DATA. THE PROGRAM WILL
03780 C THEN ASSIGN IT A VALUE OF HALF THE TOTAL CONTACT LENGTH.
03800 IF(PCL.EQ.CL)GO TO 715
03820 DO 714 I=1,NFE
03840 K=NFLUX(I,2)
03860 YK=X(K,2)
03880 IF(YK.LT.YPCL)GO TO 714
03900 NFHALF=I
03920 YPCL=YK
03940 PCL=YPCL/COS(ALPHR)
03960 GO TO 716
03980 714 CONTINUE
04000 715 NFHALF=NFE
04020 716 NFH1=NFHALF+1
04040 J3=NOD(NITL1+1+NFHALF*NY,2)

04060 WRITE(3,618)NFHALF,PCL,J3
04080 618 FORMAT('/' NFHALF=',I4,' PCL=',F8.4,' J3=',I6//)
04100 NFEF=NFHALF

04120 DO 751 I=1,NFEF

04140 N=NITL1+1+I*NY

04160 IF(I.EQ.1) N=NITL2

04180 J1=NOD(N,1)

04200 J2=NOD(N,4)

04220 DIST= SQRT((X(J1,1)-X(J2,1))**2 + (X(J1,2)-X(J2,2))**2)

04240 ANG=ATAN((X(J2,2)-X(J1,2))/(X(J1,1)-X(J2,1))) - ALPHR

04260 IF(I.NE.1) GO TO 752
04280 BIT=DT2/COS(ANG)/DIST

04300 HEFF=PCL-DT2*TAN(ANG)
04320 PSY=ATAN(HEFF/DT2)

04340 XSEC(NFH1,1)=X(J3,1)

04360 XSEC(NFH1,2)=X(J3,2)

04380 GO TO 753

04400 752 CONTINUE

04420 ANG1=PI-ANG-PSY
04440 DIS = SQRT((X(J1,1)-X(J3,1))**2 + (X(J1,2)-X(J3,2))**2)

04460 DSEC=DIS/HEFF*DT2

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04480          BIT=DSEC*SIN(PHY)/SIN(ANGL)/DIST
04500      753 CONTINUE
04520          DO 751 J=1,2
04540          XSEC(I,J)=X(J1,J)+BIT*(X(J2,J)-X(J1,J))
04560      751 CONTINUE
04580          WRITE (3,8) ((XSEC(I,J),J=1,2),I=1,NFH1)
04600      C
04620      C      CALCULATING Q DISTRIBUTION IN SECONDARY ZONE
04640      C
04660          TAUINT=F*2./(PCL+CL)/W
04680          GMDMAX=VC/DT2
04700          QSITL=TAUINT*GMDMAX/16800.
04720          DO 456 K=1,NFHALF
04740          DO 456 L=1,2
04760          QSEC(K,L)=QSITL
04780      456 CONTINUE
04800          DO 810 I=1,NFHALF
04820          QSEC(I,3)= 0.
04840          QSEC(I,4)= 0.
04860      810 CONTINUE
04880          WRITE (3,8) ((QSEC(I,J),J=1,4),I=1,NFHALF)
04900      840 CONTINUE
04920      C
04940      C      ITERATING FOR TEMPERATURE DISTRIBUTION
04960      C
04980          DO 100 ITER=ITST,ITMAX
05000          IF(ITER.NE.ITST) GO TO 133
05020          IF(ITER.NE.1) GO TO 131
05040          DO 135 I=1,NPOIN
05060          TOLD(I)= TROOM
05080      135 CONTINUE
05100          DO 136 I=1,NPR1
05120          Q(I)= 0.1000000E+05
05140      136 CONTINUE
05160          GO TO 134
05180      131 READ (22,980) (TOLD(I),I=1,NPOIN)
05200          READ (22,980) (Q(I),I=1,NPR1)
05220      980 FORMAT(5F10.2)
05240          GO TO 134

```

```

05260      133 DO 130 I=1,NPOIN

05280      130 TOLD(I)=T(I)

05300      134 CONTINUE

05320      C

05340      C      CALCULATING DISTRIBUTION OF HEAT SOURCES IN PRIMARY ZONE.

05360      C      SINCE STRESS IS A FUNCTION OF STRAIN RATE ONLY, THIS ONLY
05380      C      NEEDS TO BE DONE ON THE FIRST ITERATION.
05400      C

05420          IF(ITER-GT.1) GO TO 140
05440          CALL QRATE(Q,GAMMA,GAMMAD,NPR1,TOLD,NPOIN,NELSL1,NX1,NY1,QITL,
05460          SIQTL,IHCWT,ITER,ITST,NXBT1,NITL2,NOD,NELEM,NSTEEL,DELTAU)

05480      140 CONTINUE
05500      C

05520      C      ASSEMBLYING PROBLEM MATRICES (H) AND (P)

05540      C

05560          CALL HMATEL(NOD,X,NELEM,NPOIN,NTYPE,NPE,DENCPS,CONDS,
05580          &QC,WTG,VC,U,ALPHR,NENDR1,NENDR2,NENDR3,NENDR4,NFE,NGP,T,UV,Q,NPR1,
05600          &XEG,H,LH,ND,TOLD,QTOT,NITL1,NITL2,NFLUX,NUVQ,IQTL,NDATA,ITER,NBANR
05620          &PELQS,SUMA)

05640      C

05660      C      MODIFYING (H) AND (P) ACX^RDIIG TO INTERFACIAL VELOCITY DISTRIBUTION
05680      C      AND SECONDARY ZONE HEAT SOURCES

05700      C

05720          CALL HSECP(NOD,X,NELEM,NPOIN,NTYPE,NPE,DENCPS,ONDS,
05740          &QC,WTG,VC,U,ALPHR,NENDR1,NENDR2,NENDR3,NENDR4,NFE,NGP,T,UV,Q>HPR1,
05760          &XEG,H,LH,ND,TOLD,QTOT,NITL1,NITL2,NFLUX,NUVQ,IQTL,NDATA,ITER,NBANR
05780          &QSEC,XSEC,NFE1,NX1,NBT,CL,NY,VSEC,DT2,PELQS,SUMA,ISHAPE,QSITL,
05800          &NFHALF,PCL,TAUINT)

05820      C

05840          SHK<<0.

05860          W3 702 I=1,NPOIN

05880          SUM=SUM+T(I)
05900      702 CONTINUE
05920          WRITE (3,9) SUM

```

```
05940      9 FORMAT(/' TEMP.SUM =' ,E20.7/)
05960      C
05980      C      IMPOSING BOUNDARY CONDITIONS
06000      C
06020      CALL      BC(H,LH,NKNOW,NBOUN,ND,NBANR,T,NPOIN,X,NHCWT,IHCWT,HCWT,
06040      &TROOM,IHST,IHEND,HINTF,TSHANK)
06060      C
06080      C      SOLVING FOR TEMPERATURE DISTRIBUTION
06100      C
06120      CALL      GBAND(NPOIN,H,LH,ND,T,NBANR )
06140      C
06160      WRITE (3,622) ITER
06180      622 FORMAT(/' NUMBER OF ITERATIONS  =' ,I5)
06200      WRITE (3,11)
06220      11 FORMAT(//' TEMPERATURES:  (DEG C)'/)
06240      WRITE (3,4) (I,T(I),I=1,NPOIN)
06260      4 FORMAT(I10,F10.2,I10,F10.2,I10,F10.2,I10,F10.2,I10,F10.2)
06280      C
06300      C      TESTING CONVERGENCE OF TEMPERATURE DISTRIBUTION
06320      C
06340      DIFMAX=0.
06360      RERMAX=0.
06380      TEST=.FALSE.
06400      DO 110 I=1,NPOIN
06420      TNEW=T(I)
06440      TOLE=TOLD(I)
06460      IF(TOLE.LT.0.1) GO TO 110
06480      DIFF=TNEW-TOLE
06500      RDIFF=DIFF/TOLE
06520      DIFF=ABS(DIFF)
06540      RDIFF=ABS(RDIFF)
```

```

06560      IF(DIFF.GT.DIFMAX) DIFMAX=DIFF
06580      IF(RDIFF.GT.RERMAX) RERMAX=RDIFF
06600      IF(RDIFF.GT.RERROR) TEST=.TRUE.
06620      110 CONTINUE
06640      WRITE (3,634) DIFMAX,RERMAX
06660      634 FORMAT('/' MAX ERROR=' ,E20.6,8X,'MAX RELATIVE ERROR=' ,E20.6)
06680      IF(TEST) GO TO 100
06700      WRITE (3,400)
06720      400 FORMAT('//' CONVERGENCE HAS BEEN REACHED')
06740      C
06760      CALL TEMPLT(NPOIN,NELEM,NHCWT,NKNOW,NOD,X,T,IHC,IHW,IHT,NBOUN,
06780      & NENDR3,IHCWT)
06800      C
06820      GO TO 120
06840      100 CONTINUE
06860      WRITE (3,401)
06880      401 FORMAT('//' CONVERGENCE HAS NOT BEEN REACHED')
06900      120 CONTINUE
06920      WRITE (22,980) (T(I),I=1,NPOIN)
06940      WRITE (22,980) (Q(I),I=1,NPR1)
06960      WRITE (24,980) (T(I),I=1,NPOIN)
06980      STOP
07000      END
07020      C*****
07040      SUBROUTINE HMATL(NOD,X,NELEM,NPOIN,NTYPE,NPE,DENCPS,CONDS,
07060      &QC,WTG,VC,U,ALPHR,NENDR1,NENDR2,NENDR3,NENDR4,NFE,NGP,T,UV,Q,NPR1,
07080      &XEG,H,LH,ND,TOLD,QTOT,NITL1,NITL2,NFLUX,NUVQ,IQTL,NDATA,ITER,NBANR
07100      &,PELQS,SUMA)
07120      C
07140      C ASSEMBLING PROBLEM MATRICES (H) AND (P)
07160      C CONSIDERING ONLY THE PLANE UNIFORM HEAT SOURCE ALONG THE
07180      C INTERFACE DUE TO SLIDING FRICTION.
07200      C
07220      DIMENSION DENCPS(NDATA),CONDS(NDATA)
07240      DIMENSION NOD(NELEM,4),X(NPOIN,2),WTG(NGP,NGP),
07260      &XEG(NGP,NGP,2),H(LH),ND(NPOIN),UV(NPR1,2),Q(NPR1),TOLD(NPOIN),TE(4
07280      &),PELQS(3,4),T(NPOIN),NUVQ(NENDR1,4),NFLUX(NFE,2),NBANR(NPOIN)

