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Appendix

A. Publications Arising During The Present Study

Journal Papers

ZHANG, L. C. and MAHDI. M., (1995a), Applied Mechanics in Grinding, Part IV: Grinding Induced Phase Transformation. *Int. J. Mach. Tools Manuf.*, **35**/10, (1995) 1397-1409.

MAHDI, M. and ZHANG, L. C., (1995b), The Finite Element Thermal Analysis of Grinding Processes by ADINA, *Computer & Structure*, **56**, (2/3) (1995) 313-320.

ZHANG L. C and MAHDI, M, (1996a), Plastic Behaviour of Silicon Subjected to Micro-Indentation, *Journal of Materials Science*, **31**/21 (1996) 5671-5676.

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MAHDI, M. and ZHANG, L., (1997b), Applied Mechanics in Grinding , Part VI: Residual Stresses and Surface Hardening by Coupled Thermo-Plasticity and Phase Transformation, *Int. J. Mach. Tools Manufact*, 38/10-11 (1998) 1289-1304.

MAHDI, M. and ZHANG, L., (1998a), Applied Mechanics in Grinding, Part VII: Residual Stresses Induced by the Full Coupling of Mechanical Deformation, Thermal Deformation and Phase Transformation, *Int. J. Mach. Tools Manufact* , accepted for publication in July 1998.

MAHDI, M. and ZHANG, L., (1998b), Residual Stresses in Ground Components Caused by Coupled Thermal and Mechanical Plastic Deformation, Submitted in May 1998 to *Journal of Materials processing Tecgnology,* under review.

Conference Papers

ZHANG L. and MAHDI M. (1994), A Numerical Investigation into The Micro-Indentation of Silicon, *International Ceramic Monographs, International Conference*, Sydney, Australasian Ceramic Society, **2**, (1994) 644-650.

MAHDI. M. and ZHANG. L., (1994), Correlation Between Grinding Conditions and Phase Transformation of An Alloy Steel, *Proceedings of advanced computational methods in heat transfer* **III**, , August, (1994) 193-200.

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MAHDI M and ZHANG L., (1998c), Residual Stresses in Ground Components: Fully Coupled Thermo-Mechanical Deformation and Phase Transformation, *Proceedings of International Conference on Progress of Cutting and Grinding*, Urumqi and Turpan, China, 5-9 October (1998) 453-458.

MAHDI M and ZHANG L., (1998d), Residual Stresses in Ground Components: Effect of thermo-mechanical deformation, *Proceedings of International Conference on Progress of Cutting and Grinding*, Urumqi and Turpan, China, 5-9 October(1998) 447-452.

MAHDI, M. and ZHANG, L., (1999a), Residual Stresses in Ground Components: Distribution Effect of Surface Traction, *The Second Australasian Congress on Applied Mechanics*, Canberra, Australia, 10-12 February (1999) (Abstract submitted)

MAHDI, M. and ZHANG, L., (1999b), A Treatment of The Full Coupling of Mechanical Deformation, Thermal Deformation and Phase Transformation Associated With Surface Grinding, *12th Conference of the Nonlinear Finite Element Analysis and ADINA*, Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.A. 9-11 June (1999).(in preparation).

