APPENDIX 1

APDL PROGRAM

!Friction Stir Welding:
!Thermal modeling of Friction Stir Welding
finish
/clear
/config,nres,8000
/filnam, THERMALEXP5
/prep7
/title, Thermal Analysis in Friction Stir Welding
et,1,70
! Specifying material properties
mp,dens,1,2800
MPTEMP,,,,,,
MPTEMP,1,44
MPTEMP,2,100
MPTEMP,3,144
MPTEMP,4,211
MPTEMP,5,311
MPTEMP,6,433
MPTEMP,7,633
MPDATA,KXX,1,,86.5
MPDATA,KXX,1,,103.8
MPDATA,KXX,1,,121.2
MPDATA,KXX,1,,138.5
MPDATA,KXX,1,,155.8
MPDATA,KXX,1,,177.1
MPDATA,KXX,1,,190.4
MPDATA,KYY,1,,86.5
MPDATA,KYY,1,,103.8
MPDATA,KYY,1,,121.2
MPDATA,KYY,1,,138.5
MPDATA,KYY,1,,155.8
MPDATA,KYY,1,,177.1
MPDATA,KYY,1,,190.4
MPDATA,KZZ,1,,86.5
MPDATA,KZZ,1,,103.8
MPDATA,KZZ,1,,121.2
MPDATA,KZZ,1,,138.5
MPDATA,KZZ,1,,155.8
MPDATA,KZZ,1,,177.1
MPDATA,KZZ,1,,190.4
MPTEMP,,,,,,
MPTEMP,1,311
MPTEMP,2,366.5
MPTEMP,3,422
MPTEMP,4,477.6
MPTEMP,5,533.2
MPDATA,C,1,,858
MPDATA,C,1,,900
MPDATA,C,1,,942
MPDATA,C,1,,963
MPDATA,C,1,,983

BLOCK,0,0.128,0,0.060,0,0.0054
lesize,1, ,40 ,1, , 1,
lesize,8, ,40 ,1, , 1,

FLST,5,2,4,ORDE,2
FITEM,5,1
FITEM,5,8
CM,_Y1,LINE
LSEL, , ,P51X
*GET,_z1,LINE,,COUNT
*SET,_z2,0
*DO,_z5,1,_z1
*SET,_z2,LSNEXT(_z2)
*GET,_z3,LINE,_z2,ATTR,NDNX
*GET,_z4,LINE,_z2,ATTR,SPNX
*get,_z6,line,_z2,attr,kynd
*IF,_z3,GT,0,THEN
*IF,_z4,NE,0,THEN
LESIZE,_z2,,_z3,1/_z4,,,_z6
*ENDIF
*ENDIF
*ENDDO
CMSEL,S,_Y1
CMDELE, _Y1
lesize,3, , , 40,4,1, , , 1,
lesize,6, , , 40,4,1, , , 1,
lesize,2,0.002, , , 1,1, , , 1,
lesize,7,0.002, , , 1,1, , , 1,
lesize,4,0.002, , , 1,1, , , 1,
lesize,5,0.002, , , 1,1, , , 1,
lesize,9,0.002, , , 1,1, , , 1,
lesize,10,0.002, , , 1,1, , , 1,
lesize,11,0.002, , , 1,1, , , 1,
lesize,12,0.002, , , 1,1, , , 1,
MSHKEY,1
VMESH,all

/SOL
!outres,,all
outres,nsol, ,
antype,trans    ! defining transient nature
timint,off
time,1e-6
nsel,s,loc,x,0
sf,all,conv,15,303
nsel,s,loc,x,128e-3
sf,all,conv,15,303
nsel,s,loc,y,5.4e-3
sf,all,conv,15,303
nsel,s,loc,y,0
sf,all,hflux,,0
nsel,s,loc,z,0
sf,all,conv,300,303
nsel,s,loc,z,5.4e-3
sf,all,conv,15,303
allsel
lswrite,1  ! this completes the steady state solution
timint,on  ! begin transient analysis
delttime,0.1 ! time step size
kbc,1

i=0
j=11
k=1
m= 0
*do,i,0,128e-3,0.002
ASEL,S,,2 ! (60 mm/min)first load step
NSLA,S,1
NPLOT
LOCAL,j,1,i,0,0,,1,1,
CSYS,j
R1=10e-3
R2=0
nsel,s,loc,x,R2,R1
nsel,r,loc,z,5.4e-3
cm,tool,node
q = 5.5e6
sf,tool,hflux,q

NPLOT

! convective heat transfer in the place of heat flux
nsel,inve,loc,x,R2,R1
nsel,r,loc,z,5.4e-3
Nplot
cm,tool2,node
sf,tool2,conv,15,303
Nplot