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```
07300      DIMENSION XE(4,2),NPE(3),ZETA(4,2),HEL(4,4),PEL(4)
07320      VCX=VC*SIN(ALPHR)
07340      VCY=VC*COS(ALPHR)
07360      KNTL=0
07380      ZETA(1,1)=-1.
07400      ZETA(1,2)=-1.
07420      ZETA(2,1)= 1.
07440      ZETA(2,2)=-1.
07460      ZETA(3,1)= 1.
07480      ZETA(3,2)= 1.
07500      ZETA(4,1)=-1.
07520      ZETA(4,2)= 1.
07540      DO 80 I=1,LH
07560      80 H(I)= 0.
07580      DO 81 I=1,NPOIN
07600      81 T(I)= 0.
07620      C
07640      C      ASSEMBLYING PROBLEM MATRICES (H) AND (P)
07660      C
07680      DO 20 N=1,NELEM
07700      LL=NPE(NTYPE)
07720      DO 51 I=1,LL
07740      PEL(I)= 0.
07760      DO 51 J=1,LL
07780      51 HEL(I,J)= 0.
07800      DO 30 I=1,LL
07820      JJ=NOD(N,I)
07840      TE(I)=TOLD(JJ)
07860      XE(I,1)=X(JJ,1)
07880      30 XE(I,2)=X(JJ,2)
```

```
07900      CALL      ESTQ4L(XE,XEG,LL,UV,Q,NPR1,NGP,HEL,PEL,DENCPS,CONDS,
07920      &NDATA,WTG,NENDR1,NENDR2,NENDR3,NENDR4,VCX,VCY,U,ZETA,N,TOLD,TE
07940      &,NITL1,NITL2,PELQS,KNTL,IQTL,NPOIN,NUVQ)

07960      40 CONTINUE

07980      CALL      ASMBLY(H,LH,NOD,ND,NELEM,NPOIN,HEL,PEL,LL,N,T,NENDR1)

08000      20 CONTINUE

08020      C

08040      C      ADJUSTING QITL FOR ENERGY BALANCE

08060      C

08080      SUMQ=0.

08100      DO 100 I=1,NPOIN

08120      100 SUMQ=SUMQ+T(I)

08140      WRITE (3,3) SUMQ

08160      3 FORMAT(//' SUMQ  =',E20.7)

08180      SUMA=0.

08200      DO 110 I=1,KNTL

08220      DO 110 J=1,4

08240      110 SUMA=SUMA+PELQS(I,J)

08260      WRITE(3,4)
08280      4 FORMAT('/' PELQS VALUES, FOLLOWED BY SUMA:')
08300      WRITE (3,5) ((PELQS(I,J),J=1,4),I=1,KNTL),SUMA

08320      5 FORMAT(/4E20.7)
08340      QDIFF=(QTOT-SUMQ)/SUMA

08360      Q(IQTL)=Q(IQTL) +QDIFF

08380      WRITE (3,5) Q(IQTL)

08400      DO 120 I=1,KNTL

08420      N=NITL1+I-1

08440      DO 120 J=1,4

08460      II=NOD(N,J)

08480      120 T(II)=T(II)+PELQS(I,J)*QDIFF

08500      C

08520      C      ADDITIONAL CONTRIBUTIONS FROM HEAT FLUX ALONG INTERFACE

08540      C
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```

08560      DO 60 K=1,NFE
08580      J1= NFLUX(K,1)
08600      J2=NFLUX(K,2)
08620      DIST= SQRT((X(J1,1)-X(J2,1))**2+(X(J1,2)-X(J2,2))**2)
08640      WRITE (3,74) J1,J2,DIST
08660      T(J1)= T(J1) + QC*DIST/2.
08680      74 FORMAT('/ J1 =',I10,'      J2 =',I10,'      DIST =',F12.6)
08700      60 T(J2)= T(J2) + QC*DIST/2.
08720      RETURN
08740      END
08760      C*****
08780      SUBROUTINE MULT(A,B,C,L,M,N)
08800      C
08820      C      MATRIX MULTIPLICATION  A * B = C
08840      C
08860      DIMENSION A(L,M),B(M,N),C(L,N)
08880      DO 10 I=1,L
08900      DO 10 J=1,N
08920      SUM=0.
08940      DO 20 K=1,M
08960      20 SUM=SUM+A(I,K)*B(K,J)
08980      10 C(I,J)=SUM
09000      RETURN
09020      END
09040      C*****
09060      SUBROUTINE ESTQ4L(XE,XEG,LL,UV,Q,NPR1,NGP,HEL,PEL,DENCPS,CONDS,
09080      &NDATA,WTG,NENDR1,NENDR2,NENDR3,NENDR4,VCX,VCY,U,ZETA,N,TOLD,TE
09100      $,NITL1,NITL2,PELQS,KNTL,IQTL,NPOIN,NUVQ)
09120      C
09140      C      CALCULATION OF ELEMENT MATRICES:-
09160      C      LOCAL VALUES OF MATERIAL PROPERTIES ARE USED.
09180      C
09200      DIMENSION XE( 4,2),XEG(NGP,NGP,2),UV(NPR1,2),Q(NPR1),WTG(NGP,NGP),

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09220      &HEL(4,4),PEL(4),TE(4),TOLD(NPOIN),PELQS(3,LL),DENCPS(NDATA),
09240      &CONDS(NDATA),PELQ(4,4),QE(4),SSA(2,4),NUVQ(NENDR1,4)
09260      DIMENSION      SFN(4),AJ(2,2),ZETA(4,2),AJI(2,2),DELN(2,4)

09280      IF(N.GT.NENDR1) GO TO 10

09300      DO 160 I=1,LL

09320      DO 160 J=1,LL

09340      160 PELQ(I,J)=0.

09360      10 CONTINUE

09380      DO 40 II=1,NGP

09400      DO 40 JJ=1,NGP

09420      WT=WTG(II,JJ)

09440      XZ=XEG(II,JJ,1)

09460      YZ=XEG(II,JJ,2)

09480      C

09500      C      COMPUTING SHAPE FUNCTIONS AND THEIR DERIVATIVES

09520      C

09540      SFN(1)= (1.-XZ)*(1.-YZ)/4.

09560      SFN(2)= (1.+XZ)*(1.-YZ)/4.

09580      SFN(3)= (1.+XZ)*(1.+YZ)/4.

09600      SFN(4)= (1.-XZ)*(1.+YZ)/4.

09620      DO 60 I=1,LL

09640      DELN(1,I)= ZETA(I,1)*(1.+YZ*ZETA(I,2))/4.

09660      60 DELN(2,I)= ZETA(I,2)*(1.+XZ*ZETA(I,1))/4.

09680      C

09700      C      COMPUTING JACOBIAN MATRIX, IT'S DETM AND INVERSE

09720      C

09740      CALL MULT(DELN,XE,AJ,2,LL,2)

09760      DETJ= AJ(1,1)*AJ(2,2)-AJ(2,1)*AJ(1,2)

09780      AJI(1,1)= AJ(2,2)/DETJ

09800      AJI(1,2)=-AJ(1,2)/DETJ

09820      AJI(2,1)=-AJ(2,1)/DETJ

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09840      AJI(2,2)= AJ(1,1)/DETJ
09860      CALL MULT(AJI,DELN,SSA,2,2,LL)
09880      TZ= 0.
09900      DO 120 1=1,LL
09920      120 TZ=TZ+SFN(I)*TE(I)
09940      CALL      PROPTY (DENCPS, CONDS, NDATA, TZ, DENCPC, COND, N, NENDR3,
09960      & NENDR4)
09980      C      COMPUTING ELEMENT STIFNESS MATRIX
10000      IF(N-GT.NENDR1) GO TO 90
10020      UZ=0.
10040      VZ= 0-
10060      QZ=0.
10080      DO 50 1=1,LL
10100      NN=NUVQ(NfI)
10120      QE(I)=Q{NN}
10140      UZ=UZ+SFN(I)*UV(NNr1)
10160      VZ=VZ+SFN(I)*UV(NN#2)
10180      50 CONTINUE
10200      SO 81 1=1,LL
10220      BO 81 J=1,LL
10240      81 PELQ(I#J)=PELQ(I#J)+SFM(I)*SFM(J)*DETJ«WT
10260      GO TO 91
10280      90 IF(H.GT.KENBR2) O3 TO 92
10300      UZ=VCX
10320      VZ=VCY
10340      GO TO 91
10360      92 IF(N*GT,NEMBR3) GO TO 93
10380      UZ=iJ
10400      VZ=0.
10420      91 COITIIUE
10440      SA= (UZ*AJI(1,1)+VZ*AJI(2,1))*DETJ

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10460      SB= (UZ*AJI(1,2)+VZ*AJI(2,2))*DETJ
10480      DO 80 I=1,LL
10500      DO 80 J=1,LL
10520      SCONV= DENCPC*SFN(I)*(SA*DELN(1,J)+SB*DELN(2,J))
10540      SCOND= COND*DETJ*(SSA(1,I)*SSA(1,J)+SSA(2,I)*SSA(2,J))
10560      80 HEL(I,J)=HEL(I,J)+WT*(SCONV+SCOND)
10580      GO TO 40
10600      93 CONTINUE
10620      DO 110 I=1,LL
10640      DO 110 J=1,LL
10660      SCOND= COND*DETJ*(SSA(1,I)*SSA(1,J)+SSA(2,I)*SSA(2,J))
10680      110 HEL(I,J)=HEL(I,J)+WT*SCOND
10700      40 CONTINUE
10720      CALL MULT(PELQ,QE,PEL,LL,LL,1)
10740      IF(N.LT.NITL1) GO TO 1000
10760      IF(N.GT.NITL2) GO TO 1000
10780      KNTL=KNTL+1
10800      DO 130 J=1,LL
10820      IF(NUVQ(N,J).EQ.IQTL) GO TO 140
10840      130 CONTINUE
10860      140 DO 150 I=1,LL
10880      150 PELQS(KNTL,I)=PELQ(I,J)
10900      1000 CONTINUE
10920      RETURN
10940      END