B. ADINA Code User-Subroutines

B.1 GRINDING ZONE HEAT SOURCE AND CONVECTION SUBROUTINES

```
      SUBROUTINE CUSER2 (NG,NEL,IPT,IT2D,TEMP,TIME,DT,CTI,CTD,Y,Z,
     1                  TGRDT,STRAIN,FLUX,D,SH,KEY)
C*I
C*I   THIS SUBROUTINE IS TO BE SUPPLIED BY THE USER TO CALCULATE
C*I   THE FLUXES AND CONSTITUTIVE MATRIX OF A SPECIAL MATERIAL
C*I
C*I   THIS SUBROUTINE IS CALLED IN USER2 FOR EACH INTEGRATION POINT
C*I   FOR EACH 2-D CONDUCTION ELEMENT TO PERFORM THE
C*I   FOLLOWING OPERATIONS :
C*I
C*I     KEY.EQ.1   CALCULATE THE ELEMENT FLUXES
C*I
C*I     KEY.EQ.2   CALCULATE THE CONSTITUTIVE MATRIX
C*I
C*I     KEY.EQ.3   CALCULATE THE SPECIFIC HEAT CAPACITY
C*I
C*I     KEY.EQ.4   PRINT CALCULATED FLUXES DURING THE FLUX PRINTOUT
C*I
C*I
C*I   THE FOLLOWING VARIABLES ARE USED TO PERFORM THE ABOVE
C*I   OPERATIONS:
C*I
C*I     NG         ELEMENT GROUP NUMBER
C*I
C*I     NEL        ELEMENT NUMBER
C*I
C*I     IPT        INTEGRATION POINT NUMBER
C*I
```

```
C*I     IT2D      2D ELEMENT TYPE IDENTIFIER ( NPAR(5) )
C*I    EQ.0    AXISYMMETRIC (IN Y-Z PLANE)
C*I    EQ.1    PLANAR       (IN Y-Z PLANE)
C*I
C*I    TEMP      TEMPERATURE AT THE INTEGRATION POINT AT
C*I    CURRENT TIME STEP
C*I
C*I    TIME      TIME AT CURRENT STEP, T+DT
C*I
C*I    DT        TIME STEP INCREMENT, DT
C*I
C*I    CTI(12)    TEMPERATURE-INDEPENDENT MATERIAL CONSTANTS
C*I
C*I    CTD(12)    TEMPERATURE-DEPENDENT MATERIAL CONSTANTS
C*I    AT CURRENT TIME
C*I
C*I    Y         GLOBAL Y COORDINATE OF THIS INTEGRATION POINT
C*I    Z         GLOBAL Z COORDINATE OF THIS INTEGRATION POINT
C*I
C*I    TGRDT(2)   TEMPERATURE GRADIENT COMPONENTS AT CURRENT TIME
C*I
C*I    STRAIN(4)  ENGINEERING STRAIN COMPONENTS AT CURRENT TIME
C*I    TO BE USED IN THE PIEZOELECTRIC ANALYSIS
C*I
C*I    FLUX(2)    FLUX COMPONENTS TO BE CALCULATED BY THE USER
C*I
C*I    D(2,2)     FLUX/TEMPERATURE-GRADIENT MATRIX, TO BE
C*I    CALCULATED BY USER-SUPPLIED CODING
C*I
C*I    SH        HEAT CAPACITY PER UNIT VOLUME, TO BE SUPPLIED
C*I    BY THE USER
C*I
C*I
```

```
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION FLUX(2),TGRDT(2),D(2,2),CTD(12),CTI(12),STRAIN(4)

      IF (K.EQ.0) THEN
      K=K+1
      OPEN (13,FILE='CHECK.DAT')
      READ (13,*) QP,ALP,PE,H,W
      CLOSE (13)
      END IF

C
      GO TO (1,2,3,4), KEY
C*I
C*I
C*I  K E Y = 1
C*I
C*I  CALCULATIONS OF ELEMENT FLUXES
C*I
    1 CONTINUE
C*I
C*I  * * *   I N S E R T   U S E R - S U P P L I E D   C O D I N G
C*I
C*I
      FLUX(1)=0.D0
      FLUX(2)=0.D0
C MODIFIED
   12 FLUX(1)=-CTD(1)*TGRDT(1)
      FLUX(2)=-CTD(1)*TGRDT(2)
   13 CONTINUE
      RETURN
C*I
C*I
C*I  K E Y = 2
```

```
C*I
C*I   CALCULATIONS OF THE CONSTITUTIVE MATRIX
C*I
    2       CONTINUE
C*I
C*I   *** INSERT USER-SUPPLIED CODING
C*I
            D(1,1)=CTD(1)
            D(2,2)=CTD(1)
            RETURN
C*I
C*I
C*I   KEY=3
C*I
C*I   CALCULATIONS OF SPECIFIC HEAT CAPACITY
C*I
    3       CONTINUE
C*I
C*I   *** INSERT USER-SUPPLIED CODING
C*I
            SH=CTD(2)*PE
            RETURN
C*I
C*I
C*I   KEY=4
C*I
C*I   PRINTING OF ELEMENT FLUXES
C*I
    4      CONTINUE

C MODIFIED
            RETURN
C*I
```

```
C*I  * * *  INSERT  USER-SUPPLIED  CODING
C*I