LOCAL,j,0,i,0,0, , ,1,1,
CSYS,j
nsel,s,loc,y,0
nsel,r,loc,x,-3e-3,3e-3
cm,toolpin,node
q1=30000
sf,toolpin,hflux,q1
nplot

! convective heat transfer in the place of heat flux
nsel,inve,loc,x,-3e-3,3e-3
nsel,r,loc,y,0
nplot
cm,toolpin,node
sf,toolpin,conv,0,303
nplot
LOCAL,j,1,i,0,0, , ,1,1,
CSYS,j
! contact conductance below the tool between workpiece/backplate
nsel,s,loc,x,0,10e-3
nsel,r,loc,z,0
cm,tool1,node
sf,tool1,conv,3500,303
!ALLSEL,ALL
NPLOT
time,2.0*k
m = 2.0 * k
lswrite,k+1
sfdele,tool,hflux
sfdele,tool1,conv

! replace contact conductance below the tool between
workpiece/backplate
sf,tool1,conv,300,303
ALLSEL,ALL
NPLOT
j=j+1
k=k+1
*enddo

j=j-1
num=70 ! after welding
*dowhile,num
ASEL,S, 2 ! (1mm/s)first load step
NSLA,S,1
NPLOT
LOCAL,j,1,i,0,0, , , ,1,1,

CSYS,j
R1=10e-3
R2=0
nsel,s,loc,x,R2,R1
nsel,r,loc,z,5.4e-3
cm,tool,node
q = 0.0e6
sf,tool,hflux,q
NPLOT
! convective heat transfer in the place of heat flux
nsel,inve,loc,x,R2,R1
nsel,r,loc,z,5.4e-3
Nplot
cm,tool2,node
sf,tool2,conv,15,303
Nplot
! contact conductance below the tool between workpiece/backplate
nsel,s,loc,x,0,10e-3
nsel,r,loc,z,0
cm,tool1,node
sf,tool1,conv,300,303
!ALLSEL,ALL
NPLOT
time,2.0*k
m = 2.0 * k
lswrite,k+1
sfdele,tool,hflux
sfdele,tool1,conv

! replace contact conductance below the tool between
   workpiece/backplate
sf,tool1,conv,300,303

ALLSEL,ALL

NPLOT

! j=j+1
k=k+1
num=num-1
*enddo

lssolve,1,135,1

Save
APPENDIX 2

APDL PROGRAM

!Friction Stir Welding:
finish
/clear
/config,nres,8000
/filnam, Residual-Exp6
/prep7
bfdele,all,all
sfdele,all,all
/title, Residual Stress Analysis in Friction Stir Welding (solid 45)
ET,1,SOLID45
MPTEMP,........
MPTEMP,1,273
MPDE,DENS,1
MPDATA,DENS,1,,2800
MPTEMP,........
MPTEMP,1,273
MPDE,C,1
MPDATA,C,1,,963
MPTEMP,........
MPTEMP,1,273
MPDE,alpx,1
MPDATA, alpx, 1,, 25e-6
MPTEMP, .......
MPTEMP, 1, 273
MPTEMP, 2, 366
MPTEMP, 3, 422
MPTEMP, 4, 478
MPTEMP, 5, 533
MPTEMP, 6, 588
MPDE, EX, 1
MPDE, PRXY, 1
MPDATA, EX, 1,, 7E+010
MPDATA, EX, 1,, 6.79e10
MPDATA, EX, 1,, 6.65e10
MPDATA, EX, 1,, 6.16E+010
MPDATA, EX, 1,, 5.6e10
MPDATA, EX, 1,, 4.9e10
MPDATA, PRXY, 1,, 0.3
MPDATA, PRXY, 1,, 0.3
MPDATA, PRXY, 1,, 0.3
MPDATA, PRXY, 1,, 0.3
MPDATA, PRXY, 1,, 0.3
MPDATA, PRXY, 1,, 0.3
TB, KINH, 1, 6, 7, 0
TBTEMP, 273
TBPT, 0.001, 170e6
TBPT, 0.002, 140e6
TBPT,,0.003,210e6
TBPT,,0.004,275.6e6
TBPT,,0.005,344.74e6
TBPT,,0.006,399.89e6
TBPT,,0.007,413.69e6
TBTEMP,366
TBPT,,0.001,67.90e6
TBPT,,0.002,135.8e6
TBPT,,0.003,203.7e6
TBPT,,0.004,271.6e6
TBPT,,0.005,339.1e6
TBPT,,0.006,379.89e6
TBPT,,0.007,399.89e6
TBTEMP,422
TBPT,,0.001,66.5e6
TBPT,,0.002,133e6
TBPT,,0.003,199.5e6
TBPT,,0.004,248.211e6
TBPT,,0.005,289.57e6
TBPT,,0.006,324.05e6
TBPT,,0.007,344.73e6