10960      C*****
10980      SUBROUTINE QRATE(Q,GAMMA,GAMMAD,NPR1,TOLD,NPOIN,NELSL1,NX1,NY1,
11000      &QITL,IQTL,IHCWT,ITER,ITST,NXBT1,NITL2,NOD,NELEM,NSTEEL,DELTAU)

11020      C
11040      C      COMPUTING HEAT GENERATION RATE AT POINTS IN THE PRIMARY ZONE
11060      C      IF ITER = 1 THE FIRST APPROXIMATION TO Q(I) WILL BE USED

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11080 C
11100 DIMENSION GAMMA(NPR1),GAMMAD(NPR1),TOLD(NPOIN),NELSL1(27)
11120 DIMENSION Q(NPR1),NOD(NELEM,4)
11140 WRITE (3,3)
11160 3 FORMAT(/' JJ NODE',T18,'GAMMA',T33,'GAMMA-DOT',T47,' K1 '
11180 &,T63,'EXPN',T77,' TAU ',T92,'Q(JJ)',T107,'QDIFF',T123,'TEMP')
11200 JJ=0
11220 NIT=NITL2+NY1-2
11240 DO 12 I=1,NY1
11260 IF(I.EQ.3) NELSL1(NXBT1)=NITL2
11280 DO 10 J=1,NX1
11300 JJ=JJ+1
11320 IF(I.NE.1) GO TO 500
11340 NEL=NELSL1(J)
11360 NN=NOD(NEL,4)
11380 GO TO 510
11400 500 NEL=NELSL1(J)+I-2
11420 IF(I.NE.NY1) GO TO 520
11440 IF(NEL.NE.NIT) GO TO 520
11460 NEL=NITL2
11480 NELSL1(NXBT1)=NIT
11500 520 NN=NOD(NEL,1)
11520 510 CONTINUE
11540 GAM=GAMMA(JJ)
11560 GAMDOT=GAMMAD(JJ)
11580 IF(GAMDOT.GT.0.1) GO TO 40
11600 Q(JJ)=0.
11620 IF(JJ.EQ.IQTL) QITL=Q(JJ)
11640 GO TO 10
11660 40 CONTINUE
11680 CALL STRESS(GAMDOT,NSTEEL,TAU)
11700 TAU1=TAU + DELTAU
11720 EXPN = 0.001
11740 C STRAIN HARDENING IS CONSIDERED NEGLIGIBLE FOR THE PRESENT
11760 C MATERIAL, SO EXPONENT N IS GIVEN A VERY SMALL VALUE.

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11780      TAU=TAU1*GAM**EXPN
11800      QOLD=Q(JJ)

11820      TEMP=TOLD(NN)

11840      Q(JJ)=TAU*GAMDOT/16800.
11860      QDIFF=Q(JJ)-QOLD

11880      IF(JJ.EQ.IQTL) QITL=Q(JJ)

11900      11 WRITE (3,4) JJ,NN,GAM,GAMDOT,TAU1,EXPN,TAU,Q(JJ),QDIFF,TEMP

11920      4  FORMAT(I5,I7,8E15.7)
11940      10 CONTINUE

11960      12 CONTINUE

11980      JJ=JJ+1

12000      DO 50 I=JJ,NPR1

12020      50 Q(I)= 0.

12040      RETURN

12060      END

12080      C*****
12100      SUBROUTINE ASMBLY(H,LH,NOD,ND,NELEM,NPOIN,HEL,PEL,LL,N,T,NENDR1)

12120      C

12140      C   ASSEMBLYING ELEMENT MATRICES INTO PROBLEM MATRIX

12160      C

12180      DIMENSION H(LH),NOD(NELEM,4),ND(NPOIN),HEL(4,4),PEL(4),T(NPOIN)

12200      DO 10 I=1,LL

12220      II=NOD(N,I)

12240      IF(N.GT.NENDR1) GO TO 20

12260      T(II)=T(II)+PEL(I)

12280      20 CONTINUE

12300      DO 10 J=1,LL

12320      JJ=NOD(N,J)-II+ND(II)

12340      10 H(JJ)=H(JJ)+HEL(I,J)

12360      RETURN

12380      END

12400      C*****
12420      SUBROUTINE ASM(H,LH,NOD,ND,NELEM,NPOIN,HEL,PEL,LL,N,T)

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12440  C
12460  C   SUBTRACTING ELEMENT MATRIX HEL FOR SIMPLE SLIDING FRICTION
12480  C   FROM PROBLEM MATRIX H.
12500  C
12520      DIMENSION H(LH) ,NOD(NELEM,4) ,ND(NPOIN)#HEL(4,4) ,PEL(4) ,T(NPOIN)
12540      DO 10 1=1,LL
12560      II=NOD(N,I)
12580      DO 10 J=1,LL
12600      JJ=NOD(N,J)-II+ND(II)
12620      10 H(JJ)=H(JJ)-HEL(I,J)
12640      RETURN
12560      END
12680  C***** *****
12700      SUBROUTINE ASMBL(H,LH,NOD,ND,NELEM,NPOIN,HEL,PEL,LL,N,T)
12720  C
12740  C   ASSEMBLING ELEMENT MATRIX HEL FOR ACTUAL INTERFACE VELOCITY
12760  C   DISTRIBUTION INTO PROBLEM MATRIX H.
12780  C
12800      DIMENSION H(LH) ,NOD(NELEM,4) ,HD(HPOIM) ,HEL(4,4) ,PEL(4) ,T(NPOIN)
12820      DO 10 1=1,LL
12840      II=NOD(NfI)
12860      K) 10 J=1,LL
12880      JJ=NOD(KfJ)-II+ND(11)
12900      10 H(JJ)>>H(JJ)+HEL(IfJ)
12920      RETURN
12940      EHD
12960  C ***** it *****
12980      SUBROUTINE HSECP(NOD,X,NELEM,NPOIH,MT1PE,NPE,DENCPS,CONDS,
13000      &^YTGfVCfU,ALPHR,MENDR1,NENDR2fNENDR3,NENDR4,NFE,NGP,TfUV,Q#IPR1#
13020      &XEG,H,LH,ND,TOLD,QTOT,NITL1,NITL2,MFLUX,NUVQ,IQTL,NDATA,ITER,NBAMB
13040      &fQSECfXSB: ,NFELfNXLMBTfCL,MY#VSEC,I)T2,PELQSfSUMA,ISHAPE,QSITLf
13060      & IFHALF,PCL,TMIIT)
13080  C

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13100 C SUBROUTINE MODIFIES (H) & (P) FROM THE PLANE UNIFORM FRICTION
13120 C SOURCE ANALYSIS TO ALLOW FOR SECONDARY PLASTIC DEFORMATION.
13140 C THE INTERFACE CHIP VELOCITY VARIES WITH DRAG-BACK, STARTING AT
13160 C VC/3 AT THE TOOL EDGE, & REACHING VC AT THE END OF PLASTIC
13180 C CONTACT.
13200 C

13220 DOUBLE PRECISION XE(4,2),XX,YY,A1,A2,B1,B2,C1,C2,D1,D2,EE,FF,GG,

13240 &EGG,FF2
13260 DIMENSION DENCPS(NDATA),CONDS(NDATA)
13280 DIMENSION NOD(NELEM,4),X(NPOIN,2),WTG(NGP,NGP),
13300 &XEG(NGP,NGP,2),H(LH),ND(NPOIN),UV(NPR1,2),Q(NPR1),TOLD(NPOIN),TE(4

13320 &),PELQS(3,4),T(NPOIN),NUVQ(NENDR1,4),NFLUX(NFE,2),NBANR(NPOIN)

13340 DIMENSION XK(4,2),NPE(3),ZETA(4,2),HEL(4,4),PEL(4)

13360 DIMENSION QSEC(NFE,4),XSEC(NFE1,2),VSEC(NFE1),SFN(4),DELN(2,4),

13380 &AJ(2,2),XES(4,2)

13400 VCX=VC*SIN(ALPHR)

13420 VCY=VC*COS(ALPHR)

13440 TCOS=COS(ALPHR)

13460 TSIN=SIN(ALPHR)

13480 ZETA(1,1)=-1.

13500 ZETA(1,2)=-1.

13520 ZETA(2,1)= 1.

13540 ZETA(2,2)=-1.

13560 ZETA(3,1)= 1.

13580 ZETA(3,2)= 1.

13600 ZETA(4,1)=-1.

13620 ZETA(4,2)= 1.

13640 C

13660 C MODIFYING (H) AND (P)

13680 C

13700 VSEC(1) = VC/3.
13720 Q1 = TAUINT*VC/3./16800.-QC
13740 SDS=0.

13760 DO 60 K=1,NFE

13780 J1= NFLUX(K,1)

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13800      J2=NFLUX(K,2)

13820      DIST= SQRT((X(J1,1)-X(J2,1))**2+(X(J1,2)-X(J2,2))**2)

13840      SDS=SDS+DIST

13860      FUN = SQRT(1.+8.*SDS/PCL)/3.
13880      Q2 = TAUINT*VC*FUN/16800.-QC
13900      VSEC(K+1)=VC*FUN
13920      IF(DT2.LT.0.0001)Q2=QC/3.
13940      IF(SDS.LE.PCL)GO TO 62
13960      VSEC(K+1)=VC
13980      Q2 = TAUINT*VC*2.*(1.-SDS/CL)/16800.-QC
14000      62 CONTINUE

14020      WRITE (3,74) J1,J2,DIST,SDS,VSEC(K+1)

14040      74 FORMAT('/' J1 =',I10,'      J2 =',I10,'      DIST =',F12.6,
14060      & '      SDS =',F12.6,'      VSEC(K+1) =',F12.6)
14080      T(J1)= T(J1) + (Q1/3.+Q2/6.)*DIST

14100      T(J2)= T(J2) + (Q2/3.+Q1/6.)*DIST

14120      60 Q1=Q2

14140      C

14160      C      DOES A SECONDARY ZONE EXIST?

14180      C

14200      IF(DT2.LT.0.0001) RETURN

14220      DO 20 NT=1,2

14240      DO 78 IS=1,NFHALF

14260      N=NITL1+1+NY*IS

14280      IF(IS.EQ.1) N=NITL2

14300      LL=NPE(NTYPE)
14320      DO 51 I=1,LL

14340      PEL(I)= 0.

14360      DO 51 J=1,LL

14380      51 HEL(I,J)= 0.