            IF (NEL.EQ.1 .AND. IPT.EQ.1) WRITE (6,2032)
            IF (IPT.EQ.1) WRITE (6,2033) NEL
            WRITE (6,2042) IPT,FLUX(1),FLUX(2)
 2032 FORMAT(/3X,5H NEL ,4X,3HIPT,8X,11HHEAT FLUX-Y,4X,11HHEAT FLUX-Z
      $/)
 2033 FORMAT(/ I6 / )
 2042 FORMAT(10X,I4,5X,2E15.6)
      RETURN
      END

      CUSERH (NG,NEL,IPT,IT2D,TEMP,TEMPE,TIME,DT,
     1             CTI,CTD,X,Y,Z,FLUX,CONVCF,KEY)
C*I
C*I   THIS SUBROUTINE IS TO BE SUPPLIED BY THE USER TO CALCULATE
C*I   THE CONVECTIVE FLUXES AND CONVECTION COEFFICIENT OF
C*I   A SPECIAL MATERIAL
C*I
C*I   THIS SUBROUTINE IS CALLED IN USERH FOR EACH INTEGRATION POINT
C*I   FOR EACH CONVECTION ELEMENT (NODE, LINE OR SURFACE)
C*I   TO PERFORM THE FOLLOWING OPERATIONS :
C*I
C*I     KEY.EQ.1   CALCULATE THE CONVECTIVE FLUXES
C*I
C*I     KEY.EQ.2   CALCULATE THE CONVECTION COEFFICIENT
C*I
C*I
C*I THE FOLLOWING VARIABLES ARE USED TO PERFORM THE ABOVE
C*I OPERATIONS:
C*I     NG        ELEMENT GROUP NUMBER
C*I
C*I     NEL       ELEMENT NUMBER
```

```
C*I
C*I   IPT      INTEGRATION POINT NUMBER
C*I
C*I   TEMP      TEMPERATURE AT THE INTEGRATION POINT AT
C*I             THE CURRENT STEP
C*I
C*I   TEMPE     ENVIRONMENTAL TEMPERATURE AT THE CURRENT STEP
C*I
C*I   TIME      TIME AT THE CURRENT STEP, T+DT
C*I
C*I   DT        TIME STEP INCREMENT, DT
C*I
C*I   CTI(12)   TEMPERATURE-INDEPENDENT MATERIAL CONSTANTS
C*I
C*I   CTD(12)   TEMPERATURE-DEPENDENT MATERIAL CONSTANTS
C*I             AT THE CURRENT TIME
C*I
C*I   X         GLOBAL X COORDINATE OF THIS INTEGRATION POINT
C*I   Y         GLOBAL Y COORDINATE OF THIS INTEGRATION POINT
C*I   Z         GLOBAL Z COORDINATE OF THIS INTEGRATION POINT
C*I
C*I   FLUX      CONVECTIVE FLUX, TO BE CALCULATED BY USER-SUPPLIED
C*I             CODING
C*I
C*I   CONVCF    CONVECTION COEFFICIENT, TO BE
C*I             CALCULATED BY USER-SUPPLIED CODING
C*I
C*I
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION CTD(12),CTI(12)
C
      IF (K.EQ.0) THEN
      K=K+1
```

```
      OPEN (13,FILE='CHECK.DAT')
      READ (13,*) QP,ALP,PE,H,W
      CLOSE (13)
      END IF

      GO TO (1,2), KEY
C*I
C*I
C*I   K E Y = 1
C*I
C*I   CALCULATIONS OF CONVECTIVE FLUXES
C*I
    1 CONTINUE
C*I
C*I   * * *   I N S E R T   U S E R - S U P P L I E D   C O D I N G
C*I
      YL=Y/(1.E-3)-TIME*0.25+1.
      FACTOR=0.0
      IF (YL.GE.-1.0.AND.YL.LE.ALP) THEN
      FACTOR=(YL+1.)/(ALP+1.)
      ELSE IF (YL.GE.ALP.AND.YL.LE.1.0) THEN
      FACTOR=(YL-1.)/(ALP-1.)
      ELSE
      FACTOR=0.0
      END IF
      ALPHA=CTD(1)/CTD(2)/0.0101396
      V=2.*ALPHA/1.E-3*PE
      HH=CTD(1)*H/2./ALPHA*V

      IF (TIME.LT.20.0) THEN
      FAC=FACTOR*TIME/20.
      FACTOR=FAC
      END IF
```

```
      IF (FACTOR.GT.0.0) THEN
      FLUX=(QP*FACTOR-W*HH*TEMP)
      ELSE
      FLUX=(-HH*TEMP)
      END IF

      IF (ABS(FLUX).GT.(1.0E-1)) THEN
C      WRITE (*,*) TIME,Y,FLUX
      END IF
      IF (FACTOR.GT.0.0) THEN
      WRITE (*,9) TIME,Y,TEMP
      END IF
  9   FORMAT (2X,F6.3,3(1X,E12.6))

      RETURN
C*I
C*I
C*I   K E Y = 2
C*I
C*I   CALCULATIONS OF THE CONSTITUTIVE MATRIX
C*I
    2 CONTINUE
C*I
C*I   * * *   I N S E R T   U S E R - S U P P L I E D   C O D I N G
C*I
      CONVCF=0.0
      RETURN
C*I
      END
```