TBTEMP,478
TBPT,,0.001,61.6e6
TBPT,,0.002,123.2e6
TBPT,,0.003,184.8e6
TBPT, 0.004, 246.4e6
TBPT, 0.005, 282.6e6
TBPT, 0.006, 303.37e6
TBPT, 0.007, 324.05e6
TBTEMP, 533
TBPT, 0.001, 56.00e6
TBPT, 0.002, 102.00e6
TBPT, 0.003, 131e6
TBPT, 0.004, 144.79e6
TBPT, 0.005, 151.6846e6
TBPT, 0.006, 158.58e6
TBPT, 0.007, 165.47e6
TBTEMP, 588
TBPT, 0.001, 49.0e6
TBPT, 0.002, 51.7e6
TBPT, 0.003, 62.05e6
TBPT, 0.004, 67.22e6
TBPT, 0.005, 72.39e6
TBPT, 0.006, 75.84e6
TBPT, 0.007, 75.84e6
/solu
!outres, all
antype, trans  ! defining transient nature
outres, strs, ,
timint, off
SSTIF, ON       ! Stress stiffening effects
time,1e-6
csys,0
nsel,s,loc,x,0
D,all,UX,0
allsel
nsel,s,loc,x,0.128
cm,surface,node
sf,surface,pres,-200e6

!D,all,UX,0
!allsel
nsel,s,loc,y,0
D,all,UY,0
allsel
!nsel,s,loc,y,0.060
!D,all,UY,0
!allsel
nsel,s,loc,z,0
D,all,UZ,0
allsel
tref,298
ldread,temp,0,0,1e-6,0,,rth
NLGEOM,1
nropt,full
lswrite,1 ! this completes the steady state solution
timint, on
deltim,0.5 ! time step size

kbc,1

i=0
j=11
k=1
*do,i,0,128e-3,0.002
LOCAL,j,1,i,0,0,,1,1,
CSYS,j
nsel,s,loc,x,0,10e-3
nsel,r,loc,z,5.4e-3
cm,tool,node
sf,tool,pres,2.321e7
time,2.0*k
m=2.0*k
tref,303
ldread,temp,0,0,m,0,,rth
NLGEOM,ON
nropt,full
NPLOT
ALLSEL,ALL
NPLOT
lswrite,k+1
SFDELE,tool,pres
ALLSEL,ALL
NPLOT
j=j+1
k=k+1
*enddo

csys,0
nsel,s,loc,x,0
Ddele,all,UX
allsel
nsel,s,loc,x,0.128
cm,surface1,node
sfdele,surface1,pres
!DDELE,all,UX
!allsel
!nsel,s,loc,y,0
!D,all,UY,0
a!llsel
!nsel,s,loc,y,0.060
!DDELE,all,UY
!allsel
!nsel,s,loc,z,0
!D,all,UZ,0
!allsel
j=j-1

num=70 ! after welding
*dowhile,num
LOCAL,j,1,i,0,0, , , ,1,1,
CSYS,j
nsel,s,loc,x,0,10e-3
nsel,r,loc,z,5.4e-3
cm,tool,node
sf,tool,pres,0
time,2.0*k
m=2.0*k
tref,303
dlread,temp,0,0,m,0,,rth
!NLGEOM,ON
nropt,full
NPLOT
ALLSEL,ALL
NPLOT
lswrite,k+1  ! After welding
k=k+1
num=num-1
*enddo
lssolve,1,135,1
Save
finish
APPENDIX 3

SIMULATION RESULTS OF THERMAL MODEL

Figure A3.1  Temperature distribution in weld specimen for trial E1
Figure A3.2 Temperature distribution in weld specimen for trial E2
Figure A3.3 Temperature distribution in weld specimen for trial E3
Figure A3.4 Temperature distribution in weld specimen for trial E4
Figure A3.5  Temperature distribution in weld specimen for trial E5
Figure A3.6 Temperature distribution in weld specimen for trial E6
Figure A3.7  Temperature distribution in weld specimen for trial E7
Figure A3.8  Temperature distribution in weld specimen for trial E8
Figure A3.9  Temperature distribution in weld specimen for trial E9
APPENDIX 4

SIMULATION RESULTS OF THERMO-MECHANICAL MODEL

Figure A4.1  Longitudinal stress distribution immediately after welding for trial E6
Figure A4.2 Longitudinal stress distribution after the weld specimen reached room temperature for trial E6
Figure A4.3 Longitudinal stress distribution across the plate for trial E6
Figure A4.4 Transverse stress distribution immediately after welding for trial E6
Figure A4.5  Transverse stress distribution after the weld specimen reached room temperature for trial E6