14400      DO 30 I=1,LL

14420      JJ=NOD(N,I)

14440      TE(I)=TOLD(JJ)

14460      XK(I,1)=X(JJ,1)

14480      30 XK(I,2)=X(JJ,2)

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```

14500      CALL      EQ4SCM (XK, XEG, LL, UV, Q, NPR1, NGP, HEL, PEL, DENCPS, CONDS,
14520      &NDATA, WTG, NENDR1, NENDR2, NENDR3, NENDR4, VCX, VCY, U, 2ETA, N, TOLD, TE
14540      &fNITL1_fNITL2, PELQS_rKNTL_rIQTL#NPOIN, NUVQ, VSEC#NFEL, TSIN, TCOS#NT, IS)

14560      IF (NT.NE.1) GO TO 79

14580      CALL      A. ^ (H/LH_rNOD.ND_rNELEM^NPOIN^HEL_rPEL_rLL_rN.T)

14600      GO TO 78

14620      79 CALL      ASMBL (H_rLH, NOD_rND_rNELEM_fNPOIN#HEL_fPEL_fLL_fN_fT)

14640      78 CONTINUE

14660      20 CONTINUE

14680      C

14700      C      MODIFYING (P)      ACCORDING TO Q DISTRIBUTION IN SECONDARY ZONE

14720      C      TRIANGULAR SECONDARY DEFORMATION ZONE ASSUMED

14740      C

14760      QDTFF=QSITL-Q (IQTL)

14780      Q(IQTL)= QSITL

14800      DO 120 I=1,3

14820      N=NITL1+I-1

14840      DO 120 J=1_f4

14860      II=NOD(N_fJ)

14880      120 T(II)=T(II)+PELQS(I,J)*QDIFF

14900      DO 90 IS=1#NFHALF

14920      N=NITL1+1+NY*IS

14940      IF (IS.EQ.1) N=NITL2

14960      IX) 98 I=1,4

14980      98 PEL(I)= 0.

15000      DO 91 I*1,2

15020      IX) 91 J*1,2 *

15040      91 XES(I_fJ)«X(MOD(X,X),J)

15060      IX) 92 J«1.2

15080      XES(3, J)=XSEC (IS+1, J)

15100      92 XES(4_fJ)«ZSBC (IS, J)

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```

15120      DO 97 1=1,4
15140      DO 97 J=1,2
15160      97 XE(I,J)=X(NOD(N,I),J)
15180      DO 93 11=1,NGP
15200      DO 93 JJ=1,NGP
15220      WT=WTG(II,JJ)
15240      XZ=XEG(II,JJ,1)
15260      YZ=XEG(11,JJ,2)
15280      SFN(1)=(1.-XZ)*(1.-YZ)/4*
15300      SFN(2)=(1.+XZ)*(1.-YZ)/4-
15320      SFN(3)=(1.+XZ)*(1.+YZ)/4.
15340      SFN(4)=(1.-XZ)*(1.+YZ)/4.
15360      QZ=0.
15380      DO 94 1=1#4
15400      94 QZ=QZ+SFM(I)*QSEC(IS,I)
15420      DO 95 1=1f4
15440      DELN(1#I)=ZETA(I_f1)*(1.+YZ*ZETA(I#2))/4-
15460      95 DELN(2fI)=ZETA(I_f2)*(1.+XZ*ZETA(I_r1))/4*
15480      CALL MHLT(DELN,XES,AJ_f2,4,2)
15500      DETJ=AJ(1_f1)*AJ(2_r2)-AJ(2_f1)*AJ(1_f2)
15520      Xlt=0.
15540      II<0.
15560      DO 96 I<1,4
15580      XX<XX+SFM(I)*XES(I_f1)
15600      96 YMI+SFM(I)>>XES(I,2)
15620      A1<4**XK-XE(1_f1)-XE(2#1)-XE(3,1)-XE(4_f1)
15640      A2<4.*XT-ZE(1_r2)-ZE(2,2)-ZE(3,2)-XE(4,2)
15660      B1<XE(1_f1)+XE(2f1)-XE(3_f1)-XE(4,1}
15680      B2=XE(1,2)+XE(2,2)-XE(3,2)-XE(4,2}
15700      C1<ZB(2,2)-ZE(1f2)">-ZB(3ff2)-*XE(4,2)