B.2 SUBROUTINES FOR CONSISTENT NODAL FORCE OF TRACTION FORCES

```
SUBROUTINE CFORCE (YMIN,YMAX,NNODE,T,ALP,XLOC,F)
IMPLICIT REAL*8 (A-H,O-Z)
REAL*8 W(4),ETA(4) , XV(1024)
DIMENSION XLOC(2000),F(2000)
IF (NNODE.LT.1) WRITE (*,*) 'NNODE LT 1'
IF (NNODE.LT.1) STOP 'NNODE LT 1'
NELEM=(NNODE-1)/2

DO II=1,NNODE
F(II)=0.0
XV(II)=XLOC(II)
END DO

TIME=T

ETA(1)=0.861136311594053
ETA(2)=0.339981043584856
ETA(3)=-ETA(1)
ETA(4)=-ETA(2)

W(1)=0.347854845137454
W(2)=0.652145154862546
W(3)=W(1)
W(4)=W(2)

QP=1.0
V=0.25E-3
YMINN=YMIN

DO LL=1,NELEM
SUM1=0.0
```

```
 SUM2=0.0
 SUM3=0.0

 X1=XV(2*LL-1)
 X2=XV(2*LL  )
 X3=XV(2*LL+1)

 F1=TRACT(X1,T,V,QP,ALP,YMIN)
 F2=TRACT(X2,T,V,QP,ALP,YMIN)
 F3=TRACT(X3,T,V,QP,ALP,YMIN)
 IF (F1.EQ.0.0.AND.F2.EQ.0.0.AND.F3.EQ.0.0) GOTO 400
DO I=1,4
 X=X1*AN1(ETA(I))+X2*AN2(ETA(I))+X3*AN3(ETA(I))
 DX=X1*DAN1(ETA(I))+X2*DAN2(ETA(I))+X3*DAN3(ETA(I))
 S=X1*(1.-2.*ETA(I))+X2-X1
 SUM1=SUM1+DX*AN1(ETA(I))*W(I)*TRACT(X,T,V,QP,ALP,YMIN)
 SUM2=SUM2+DX*AN2(ETA(I))*W(I)*TRACT(X,T,V,QP,ALP,YMIN)
 SUM3=SUM3+DX*AN3(ETA(I))*W(I)*TRACT(X,T,V,QP,ALP,YMIN)
 END DO
 F(LL*2-1)=F(LL*2-1)+SUM1
 F(LL*2  )=F(LL*2  )+SUM2
 F(LL*2+1)=F(LL*2+1)+SUM3
 400 CONTINUE
 END DO
 END

 DOUBLE PRECISION FUNCTION AN1(X)
 IMPLICIT REAL*8 (A-H,O-Z)
 AN1=0.
 AN1=X*(X-1.)/2.
 RETURN
 END
```

```
DOUBLE PRECISION FUNCTION AN2(X)
IMPLICIT REAL*8 (A-H,O-Z)
AN2=0.
AN2=-(X+1.)*(X-1.)
RETURN
END

DOUBLE PRECISION FUNCTION AN3(X)
IMPLICIT REAL*8 (A-H,O-Z)
AN3=0.
AN3=(X+1.)*X/2.0
RETURN
END

DOUBLE PRECISION FUNCTION DAN1(X)
IMPLICIT REAL*8 (A-H,O-Z)
DAN1=0.
DAN1=(2.*X-1.)/2.0
RETURN
END

DOUBLE PRECISION FUNCTION DAN2(X)
IMPLICIT REAL*8 (A-H,O-Z)
DAN2=0.
DAN2=-2.*X
RETURN
END

DOUBLE PRECISION FUNCTION DAN3(X)
IMPLICIT REAL*8 (A-H,O-Z)
DAN3=0.
DAN3=(2.*X+1.)/2.
RETURN
```

```
      END

      DOUBLE PRECISION FUNCTION TRACT(X,T,V,QP,ALP,YMIN)
      IMPLICIT  REAL*8 (A-H,O-Z)

      XL=X-V*T-YMIN+1.E-3
      XXL=XL/1.E-3
      TRACT=0.0
      IF (ABS(XXL).GT.1.) THEN
      TRACT=0.0
      ELSE IF (XXL.GT.(-1).AND.XXL.LE.ALP) THEN
      TRACT=(XXL+1.)/(ALP+1.)*QP
      ELSE IF (XXL.GT.(ALP).AND.XXL.LE.1.0) THEN
      TRACT=(XXL-1.)/(ALP-1.)*QP
      END IF
      IF (T.LT.20.) THEN
      TRA=TRACT*T/20.
      TRACT=TRA
      ELSE
      END IF
      RETURN
      END
```