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15720      C2=XE(2,1)-XE(1,1)+XE(3,1)-XE(4,1)
15740      D1=XE(1,2)-XE(2,2)+XE(3,2)-XE(4,2)
15760      D2=XE(1,1)-XE(2,1)+XE(3,1)-XE(4,1)
15780      EE=B1*D1-B2*D2
15800      FF=B1*C1+A1*D1-B2*C2-A2*D2
15820      GG=A1*C1-A2*C2
15840      EGG=4.*EE*GG
15860      FF2=FF*FF
15880      IF(N.GT.NENDR1) GO TO 72
15900      IF(DABS(EE).LT.0.1D-30) GO TO 72
15920      YYZ=(DSQRT(FF2-EGG)-FF)/2./EE
15940      IF(ABS(YYZ).LT.1.) GO TO 99
15960      YYZ=-(FF/EE+YYZ)
15980      GO TO 99
16000      72 YYZ=-GG/(B1*C1-B2*C2)
16020      99 XXZ=(4.*XX-(XE(1,1)+XE(2,1))*(1.-YYZ)-(XE(3,1)+XE(4,1))*(1.+YYZ))/
16040      &((XE(2,1)-XE(1,1))*(1.-YYZ)+(XE(3,1)-XE(4,1))*(1.+YYZ))
16060      WJQ=WT*DETJ*QZ
16080      PEL(1)=PEL(1)+WJQ*(1.-XXZ)*(1.-YYZ)/4.
16100      PEL(2)=PEL(2)+WJQ*(1.+XXZ)*(1.-YYZ)/4.
16120      PEL(3)=PEL(3)+WJQ*(1.+XXZ)*(1.+YYZ)/4.
16140      PEL(4)=PEL(4)+WJQ*(1.-XXZ)*(1.+YYZ)/4.
16160      93 CONTINUE
16180      DO 70 I=1,4
16200      JJ=NOD(N,I)
16220      T(JJ)=T(JJ)+PEL(I)
16240      70 CONTINUE
16260      90 CONTINUE
16280      RETURN
16300      END

```

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16320 C*****
16340 SUBROUTINE EQ4SCM(XE,XEG,LL,UV,Q,NPRL,NGP,HEL,PEL,DENCPS,CONDS,
16360 &NDATA,WTG,NENDR1,NENDR2,NENDR3,NENDR4,VCX,VCY,U,ZETA,N,TOLD,TE
16380 &,NITL1,NITL2,PELQS,KNTL,IQTL,NPOIN,NUVQ,VSEC,NFEL,TSIN,TCOS,NT,IS)

16400 C

16420 C COMPUTING STIFFNESS MATRIX OF A SECONDARY ZONE ELEMENT FOR
16440 C MODIFYING (H) ACCORDING TO ACTUAL INTERFACE VELOCITY
16460 C DISTRIBUTION. LOCAL VALUES OF MATERIAL PROPERTIES ARE USED.
16480 C

16500 DIMENSION VSEC(NFEL)

16520 DIMENSION XE( 4,2),XEG(NGP,NGP,2),UV(NPRL,2),Q(NPRL),WTG(NGP,NGP),

16540 &HEL(4,4),PEL(4),TE(4),TOLD(NPOIN),PELQS(3,LL),DENCPS(NDATA),
16560 &CONDS(NDATA),PELQ(4,4),QE(4),SSA(2,4),NUVQ(NENDR1,4)
16580 DIMENSION SFN(4),AJ(2,2),ZETA(4,2),AJI(2,2),DELN(2,4)

16600 DO 40 II=1,NGP
16620 DO 40 JJ=1,NGP
16640 WT=WTG(II,JJ)
16660 XZ=XEG(II,JJ,1)
16680 YZ=XEG(II,JJ,2)

16700 C
16720 C COMPUTING SHAPE FUNCTIONS AND THEIR DERIVATIVES
16740 C

16760 SFN(1)= (1.-XZ)*(1.-YZ)/4.
16780 SFN(2)= (1.+XZ)*(1.-YZ)/4.
16800 SFN(3)= (1.+XZ)*(1.+YZ)/4.
16820 SFN(4)= (1.-XZ)*(1.+YZ)/4.
16840 DO 60 I=1,LL
16860 DELN(1,I)= ZETA(I,1)*(1.+YZ*ZETA(I,2))/4.
16880 60 DELN(2,I)= ZETA(I,2)*(1.+XZ*ZETA(I,1))/4.

16900 C
16920 C COMPUTING JACOBIAN MATRIX, IT'S DETM AND INVERSE
16940 C

16960 CALL MULT(DELN,XE,AJ,2,LL,2)
16980 DETJ= AJ(1,1)*AJ(2,2)-AJ(2,1)*AJ(1,2)

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17000      AJI(1,1)= AJ(2,2)/DETJ
17020      AJI(1,2)=-AJ(1,2)/DETJ
17040      AJI(2,1)=-AJ(2,1)/DETJ
17060      AJI(2,2)= AJ(1,1)/DETJ
17080      CALL MULT(AJI,DELN,SSA,2,2,LL)
17100      TZ= 0.
17120      DO 120 I=1,LL
17140      120 TZ=TZ+SFN(I)*TE(I)
17160      CALL      PROPTY(DENCPS,CONDS,NDATA,TZ,DENCP,COND,N,NENDR3,
17180      & NENDR4)
17200      C
17220      C      COMPUTING ELEMENT STIFNESS MATRIX
17240      IF(N.GT.NENDR1) GO TO 90
17260      IF(NT.EQ.1) GO TO 51
17280      UZ=(SFN(1)*VSEC(IS)+SFN(2)*VSEC(IS+1))*TSIN+SFN(3)*UV(NUVQ(N,3),1)
17300      &+SFN(4)*UV(NUVQ(N,4),1)
17320      VZ=(SFN(1)*VSEC(IS)+SFN(2)*VSEC(IS+1))*TCOS+SFN(3)*UV(NUVQ(N,3),2)
17340      &+SFN(4)*UV(NUVQ(N,4),2)
17360      GO TO 91
17380      51 CONTINUE
17400      UZ=0.
17420      VZ= 0.
17440      DO 50 I=1,LL
17460      NN=NUVQ(N,I)
17480      UZ=UZ+SFN(I)*UV(NN,1)
17500      VZ=VZ+SFN(I)*UV(NN,2)
17520      50 CONTINUE
17540      GO TO 91
17560      90 IF(NT.EQ.1) GO TO 30
17580      UZ=SFN(1)*VSEC(IS)*TSIN+SFN(2)*VSEC(IS+1)*TSIN+(SFN(3)+SFN(4))*VCX
17600      VZ=SFN(1)*VSEC(IS)*TCOS+SFN(2)*VSEC(IS+1)*TCOS+(SFN(3)+SFN(4))*VCY

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17620      GO TO 91
17640      30 CONTINUE
17660      UZ=VCX
17680      VZ=VCY
17700      91 CONTINUE
17720      SA= (UZ*AJI(1,1)+VZ*AJI(2,1))*DETJ
17740      SB= (UZ*AJI(1,2)+VZ*AJI(2,2))*DETJ
17760      DO 80 I=1,LL
17780      DO 80 J=1,LL
17800      SCONV= DENCPC*SFN(I)*(SA*DELN(1,J)+SB*DELN(2,J))
17820      SCOND= COND*DETJ*(SSA(1,I)*SSA(1,J)+SSA(2,I)*SSA(2,J))
17840      80 HEL(I,J)=HEL(I,J)+WT*(SCONV+SCOND)
17860      GO TO 40
17880      93 CONTINUE
17900      DO 110 I=1,LL
17920      DO 110 J=1,LL
17940      SCOND= COND*DETJ*(SSA(1,I)*SSA(1,J)+SSA(2,I)*SSA(2,J))
17960      110 HEL(I,J)=HEL(I,J)+WT*SCOND
17980      40 CONTINUE
18000      RETURN
18020      END
18040      C*****
18060      SUBROUTINE PROPTY(DENCPS,CONDS,NDATA,TEMP,DENCPC,COND,N,NENDR3,
18080      &NENDR4)
18100      C
18120      C      INTERPOLATING FOR MATERIAL PROPERTIES AT VARIOUS TEMPERATURES
18140      C      LINEAR INTERPOLATION USED
18160      C      STEP SIZE =50 DEGC, U ALWAYS < 1
18180      C
18200      DIMENSION DENCPS(NDATA),CONDS(NDATA)
18220      IF(TEMP.LT.22.)TEMP=22.
18240      IF(N.GT.NENDR3) GO TO 10
18260      NSTEP=TEMP/50.
18280      I1=NSTEP+1

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18300      IF(I1 .GE. NDATA) GO TO 6
18320      U= TEMP/50. -FLOAT(NSTEP)
18340      IF(U.LE. 0.0001 ) GO TO 5

18360      DENCPC=QINTER(DENCPS,NDATA,I1,U)

18380      COND=QINTER(CONDS,NDATA,I1,U)
18400      GO TO 9

18420      5 DENCPC=DENCPS(I1)

18440      COND=CONDS(I1)
18460      GO TO 9
18480      6 DENCPC=DENCPS(NDATA)
18500      COND=CONDS(NDATA)
18520      GO TO 9
18540      10 IF(TEMP.GT.1200.) TEMP=1200.
18560      COND=0.00101-0.320E-06 * (TEMP-22.)
18580      9 RETURN
18600      END

18620      C*****
18640      SUBROUTINE      BC(H,LH,NKNOW,NBOUN,ND,NBANR,T,NPOIN,X,NHCWT,IHCWT,
18660      &HCWT,TROOM,IHST,IHEND,HINTF,TSHANK)

18680      C
18700      C      IMPOSING BOUNDARY CONDITIONS
18720      C
18740      DIMENSION H(LH),NKNOW(NBOUN),ND(NPOIN),NBANR(NPOIN),X(NPOIN,2),T(N
18760      &POIN),NHCWT(IHCWT,2),HCWT(IHCWT)

18780      C
18800      C      BOUNDARY WHERE THE TEMPERATURE IS SPECIFIED:
18820      C
18840      L1= 1
18860      DO 200 K=1,NBOUN
18880      I=NKNOW(K)
18900      ID= ND(I)
18920      IF(I.EQ.1) GO TO 110
18940      L1= ND(I-1)+NBANR(I-1)
18960      110 L2= ID+NBANR(I)-1
18980      DO 101 J=L1,L2
19000      101 H(J)= 0.
19020      H(ID)=1.

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19040          T(I)= TROOM
19060          200 CONTINUE
19080          C
19100          C      WHERE CONTACT CONDUCTANCE OCCURS:
19120          C
19140          DO 10 I=IHST,IHEND
19160          J1= NHCWT(I,1)
19180          J2= NHCWT(I,2)
19200          DIST= SQRT((X(J1#1)-X(J2#1))**2+(X(J1#2)-X(J2#2))**2)
19220          HADD= HINTF*DIST/3-
19240          WRITE (3,2) HADD
19260          2 FORMAT(4E20.7)
19280          DO 20 K=1,2
19300          II=NHCWT(I,K)
19320          ID=ND(II)
19340          IDR=ID+(J1-J2)*(-1)**K
19360          WRITE (3,1) ID,IDR
19380          1 FORMAT(8I10)
19400          T(II)=T(II)+HINTF*TSHANK*DIST/2.
19420          H(ID)=H(ID)+HADD
19440          20 H(IDR)= H(IDR)+HADD/2-
19460          10 O3NTINUE
19480          RETURN
19500          EMD
19520          C*****
19540          SUBROUTINE GBMD(NPOINrH,LH,ND,PfNBANR)
19560          C
19580          C      SUBROUTINE TOR SOLVING A GENERAL BANDED MATRIX
19600          C      GAUSSIAN ELIMINATION AND BACK SUBSTITUTION EMPLOYED
19620          C      ELEMENTS OF BAID STORED HORIZONTALLY IN H(I)
19640          C      K)SITION OF DIAGONAL ELEMENT GIVEN BY KD(I)

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19660  C    LH = LENGTH OF VECTOR IKD
19680  C
19700    DOUBLE PRECISION S
19720    DIMENSION H(LH),ND(NPOIN),P(NPOIN),NBANR(NPOIN)
19740    NM= NPOIN-1
19760    DO 10 N=1,NM
19780    NN= NBANR(N)-1
19800    ID= ND(N)
19820 "    S= H(ID)
19840    DO 20 J=1,NN
19860    20 H(ID+J)= H(ID+J)/S
19880    P(N)= P(N)/S
19900  C
19920  C    GAUSSIAN ELIMINATION
19940  C
19960    DO 30 I=1,NN
19980    IDI= HD(M-H)-I
20000    IF(H(IDI)) 70,30,70
20020    70 S=H(IDI)
20040    DO 40 J=1,NN
20060    JJ= IDI+J
20080    40 H(JJ)= H(JJ)- S*H(IB+J)
20100    P(N+I}= P(M4-I)- S*PCD
20120    30 CXMTINUE
20140    10 O3NTINIE
20160  C
20180  C    BACK SUBSTITUTIOM
20200  C
20220    P(IK)IM) = P(NPOIN)/H(LH)
20240    DO 50 I*1,NN

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20260      N= NPOIN-I
20280      ID= ND(N)
20300      NN= NBANR(N)-1
20320      SUM= 0.
20340      DO 60 J=1,NN
20360      60 SUM= SUM + H(ID+J)*P(N+J)
20380      50 P(N)= P(N)-SUM
20400      RETURN
20420      END

20440      C*****
20460      FUNCTION QINTER(F,NDATA,I1,U)

20480      C
20500      C      LINEAR INTERPOLATION FUNCTION
20520      C
20540      DIMENSION F(NDATA)
20560      Y1=F(I1)
20580      Y2=F(I1+1)
20600      QINTER=Y1 +(Y2-Y1)*U
20620      RETURN
20640      END

20660      C*****
20680      SUBROUTINE BANWTH(NELEM,NPOIN,NTYPE,NPE,NOD,ND,NBANR,LH,NBANL)
20700      C
20720      C      SUBROUTINE TO DETERMINE BANDWIDTHS & DIAGONAL POSITIONS
20740      C      OF THE PROBLEM MATRIX ROWS IN THE VECTOR H.
20760      C
20780      DIMENSION NPE(8),NOD(NELEM,4),ND(NPOIN),NBANR(NPOIN),
20800      & NBANL(NPOIN),LR(8),LL(8)
20820      DO 10 I=1,NPOIN
20840      NBANR(I)=1
20860      NBANL(I)=0
20880      10 CONTINUE
20900      LT=NPE(NTYPE)
20920      DO 20 N=1,NELEM
20940      NR=1
20960      NL=1
20980      DO 30 J=2,LT
21000      IF(NOD(N,J).GT.NOD(N,NR))NR=J
21020      IF(NOD(N,J).LT.NOD(N,NL))NL=J
21040      30 CONTINUE
21060      DO 40 J=1,LT

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```

21080      LR(J)=NOD(N, NR)-NOD(N, J)+1
21100      LL(J)=NOD(N, J)-NOD(N, NL)
21120      40 CONTINUE
21140      DO 50 J=1, LT
21160      JJ=NOD(N, J)
21180      IF(NBANR(JJ).LT.LR(J))NBANR(JJ)=LR(J)
21200      IF(NBANL(JJ).LT.LL(J))NBANL(JJ)=LL(J)
21220      50 CONTINUE
21240      20 CONTINUE
21260      DO 60 N=2, NPOIN
21280      I=NPOIN-N+1
21300      IF(NBANR(N-1)-NBANR(N).GT.1)NBANR(N)=NBANR(N-1)-1
21320      IF(NBANL(I+1)-NBANL(I).GT.1)NBANL(I)=NBANL(I+1)-1
21340      60 CONTINUE
21360      LH=0
21380      DO 70 N=1, NPOIN
21400      LH=LH+NBANR(N)+NBANL(N)
21420      70 ND(N)=LH-NBANR(N)+1
21440      RETURN
21460      END
21480      C*****>.<*****xx*****
21500      SUBROUTINE STRESS(GAMDOT, MSTEEL, TAU)
21520      C .
21540      C CALCULATION OF SHEAR STRESS FROM EMPIRICAL EQUATIONS,
21560      C BASED ON TORSIONAL HOPKINSON BAR TESTS.
21580      C
21600      STRLOG=ALOG10(GAMDOT)
21620      IF (NSTEEL.EQ.1020) GO TO 10
21640      IF (NSTEEL.EQ.1114) GO TO 20
21660      WRITE(3#5)
21680      5 FORMAT(' STEEL PROPERTIES NOT AVAILABLE, 1020 DATA USED1)
21700      10 IF (GAMDOT.LT.200.) TAU=52647. + 788.*STRLOG
21720      IF (GAMDOT.GE.200.) TAU=39159. + 6672.*STRLOG
21740      GO TO 100
21760      20 IF (GAMDOT.LT.200.) TAU=45975. + 778.*STRLOG
21780      IF (GAMDOT.GE.200.) TAU=36258. + 5221*STRLOG
21800      100 CONTINUE
21820      RETURN
21840      END
21860      C!*x*xx*xxx*xxxxxxxx*x*xxxxxxxxxxxxxxxx*xxxxx*xxxxxxx*xxxxxxx**xxxxxxx
21880      SUBROUTINE TEMPLT(NPOIN, ixEM, MHCWT, KKNOW, NOD, X, T, IHC, IH, IHT,
21900      & NBOUN, NENDR3, IHCWT)
21920      C
21940      C PLOTTING TEMPERATURE DISTRIBUTIONS FOR ORTHOGOHAL MACHIIIMG?
21960      C QUADRILATERAL, ELEMENTS ARE DIVIDED INTO TWO TRIURGLS ST
21980      C LINEAR INTERPOLATION USED WITHH TOESE-
22000      C
22020      LOGICAL IPRNT(IOO)

22040      DIMENSION NHCWT(IHCWT,2), SX3IOH(22), MOD(HELEK,4), Z(IIPOIH,2),
22060      & T(MPOIN), ITC20)
22080      DATA IT/50, 100, 150, 200, 250, 300, 400, 500, 600, 650, 700 * 750, 800, 850,
22100      & 900, 1000, 1100, 1200, 1300, 1400/
22120      CALL PLOTS(0.0t0*0, 26)
22140      C

22160      SFAO0.0100
22180      YDWN=-0.012
22200      TMRHT=0.08
22220      ITPLT=1