B.3 SUBROUTINES FOR CONSTITUTIVE MATRIX OF ELASTIC-PERFECTLY-PLASTIC MATERIAL

```
      SUBROUTINE DELPLA(STRES,EE,Y,D,RATIO,IPLAS)
      IMPLICIT REAL*8 (A-H, O-Z)
      DIMENSION STRES(4),DP(4,4),D(4,4),EE(4),STS(4),STREST(4)
C     RATIO IS THE RATION OF ELASTIC DEFORMATION ONLY
      RATIO=1.0
      IPLAS=0
```

```
IF (Y.LE.0.0) STOP ' Y LT 0.0 '
DO K=1,4
DO L=1,4
D(K,L)=0.0
END DO
END DO

V=0.27

CD =1.0/(1.0+V)*(1.-V)/(1.-2.*V)
CND=1.0/(1.0+V)*V/(1.-2.*V)



D(1,1)=CD
D(2,2)=CD
D(3,3)=0.5/(1.+V)
D(4,4)=CD

D(1,2)=CND
D(1,4)=CND
D(2,4)=CND

D(2,1)=D(1,2)
D(4,1)=D(1,4)
D(4,2)=D(2,4)

DO K=1,4
STS(K)=0.
DO L=1,4
STS(K)=STS(K)+D(K,L)*EE(L)
END DO
STREST(K)=STRES(K)+STS(K)
END DO
```

```
      CALL RATI2(STREST,EFFD)
      IF (EFFD.LE.Y) THEN

      DO I=1,4
      STRES(I)=STREST(I)
      END DO

      R=(EFFD/Y)
      IPLAS=0
      RETURN
      END IF

C     WRITE (*,*) 'PLASTIC DEFORMATION '

      AC1=(STS(1)-STS(2))**2
      AC2=(STS(1)-STS(4))**2
      AC3=(STS(2)-STS(4))**2
      AC4=6.*STS(3)**2
      AC=AC1+AC2+AC3+AC4
      BC1=2.*(STS(1)-STS(2))*(STRES(1)-STRES(2))
      BC2=2.*(STS(1)-STS(4))*(STRES(1)-STRES(4))
      BC3=2.*(STS(2)-STS(4))*(STRES(2)-STRES(4))
      BC4=12.*STRES(3)*STS(3)
      BC=BC1+BC2+BC3+BC4
      CC1=(STRES(1)-STRES(2))**2
      CC2=(STRES(1)-STRES(4))**2
      CC3=(STRES(2)-STRES(4))**2
      CC4=6.*STRES(3)**2
      CC=CC1+CC2+CC3+CC4-2.*Y**2
      DET=BC**2-4.*AC*CC
      IF (DET.LT.0.0) STOP 'DET LT 0'
      RATIO=(-BC+SQRT(DET))/(2.*AC)
```

```
      DO K=1,4
      STREST(K)=STRES(K)+STS(K)*RATIO
      END DO
      CALL RATI2(STREST,EFFD)
C      WRITE (*,*) 'STRESS AT ELASTIC LIMIT =',EFFD/Y
      FACTOR=1.-RATIO
      S=2./3.*Y**2
      G=1./(2.*(1.+V))

      SH=(STREST(1)+STREST(2)+STREST(4))/3.

      S11=STREST(1)-SH
      S22=STREST(2)-SH
      S44=STREST(4)-SH
      S33=STREST(3)

      DP(1,1)=S11*S11
      DP(1,2)=S11*S22
      DP(1,3)=S11*S33
      DP(1,4)=S11*S44
      DP(2,2)=S22*S22
      DP(2,3)=S22*S33
      DP(2,4)=S22*S44
      DP(3,3)=S33*S33
      DP(3,4)=S33*S44
      DP(4,4)=S44*S44
CCCC
      DP(2,1)=DP(1,2)

      DP(3,1)=DP(1,3)
      DP(3,2)=DP(2,3)
```

```
      DP(4,1)=DP(1,4)
      DP(4,2)=DP(2,4)
      DP(4,3)=DP(3,4)



      DO I=1,4
      DO J=1,4
      D(I,J)=D(I,J)-DP(I,J)*FACTOR/S*2.*G
      END DO
      END DO

      DO K=1,4
      STS(K)=0.
      DO L=1,4
      STS(K)=STS(K)+D(K,L)*EE(L)
      END DO
      STRES(K)=STRES(K)+STS(K)
      END DO

C SCALE THE STRESSES TO YIELD STRESS SURFACE IF AWAY

      CALL RATI2(STRES,EFFD)
      R=(Y/EFFD)
      DO K=1,4
      STRES(K)= STRES(K)*R
      END DO
      CALL RATI2(STRES,EFFD)
      R=EFFD/Y
      IPLAS=1
C     WRITE (*,*) 'STRESS AFTER ELASTIC-PLASTIC LIMIT =',EFFD/Y

      RETURN
      END
```

```
      SUBROUTINE RATI2(STRES,EFF0)
      IMPLICIT REAL*8 (A-H, O-Z)
      DIMENSION STRES(4)

      EFF2=     (STRES(1)-STRES(2))**2
      EFF2=EFF2+(STRES(1)-STRES(4))**2
      EFF2=EFF2+(STRES(2)-STRES(4))**2
      EFF2=EFF2+6.*(STRES(3))**2
      EFF0=(EFF2)/2.
      EFF0=SQRT(EFF0)

      RETURN
      END

      SUBROUTINE VSPLST(TMP,T,N,IPT,TIME,DT,Y)
      IMPLICIT REAL*8 (A-H, O-Z)
      COMMON/DATAP/RMART,TEMPER

      COMMON /PHASE/ETMAX(2000,9),ETGRAD(2000,9)
      COMMON/PHASD1/EL700V(2000,9),EL756V(2000,9)
      COMMON/PHASD2/EL500V(2000,9),TMARTV(2000,9),ELHARV(2000,9)

      Y=796.E6/214.E9
      DTMAX=DT
      ALPHA=1.45E-5
      PE=1.0
C     MODIFIED
C     GOTO 401

      IF (ETMAX(N,IPT).LT.T) ETMAX(N,IPT)=T

      IF (ETMAX(N,IPT).LT.T) THEN
```

```
      WRITE (*,*) 'MAX TEMPERATURE AT INTEG P IS ',T
      END IF

C       IF (ETMAX(N,IPT).GT.850.0.AND.TMP.LT.0.0) THEN
C       WRITE (*,*) ' NEL,IPT,TMAX,TMP ',N,IPT,T,TMP
C       END IF

      IF (ETMAX(N,IPT).LT.850.0.OR.TMP.GE.0.0) GOTO 401

      TT=T-TMP
      RATIO1=(700.-TT)/(TMP)
      RATIO2=(756.-TT)/(TMP)
      RATIO3=(500.-TT)/(TMP)
      RATIO4=(320.-TT)/(TMP)

      IF (ABS(RATIO1-0.5).LE.0.5) EL700V(N,IPT)=-TMP
      IF (ABS(RATIO2-0.5).LE.0.5) EL756V(N,IPT)=TIME-DTMAX*(1.-RATIO2)
      IF (ABS(RATIO3-0.5).LE.0.5) EL500V(N,IPT)=TIME-DTMAX*(1.-RATIO3)
      IF (ABS(RATIO4-0.5).LE.0.5) TMARTV(N,IPT)=TIME-DTMAX*(1.-RATIO4)

      IF (TMARTV(N,IPT).GT.TIME ) GOTO 401
      IF (EL700V(N,IPT).LE.0.0 ) GOTO 401


       DIF=(EL500V(N,IPT)-EL756V(N,IPT))*0.0202793869488/2./PE
       IF (DIF.GT.1.6) GOTO 401
       DIFF=EL700V(N,IPT)/(0.0202793869488/2.0)*3600.0*PE

       IF (DIFF.LE.0.0) STOP 'DIFF.LE.0.0'
       HV=463.2376+21*LOG(DIFF)
       YY=80.+2.7544*HV

       YM=YY*1.E6/214.E9
```

```
      TEMPER=T
      CALL SCALE
      ELHARV(N,IPT)=RMART*YM+(1.-RMART)*Y
      Y=ELHARV(N,IPT)


401   CONTINUE
      RETURN
      END

      SUBROUTINE SCALE
      IMPLICIT REAL*8 (A-H, O-Z)
      COMMON/DATAP/RMART,TEMPER
      RMART=0.0
      IF (TEMPER.GT.320.0) THEN
      RMART=0.0
      ELSE IF (TEMPER.GT.310.AND.TEMPER.LE.320.0) THEN
      R=(TEMPER-320.)/(310.-320.)
      RMART=R*10.
      ELSE IF (TEMPER.GT.273.AND.TEMPER.LE.310.0) THEN
      R=(TEMPER-310.)/(273.-310.)
      RMART=R*40.+10.
      ELSE IF (TEMPER.GT.217.AND.TEMPER.LE.273.0) THEN
      R=(TEMPER-273.)/(217.-273.)
      RMART=R*40.+50.
      ELSE IF (TEMPER.GT.105.AND.TEMPER.LE.217.0) THEN
      R=(TEMPER-217.)/(105.-217.)
      RMART=R*10.+90.
      ELSE IF (TEMPER.LE.105) THEN
      RMART=100.
      END IF
      RMART=RMART/100.
```

```
RETURN
END
```