```

```

22240 C CHANGE ITPLT TO 1 IF A PLOT OF CONTOURS THROUGHOUT THE TOOL
22260 C IS REQUIRED; TO 0 IF IT IS NOT.
22280 IHCW=IHC+IHW

22300 IHCW1=IHCW+1

22320 C

22340 C CHIP _ WORKPIECE _ TOOL

22360 C

22380 CALCF=2.54
22400 XLIM=11.0
22420 YLIM=8.0
22440 ACTFAC=CALCF/SFAC
22460 CALL FACTOR(ACTFAC)
22480 YUP=YLIM*SFAC

22500 HT=TNRHT*SFAC
22520 CALL PLOT(0.060,0.030,-3)
22540 XLIM=XLIM*SFAC

22560 C PLOTTING OUTLINES OF WORK & CHIP.
22580 CALL PLOT(X(1,1),X(1,2),3)
22600 DO 10 I=1,IHCW

22620 DO 10 J=1,2

22640 NN=NHCWT(1,J)

22660 IF(X(NN,1).GT.XLIM.OR.X(NN,2).GT.YUP)GO TO 10
22680 CALL PLOT(X(NN,1),X(NN,2),2)

22700 10 CONTINUE

22720 C PLOTTING THE BOUNDARY BETWEEN PRIMARYZONE & WORK.
22740 NN=NKNOW(1)
22760 CALL PLOT(X(NN,1),X(NN,2),3)
22780 DO 20 I=1,NBOUN

22800 NN=NKNOW(I)

22820 IF(X(NN,1).GT.XLIM.OR.X(NN,2).GT.YUP)GO TO 20
22840 CALL PLOT(X(NN,1),X(NN,2),2)

22860 20 CONTINUE

22880 C PLOTTING PART OF TOOL OUTLINE.
22900 NN=NHCWT(IHCW1,1)

22920 CALL PLOT(X(NN,1),X(NN,2),3)

22940 ICLEAR=IHCW1+22
22960 DO 40 I=IHCW1,ICLEAR

22980 NN=NHCWT(I,2)

23000 IF(X(NN,1).GT.XLIM) GO TO 40
23020 CALL PLOT(X(NN,1),X(NN,2),2)

```

```

23040      40 CONTINUE
23060      NN=NHCWT(IHCWT,2)
23080      CALL PLOT(X(NN,1),X(NN,2),3)
23100      DO 50 I=IHCWT,140,-1
23105      NN=NHCWT(I,r1)
23110      IF(X(NN,2).GT-YUP) GO TO 50
23120      CALL PLOT(X(NN,1),rX(NN,2),2)
23140      50 CONTINUE
23160      C      PLOTTING THE ISOTHERMALS:
23180
          DO 130 1=1,100
23200
          130 IPRNT(I)=wFALSE,
23220
          DO 30 N=1,NELEM
23240
          XJ=X(NOD(N,4),r1)
23260
          YJ=X(NOD(N,4),2)
23280
          IF(yj-GT.YUP.AND.XJ,GT.XLIM-AND.N-GT.NENDR3) GO TO 120
23300
          IF(YJ.GT-YUP) GO TO 30
23320
          IF(XJ.GT-XLIM) GO TO 30
23340
          IF(YJ.LT.YDWN) GO TO 30
23360
          CALL          ISOT(N,T,NOD_f,NELim,IT,X_rNPOIN,IPRNT,HT)
23380
          30 CONTINUE
23400      C
23420      C      TOOL (CONTOURS NOT ALREADY PLOTTED ABOVE)
23440      C
23460      120 IF(ITPLT.EQ.O) GO TO 80
23480      im^NHCWT(IHCWl_r1)
23500      XTL=X(NM,1)
23520      SFAC=SFAC*5.
23540      HT=TNRHT*SFAC
23560      ACTXF=CALCF/SFAC
23580      CALL FACTOR(ACTXF)
23600      CALL PLOT(0.60_#0.00,-3)
23620      CALL PLQT(X(NI!,1)fX(NM,2K3)
23640
          IX) 70 I*IHCWl_r IHCWT
23660      NN=NHCWT(I,2)
23680      70 CALL PLOT(X(NN,1)_#X(NN_f2)_f2)
23700
          CALL PLOT(X(NM_f1)_rX(NM_f2)_f2)
23720
          DO 140 1*1,100
23740      140 IPRNT(I)=.FALSE-

```

```

23760      NN=N
23780      DO 80 N=NN,NELEM
23800      CALL          ISOT(N,T,NOD,NELEM,IT,X,NPOIN,IPRNT,HT)
23820      80 CONTINUE
23840      CALL PLOT(0.0,0.0,-999)
23860      RETURN
23880      END
23900      C*****
23920      SUBROUTINE ISOT(N,T,NOD,NELEM,IT,X,NPOIN,IPRNT,HT)
23940      C
23960      C      PLOTTING ISOTHERMALS WITHIN QUADRILATERAL ELEMENT
23980      C
24000      LOGICAL TEST,IPRNT(100)
24020      DIMENSION T(NPOIN),NOD(NELEM,4),IT(15),IE(50),XIT(100),X(NPOIN,2)
24040      I1=NOD(N,1)
24060      I2=NOD(N,2)
24080      I3=NOD(N,3)
24100      I4=NOD(N,4)
24120      T1=T(I1)
24140      T2=T(I2)
24160      T3=T(I3)
24180      T4=T(I4)
24200      IF(IT(1).GT.AMAX1(T1,T2,T3,T4)) RETURN
24220      ITMIN=MIN1(T1,T2,T3,T4)
24240      ITMIN=ITMIN/10+1
24260      ITMIN=ITMIN*10
24280      IL=0
24300      10 IL=IL+1
24320      IF(IT(IL)-ITMIN) 10,20,20
24340      20 JJ=0
24360      IH=IL

```

```

24380      CALL TCORD(T1,T2,I1,I2,X,NPOIN,IL,IE,XIT,JJ,IT,IH)
24400      CALL TCORD(T2,T3,I2,I3,X,NPOIN,IL,IE,XIT,JJ,IT,IH)
24420      CALL TCORD(T3,T1,I3,I1,X,NPOIN,IL,IE,XIT,JJ,IT,IH)
24440      CALL TCORD(T1,T4,I1,I4,X,NPOIN,IL,IE,XIT,JJ,IT,IH)
24460      CALL TCORD(T4,T3,I4,I3,X,NPOIN,IL,IE,XIT,JJ,IT,IH)
24480      TEST=.FALSE.
24500      DO 40 I=IL,IH
24520          IPEN=3
24540          IF(JJ.EQ.0) RETURN
24560          DO 40 J=1,JJ
24580          IF(IE(J).NE.I) GO TO 40
24600          CALL PLOT(XIT(J),XIT(50+J),IPEN)
24620          IPEN=2
24640          IF(IPRNT(I).OR.TEST) GO TO 40
24660          IPRNT(I)=.TRUE.
24680          TEST=.TRUE.
24700          TLEVEL=FLOAT(IT(I))
24720          CALL NUMBER(XIT(J),XIT(50+J),HT,TLEVEL,90.,-1)
24740          CALL PLOT(XIT(J),XIT(50+J),3)
24760      40 CONTINUE
24780      RETURN
24800      END
24820      C*****
24840      SUBROUTINE TCORD(T1,T2,I1,I2,X,NPOIN,IL,IE,XIT,JJ,IT,IH)
24860      C
24880      C      CALCULATING CO-ORD OF ISOTHERMALS AT SIDE I1 - I2
24900      C
24920          DIMENSION IE(50),XIT(100),X(NPOIN,2),IT(15)
24940          I=IL-1
24960      30 I=I+1
24980          TP=IT(I)