C. INPUT FILE GENERATION FOR ADINA

It should be noted that the following commands do not cover all the alternative options of the ADINA system and that they are introduced as the main essential requirements to build up an input date file under UNIX operating syatem running OSF1. The underlined characters are the minimum number of characters required to present the particular command.

Step1: To inform ADINA-IN about the type of problem the subsequent commands are either ADINA for stress analysis or ADINA-T for thermal analysis.

FEPROGRAM ADINA (*for ADINA*)

or

FEPROGRAM ADINA-T (*for ADINA-T*)

Step2: To creat a database for ADINA-IN:

DATABASE CREAT (for both)

Step3: To give the problem to be solved a heading:

HEADING STRING= 'heading information'

Step4: To define control information for the entire model:

MASTER IDOF=$abcdef$ MODEX=g NSTE=h DT= i TSTART=j TEND=k

(*for ADINA*)

MASTER MODEX=g TSTART= j TEND= k

(*for ADINA-T*) where a,b,c,d,e and f can be either 0 or 1 depending on the problem degrees of freedom, g is running mode flag such that

$$g = \begin{cases} 0 \text{ (data verifying only)} \\ 1 \quad \text{(running mode)} \\ 2 \quad \text{(restart mode)}, \end{cases}$$

h is an integer indicating the total number of solution steps, i is time step size, j and k are solution starting and ending time respectively.

Step5: To specify the type of analysis

ANALAYSIS TYPE=TRANSIENT or STEADY (*for ADINA-T*)
ANALAYSIS TYPE=STATIC or DYNAMIC (*for ADINA*)

Step6: To select the method of equilibrium iteration (for non linear problems)

ITERATION METHOD= *a*

where a is such that

$$a = \begin{cases} \underline{BFG}S \\ \underline{MO}DIFIED\text{ - }NEWTON \\ \underline{F}ULL\text{ - }NEWTON,\ (for\ ADINA\ only)\ search = \begin{cases} yes \\ no \end{cases} \end{cases}$$

Step7: TIMESTEP

a_i b_i

This command is required to specify the variation in timestep magnitudes if variable time steps are needed where a_i and b_i are the number of time steps and the corresponding timestep increment for solution block I.

Step8: Material N Type <material data and parameters>

used inclusively. The material parameters rely on the type of workmaterial and loading

and poission ratio. More parameters need to be provided for other material types.

Step 9: COORDINATES / ENTRIES NODES Y Z

NODES	Y	Z
i	x_i	y_i
.	.	.
.	.	.
j	x_j	y_j

This command is needed to define the principal nodal coordinates of nodes i,....,j

Step 10: Mesh generation is the most time consuming step of the modelling process. Basically, all node locations and element connectivities should be given to ADINA. However, many commands are available which can generate nodes and elements. The generation of elements can implicitly produce node generation by using GSURFACE command. To start element generation, element type needs to be defined by EGROUP command. A typical command of two dimensional elements definition is :
EGROUP N=I TYPE=TWODSOLID SUBTYPE=1 MATERIAL=1
For surface generation the principal node locations are required to bound the surface such as:
GSURFACE N1=I N2=J N3=K N4=L EL1=M EL2=N
where i,j,k and l are the node numbers of principal nodes. Whereas m and n are the number of elements to be generated in the direction from i to j nodes and j to k nodes respectively.

Step 10: Boundary and load conditions can be introduced by many alternative ways. In this study BOUNDARIES command is used to define the degrees of freedom for nodes. For thermal and

of USER code. To couple the temperature results into thermo-mechanical analysis, TAPESTORAGE is implemented with ITEMPERATURE flag set to 1 or -1. This command is essential not only for the grinding temperature loading in the input data but also to approximate the simulation of the cooling process. The existing tape results of temperature are also read to investigate the temperature history and associated phase change.

Step 11 Termination of input data file is done by END command.

In the following sections two typical examples of input file styles are presented. The examples are thermal and thermo-mechanical analysis. The first example deals with the transient analysis of the thermal grinding process with temperature dependent thermal properties. The second example, on the other hand, carries out thermo-mechanical analysis of an elastic-perfectly-plastic material with user supplied loading and grinding temperaure induced to account for thermal and mechanical loading coupling.

C.1 TYPICAL INPUT FILE FOR THERMAL ANALYSIS

```
*    A D I N A - I N   6 . 1   I N P U T   F I L E
FILEUNITS LIST=8 LOG=7 ECHO=7
FCONTROL HEADING=UPPER ORIGIN=UPPERLEFT
CONTROL MODE=N PLOTUNIT=PERCENT HEIGHT=1.25
*
DATABASE CREATE
*

*
FEPROGRAM PROGRAM=ADINA-T
MASTER IPDATA=4 IPRI=100 ITP56=1
ITERATION  METHOD = FULL-NEWTON   RTOL=0.001
PORTHOLE FORMATTED=YES V=MIN
WO SYSTEM =12  BACKGROU =WHITE SI = AUTOMATIC LMARGIN = 2. ,
RMARGIN = 2. TMARGIN = 2 BMARGIN = 2
AUTOMATIC-ATS NUMBER =5
ANALYSIS T=T
TIMESTEP
52 1.0
*
COORDINATES
 ENTRIES  NODE      Y    Z
        1         4.0E-3    0.
        2        -12.0E-3    0.
        3        -12.0E-3   -6.0E-3
        4         4.0E-3   -6.0E-3

*LINE S 21 42 10 1
*LINE S 1  9  3  1
MATERIAL 1 USER-SUPPLIED CTI2=1.E-3,CTI3=0.0246557,
CTI5=     4.00000E+07, CTI1=    2.50000E-04
```

```
    -1E+1     32.2  2611985   0 0  0 0 0 0 0 0 0 0
       -20     32.2  2611985   0 0  0 0 0 0 0 0 0 0
        30     33.2  3594812   0 0  0 0 0 0 0 0 0 0
        80  34.2125  3981218   0 0  0 0 0 0 0 0 0 0
       180  35.0175  3982277   0 0  0 0 0 0 0 0 0 0
       280  35.0175  4000590   0 0  0 0 0 0 0 0 0 0
       380  35.0175  4557778   0 0  0 0 0 0 0 0 0 0
       480   33.005  5562421   0 0  0 0 0 0 0 0 0 0
       580    30.59  6560817   0 0  0 0 0 0 0 0 0 0
       680    27.37  6987739   0 0  0 0 0 0 0 0 0 0
       780   24.955  6417202   0 0  0 0 0 0 0 0 0 0
       880    25.35  4813221   0 0  0 0 0 0 0 0 0 0
       980   26.565  2780568   0 0  0 0 0 0 0 0 0 0
      1080   26.565  1815542   0 0  0 0 0 0 0 0 0 0
      1100   26.565  1959919   0 0  0 0 0 0 0 0 0 0
      2220  26.565  1959919   0 0  0 0 0 0 0 0 0 0
EGROUP  1 TWODCONDUCTION SUBTYPE=PLANAR MATERIAL =1

GSURFACE  1  2  3   4 EL1= 32 EL2=12 NO=9
EDATA
 ENTRIES EL PRINT THICK INTLOC
        1  NO 1.0     1
EGROUP 2   CONVECTION     SUBTYPE=PLANAR MATERIAL =1
GLINE   1  2     NODES =3 EL = 32    NC = ALL
EDATA
   ENTRIES  EL   THICK
          1     1.0
LOADS CONVECTION TYPE = LINES
1   2     1  1
ADINA-T
END
```

C.2 TYPICAL INPUT FILE FOR THERMO-MECHANICAL ANALYSIS

```
*    A D I N A - I N   6 . 1   I N P U T   F I L E
FILEUNITS LIST=8 LOG=7 ECHO=7
FCONTROL HEADING=UPPER ORIGIN=UPPERLEFT
CONTROL MODE=N PLOTUNIT=PERCENT HEIGHT=1.25
DATABASE CREATE
HEAD 'THERMO_MECHANICAL ANALYSIS OF EN23 STEEL'
MASTER IDOF=100111 NSTE=52 DT=1.0
ITERATION METHOD=FULL
TOLERANCES PRINT=2
PORTHOLE FORMATTED=YES FILE=60
ESAVE FIRST1=44 LAST1=52 INCR1=4
NSAVE FIRST1=44 LAST1=52 INCR1=4
WO SYS=12
TAPES ITE=1
COORDINATES
 ENTRIES  NODE       Y     Z
          1        4.0E-3    0.
          2       -12.0E-3    0.
          3       -12.0E-3   -6.0E-3
          4        4.0E-3   -6.0E-3
MATERIAL 1 THERMO-P
-100.  214E9 0.27  796.E6  0. 1.4E-5 0.
2000.  214E9 0.27  796.E6  0. 1.4E-5 0.
EGROUP 1 TWODSOLID SU=1
GSURFACE 1 2 3 4 EL1=32 EL2=12 NODES=9
BO IDOF=111111 T=L
3 4
LOADS USER NODE-DEP=1
ADINA
END
```