```

```
25000      IF(TP.GT.AMAX1(T1,T2)) GO TO 100
25020      IF((TP-T1)*(TP-T2)) 20,20,30
25040      20 JJ=JJ+1
25060      IE(JJ)=I
25080      IF(I.GT.IH) IH=I
25100      XIT(JJ)=X(I1,1)+(X(I2,1)-X(I1,1))*(TP-T1)/(T2-T1)
25120      XIT(50+JJ)=X(I1,2)+(X(I2,2)-X(I1,2))*(TP-T1)/(T2-T1)
25140      GO TO 30
25160      100 RETURN
25180      END
```



```

00100      PROGRAM MESHPL
00200  C
00300  C PLOTTING THE FEM MESH IN THE PRIMARY ZONE, CHIP & TOOL.
00400  C
00500      DIMENSION X(769,2),NOD(679,4)
00600      OPEN(UNIT=7,DEVICE='DSK1',FILE='•-XYTST3.DATf')
00700      OPEN(UNIT=9,DEVICE='tDSKt',FILE='fNOD.DATf')
00800      READ(7,950)((X(T,J),J=1,2),1=1,769)
00900      950 FORMAT(8F10.6)
01000      READ(9,920)((NOD(I,J),J=1,4),1=1,679)
01100      920 FORMAT(16I5)
01200      CALL PLOTS(0.0,0.0,27)
01300      TNRHT=0.08
01310  C
01320  C C PRIMARY ZONE & PART OF CHIP.
01330  C
01340      SFAC=0.004
01350      XORIGN=0.016
01360      YORIGN=0.002
01370      NSTART=1
01380      NSTOP=222
01390      CALLELEMP(L(X,NOD,SFAC,TNRHT,XORIGN,YORIGN,NSTART,NSTOP)
01405  C
01410  C C TOOL TIP TO ELEMENT 582
01415  C
01420      SFAC=0.002
01430      XORIGN=0.000
01435      YORIGN=0.000
01445      NSTART=448
01450      NSTOP=582
01455      CALL ELEMPL(X,NOD,SFAC,TNRHT,XORIGNfYC^IGNt,NSTART,NSTOP)
01500  C
01600  C C ELEMENTS 583 TO 620
01700  C
01800      SFAC=0.008
02000      XORIGN=0.275
02100      YORIGN=0.000
02300      HSTART=583
02400      NSTOP=620
02500      CALL ELEMPL(X,NOD#SFAC,TNRHT,XORIGN,YORIGN,NSTART,NSTOP)
02600  C
02700  C C REMAINDER OF TOOL
02800  C
02900      SFAC=0.04€
03100      XORIGN=0.558
03200      YORIGN=0.000
03400      NSTART=621
03500      NSTOP=679
03600      CALL ELEMPL(X,NOD,SFAC,TNRHT,XORIGN,YORIGN,NSTART,MSTOP)
03650      CALL PLOT(0.0,0.0,-999)
03670      STOP
03690      END
03700  C*****atx*itit*****
03800      SUBROUTINEELEMPL(X,MOD,SFAC,TMRHT,XORIGN,YORIGNfIfSTART,MSTOP)
03900      DIMENSION X(769,2),MOD(679,4)
03920      ACTFAC=2.54/SFAC
03940      HT=TMRHT*SFAC
04000      CALL FACTOR(ACTFAC)
04100      CALL PIX}T(XORIGMfYORIGMf-3)
04200      M4=MOD(NSTARTA)

```

```
04300      CALL PLOT(X(N4,1),X(N4,2),3)
04400      DO 50 N=NSTART,NSTOP
04500      J4=NOD(N,4)
04600      CALL PLOT(X(J4,1),X(J4,2),3)
04700      SUMX=0.
04800      SUMY=0.
04900      DO 100 I=1,4
05000      J=NOD(N,I)
05100      SUMX=SUMX+X(J,1)
05200      SUMY=SUMY+X(J,2)
05300      CALL PLOT(X(J,1),X(J,2),2)
05400 100 CONTINUE
05500      XM=SUMX/4.
05600      YM=SUMY/4.
05700      XELEM=FLOAT(N)
05800      CALL NUMBER(XM,YM,HT,XELEM,45.,-1)
05900 50 CONTINUE
06000      RETURN
06100      END
```

PRIMD.DAT

APPENDIX VI

α	t_1	U	t_2	h	C														
-5.000000	0.010400	60.000000	0.022000	0.010000	4.670000														
1	7	15	25	37	51	69	91	119	120	147	176	207	237	238	268	269	292	293	294
317	341	365	366	386	387	403	421	441	461	483	507	529	551	574	595	596	612	613	614
627	628	640	652	664	676	690	706	728	734	740	746	752	758	764	2	8	16	26	38
52	70	92	93	121	148	177	208	209	239	240	270	271	272	295	318	342	343	367	368
388	404	422	442	462	484	508	530	552	575	576	597	598	599	615	616	629	641	653	665
677	691	707	729	735	741	747	753	759	765	3	9	17	27	39	53	71	72	94	122
149	178	179	210	211	241	242	243	273	296	319	320	344	345	369	389	405	423	443	463
485	509	531	553	554	577	578	579	600	601	617	630	642	654	666	678	692	708	730	736
742	748	754	760	766	4	10	18	28	40	54	55	73	95	123	150	151	180	181	212
213	214	244	274	297	298	321	322	346	370	390	406	424	444	464	486	510	532	533	555
556	557	580	581	602	618	631	643	655	667	679	693	709	731	737	743	749	755	761	767
5	11	19	29	41	42	56	74	96	124	125	152	153	182	183	184	215	245	275	276
299	300	323	347	371	391	407	425	445	465	487	511	512	534	535	536	558	559	582	603
619	632	644	656	668	680	694	710	732	738	744	750	756	762	768	6	12	20	30	31
43	57	75	97	98	126	127	154	155	156	185	216	246	247	277	278	301	324	348	372
392	408	426	446	466	488	489	513	514	515	537	538	560	583	604	620	633	645	657	669
681	695	711	733	739	745	751	757	763	769	21	22	32	44	58	76	77	99	100	128
129	130	131																	
2	8	7	1	3	9	8	2	4	10	9	3	5	11	10					4
6	12	11	5	8	16	15	7	9	17	16	8	10	18	17					9
11	19	18	10	12	20	19	11	16	26	25	15	17	27	26					16
18	28	27	17	19	29	28	18	20	30	29	19	21	22	30					20
26	38	37	25	27	39	38	26	28	40	39	27	29	41	40					28
30	31	41	29	22	32	31	30	38	52	51	37	39	53	52					38
40	54	53	39	41	42	54	40	31	43	42	41	32	44	43					31
52	70	69	51	53	71	70	52	54	55	71	53	42	56	55					54
43	57	56	42	44	58	57	43	70	92	91	69	71	72	92					70
55	73	72	71	56	74	73	55	57	75	74	56	58	76	75					57
92	93	119	91	72	94	93	92	73	95	94	72	74	96	95					73
75	97	96	74	76	77	97	75	93	121	120	119	94	122	121					93
95	123	122	94	96	124	123	95	97	98	124	96	77	99	98					97
121	148	147	120	122	149	148	121	123	150	149	122	124	125	150					123
98	126	125	124	99	100	126	98	148	177	176	147	149	178	177					148
150	151	178	149	125	152	151	150	126	127	152	125	100	128	127					126
177	208	207	176	178	179	208	177	151	180	179	178	152	153	180					151
127	154	153	152	128	129	154	127	208	209	237	207	179	210	209					208
180	181	210	179	153	182	181	180	154	155	182	153	129	130	155					154
209	239	238	237	210	211	239	209	181	212	211	210	182	183	212					181
155	156	183	182	130	131	156	155	156	185	184	183	211	241	240					239
212	213	241	211	183	184	213	212	239	240	268	238	240	270	269					268
241	242	270	240	213	214	242	241	184	215	214	213	185	216	215					184
270	271	292	269	242	243	271	270	214	244	243	242	215	245	244					214
216	246	245	215	271	272	293	292	243	273	272	271	244	274	273					243
245	275	274	244	246	247	275	245	272	295	294	293	273	296	295					272
274	297	296	273	275	276	297	274	247	277	276	275	295	318	317					294
296	319	318	295	297	298	319	296	276	299	298	297	277	278	299					276
318	342	341	317	319	320	342	318	298	321	320	319	299	300	321					298
278	301	300	299	342	343	365	341	320	344	343	342	321	322	344					320
300	323	322	321	301	324	323	300	343	367	366	365	344	345	367					343
322	346	345	344	323	347	346	322	324	348	347	323	367	368	386					366
345	369	368	367	346	370	369	345	347	371	370	346	348	372	371					347
368	388	387	386	369	389	388	368	370	390	389	369	371	391	390					370
372	392	391	371	388	404	403	387	389	405	404	388	390	406	405					389
391	407	406	390	392	408	407	391	404	422	421	403	405	423	422					404
406	424	423	405	407	425	424	406	408	426	425	407	422	442	441					421
423	443	442	422	424	444	443	423	425	445	444	424	426	446	445					425
442	462	461	441	443	463	462	442	444	464	463	443	445	465	464					444
446	466	465	445	462	484	483	461	463	485	484	462	464	486	485					463
465	487	486	464	466	488	487	465	484	506	507	483	485	509	508					484
486	510	509	485	487	511	510	486	488	489	511	487	506	530	529					507
509	531	530	508	510	532	531	509	511	512	532	510	489	513	512					511
530	552	551	529	531	553	552	530	532	533	553	531	512	534	533					532

ICLEAR

NOD

513	514	534	512	552	575	574	551	553	554	575	552	533	555	554	553
534	535	555	533	514	515	535	534	575	576	595	574	554	577	576	575
555	556	577	554	535	536	556	555	515	537	536	535	576	597	596	595
577	578	597	576	556	557	578	577	536	558	557	556	537	538	558	536
597	598	612	596	578	579	598	597	557	580	579	578	558	559	580	557
538	560	559	558	598	599	613	612	579	600	599	598	580	581	600	579
559	582	581	580	560	583	582	559	599	615	614	613	600	601	615	599
581	602	601	600	582	603	602	581	583	604	603	582	615	616	627	614
601	617	616	615	602	618	617	601	603	619	618	602	604	620	619	603
616	629	628	627	617	630	629	616	618	631	630	617	619	632	631	618
620	633	632	619	629	641	640	628	630	642	641	629	631	643	642	630
632	644	643	631	633	645	644	632	641	652	652	640	642	654	653	641
643	655	654	642	644	656	655	643	645	657	656	644	653	665	664	652
654	666	665	653	655	667	666	654	656	668	667	655	657	669	668	656
665	677	676	664	666	678	677	665	667	679	678	666	668	680	679	667
669	681	680	668	677	691	690	676	678	692	691	677	679	693	692	678
680	694	693	679	681	695	694	680	691	707	706	690	692	708	707	691
693	709	708	692	694	710	709	693	695	711	710	694	707	729	728	706
708	730	729	707	709	731	730	708	710	732	731	709	711	733	732	710
729	735	734	728	730	736	735	729	731	737	736	730	732	738	737	731
733	739	738	732	735	741	740	734	736	742	741	735	737	743	742	736
738	744	743	737	739	745	744	738	741	747	746	740	742	748	747	741
743	749	748	742	744	750	749	743	745	751	750	744	747	753	752	746
748	754	753	747	749	755	754	748	750	756	755	749	751	757	756	750
753	759	758	752	754	760	759	753	755	761	760	754	756	762	761	755
757	763	762	756	759	765	764	758	760	766	765	759	761	767	766	760
762	768	767	761	763	769	768	762	14	13	12	6	13	21	20	12
13	23	22	21	14	24	23	13	23	33	32	22	24	34	33	23
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172	203	202	171	173	204	203	172	174	205	204	173	175	206	205	174
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ie6	217	216	185	217	218	246	216	219	218	217	186	220	219	186	187
218	248	247	246	248	249	277	247	218	250	2*9	248	219	251	250	218
252	251	£19	220	249	279	278	277	250	280	£79	249	251	281	280	250
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281	306	305	280	282	307	306	281	302	325	324	301	303	326	325	302
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328	352	351	327	354	328	329	330	355	35*	330	331	356	355	331	332
354	353	352	328	355	379	353	354	356	380	379	355	349	373	372	348
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427	447	*46	426	428	448	447	427	429	430	*48	428	411	431	430	429
412	413	431	411	447	467	466	446	448	449	*67	447	430	450	449	448
431	432	450	430	413	433	432	431	414	43*	433	413	415	435	434	414
416	436	435	415	417	437	436	416	418	438	437	417	419	439	438	418
420	440	439	419	467	468	488	466	449	469	468	467	450	451	469	449
432	452	*51	450	433	453	452	432	434	45*	453	433	435	455	454	434
436	456	455	435	437	457	456	436	438	458	457	437	439	459	458	438
440	460	459	439	468	490	469	488	469	470	490	468	451	452	470	469
490	491	513	469	470	471	491	490	452	472	471	470	452	453	473	472
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455	475	474	454	455	456	476	475	456	478	*77	476	457	479	478	456
458	480	479	457	459	481	480	458	460	482	AB1	459	492	516	515	514
493	494	516	492	473	495	494	493	516	517	537	515	494	518	517	516
495	496	518	494	473	474	496	495	517	539	538	537	518	519	539	517
496	497	519	518	474	498	497	496	475	476	493	474	539	540	561	538
519	520	540	539	497	521	520	519	498	499	521	497	476	477	499	498
540	541	562	561	520	542	541	540	521	522	542	520	499	500	522	521
477	501	500	499	479	501	477	478	541	56*	563	562	542	543	564	541
522	523	543	542	500	524	523	522	501	502	524	500	479	503	502	501
480	504	503	479	481	505	504	480	482	506	505	481	564	565	584	563
543	544	565	564	523	545	544	543	524	525	5*5	523	503	525	524	502
504	526	525	503	505	527	526	504	506	528	527	505	565	566	585	58*
544	567	566	565	545	546	567	544	525	547	546	545	526	548	547	525
527	549	548	526	528	550	549	527	566	587	586	585	567	568	587	566
546	569	568	567	547	570	569	546	5*8	571	570	547	549	572	571	548
550	573	572	549	587	588	605	586	568	589	£38	587	569	590	589	568
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672	664	683	671	673	685	664	672	67*	666	685	673	663	697	696	682
684	698	697	663	665	686	690	664	697	713	712	696	696	699	713	697
686	700	699	690	675	689	688	674	674	688	687	686	689	705	704	693
686	687	701	700	687	703	702	701	6B8	70*	703	687	713	715	714	712.
699	716	715	713	700	717	716	699	701	702	717	700	716	720	721	715
717	719	720	716	702	718	719	717	715	721	722	714	721	726	727	722
720	725	726	721	719	724	725	720	718	723	724	719				
156	185	166	187	216	217	218	219	220	246	2A7	248	249	250	251	252"
277	278	£79	280	281	282	301	302	303	30*	305"	306	307	324	325	326
327	328	329	330	331	332	*348	349	350	351	352	353	354	355	356	372
373	374	375	376	377	376	379	380	392	393	394	395	396	397	398	399
400	401	*02	408	409	410	411	412	413	41*	415	416	417	418	419	420
426	427	*28	429	430	431	432	433	434	435	436	437	438	439	440	446
447	448	-i49	450	451	452	453	454	455	456	457	458	45*?	460	466	467
468	469	470	471	472	473	474	475	476	477	478	479	460	401	482	488
489	490	491	492	493	494	495	496	497	498	*99	500	501	502	503	50*
505	506	313	514	515	516	517	518	319	520	321	522	523	524	525	526
527	526	537	938	539	540	541	542	543	54*	545	546	547	548	549	550
561	562	563	564	565	566	567	568	569	570	371	372	373	584	385	566
587	588	589	390	391	392	393	394	603	606	607	600	609	610	681	621
622	623	&24	625	626	634	633	636	637	636	639	646	647	646	649	650
651	656	659	660	661	662	663	670	671	672	673	674	675	682	683	684
683	666	487	688	689	696	697	698	699	700	701	702	703	704	705	712
713	714	713	716	717	718	719	720	721	722	723	724	725	726	727	

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684	698	697	683	685	686	698	684	697	713	712	696	698	699	713	697j
636	700	699	6VU	673	68?	6S«	674	674	6©S	687	686	68V	703	704	688j
686	687	701	700	687	703	702	701	638	704	703	687	712	715	714	712
699	716	715	713	700	717	716	699	701	702	717	700	716	720	721	715
717	719	720	716	702	718	719	717	715	721	722	714	721	726	727	722
720	725	726	721	719	724	725	720	718	723	724	719				
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236	267	291	316	340-	364										119
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119	120	120	147	147	176	176	207	207	237	237	238	238	268	268	269
269	292	292	293	293	294	294	317	317	341	341	365	365	366	366	386
386	387	387	403	403	421	421	441	441	461	461	483	483	507	507	529
529	551	551	574	574	595	595	596	596	612	6V2	613	613	614	614	627
627	628	628	640	640	652	652	664	664	676	676	690	690	706	706	726
728	734	734	740	740	746	746	752	752	7se	758	764	769	763	763	757
757	751	751	745	745	739	739	733	733	711	711	695	695	681	681	669
669	657	657	645	645	633	633	620	620	604	604	583	583	560	560	538
156	157	157	188	188	189	189	190	190	191	191	221	221	222	222	253
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308	309	309	333	333	357	357	381	381	382	382	383	156	187	187	220
220	252	252	282	282	307	307	332	332	356	356	380	380	402	402	420
420	440	440	460	460	482	482	506	506	528	528	550	550	573	573	594
594	611	611	626	626	639	639	651	651	663	663	675	675	689	689	705
705	704	704	703	703	702	702	718	718	723	723	724	724	725	725	726
726	727	727	722	722	714	714	712	712	696	696	682	682	670	6.70	658
658	646	646	634	634	621	621	606	606	605	605	586	586	585	585	584
584	563	563	562	562	561	561	538								
156	185	185	216	216	246	246	247	247	277	277	278	278	301	301	324
324	348	348	372	372	392	392	408	408	426	426	446	446	466	466	488
488	489	489	513	513	514	514	515	515	537	537	538				
28	29	2	1	55	56	29	28	82	83	56	55	109	110	83	56
136	137	110	109	29	30	3	2	56	57	30	29	83	84	57	56
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139	140	113	112	164	165	140	139	32	33	6	5	59	60	33	32
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33	34	7	6	60	61	34	33	87	88	61	60	114	115	88	87
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143	144	117	116	168	169	144	143	36	37	10	9	63	64	37	36
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92	93	66	65	119	120	93	92	146	147	120	119	171	172	147	146
39	40	13	12	66	67	40	39	93	94	67	66	120	121	94	93
147	148	121	120	172	173	148	147	40	41	14	13	67	68	41	40
94	95	68	67	121	122	95	94	148	149	122	121	173	174	149	148
41	42	15	14	68	69	42	41	95	96	69	68	122	123	96	95
149	150	123	122	174	175	150	149	150	151	124	123	69	70	43	42
96	97	70	69	123	124	97	96	42	43	16	15	43	44	17	16
70	71	44	43	97	98	71	70	124	125	98	97	151	152	125	124
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126	127	100	99	153	154	127	126	46	47	20	19	73	74	47	46
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74	75	48	47	101	102	75	74	128	129	102	101	155	156	129	128
48	49	22	21	75	76	49	48	102	103	76	75	129	130	103	102
156	157	130	129	49	50	23	22	76	77	50	49	103	104	77	76
130	131	104	103	157	158	131	130	50	51	24	23	77	78	51	50
104	105	78	77	131	132	105	104	158	159	132	131	51	52	25	24
78	79	52	51	105	106	79	78	132	133	106	105	159	160	133	132
52	53	26	25	79	80	53	52	106	107	BO	79	133	134	107	106
160	161	134	133	53	54	27	26	80	81	54	53	107	108	81	80
134	135	108	107	161	162	135	134								

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