

A Computer Program to Calculate Heat and Material Transport during Friction Stir Welding

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1. Code capabilities

This computer code can calculate the following features of friction stir welding process:

- Three dimensional temperature fields
- Material velocities around the tool
- Cooling rates at user-specified locations in the workpiece
- Flow-stress, strain rate and viscosity of the plasticized material around the tool
- Torque on the tool due to shear at the tool-workpiece contact areas
- Effects of tool geometry, tool orientation and welding variables on temperature and velocity fields, cooling rates, torque and other important output parameters.
- Pressure field around the tool
- Spatially variable heat generation rates at different contact points between the tool and the workpiece.

2. Special features of simulation

The special features of the computer code are the following:

- Tool geometry, orientation, workpiece dimensions, the tool and workpiece materials and the welding variables like axial pressure, tool's rotational and translational speed are specified in a text file by the users.
- Properties of common tool materials and commonly welded materials do not have to be provided by the users. They are already available in the package.
- The output provides a text file showing peak temperatures, heat generation rates, peak velocities in 3 directions, heat loss at different workpiece surfaces and the overall heat balance after every 100 iterations.
- The output also provides various types of automated plots for data visualization
- Spatially variable friction coefficient, slip at the tool-workpiece contact are considered
- Temperature dependent thermophysical properties are considered for calculation

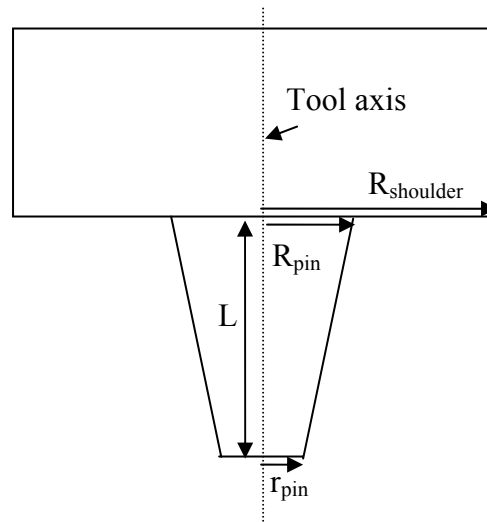
3. Description of a sample input file

Sample input files are included in the test cases presented later in this document. The input file, input.txt, contains all the user-specified variables. The input variables are grouped in six categories: material selection, tool geometry, welding parameters, numerical scheme parameters, boundary conditions and grids.

1. The material index for the tool and the workpiece indicate the alloy used based on the following table.

Index	Workpiece Material	Index	Tool Material
1	AA 6061-T6	2	1018-Mn Steel
2	1018-Mn Steel	3	304L stainless steel
3	304L stainless steel	6	Tungsten
8	Ti-6Al-4V		

2. The tool geometry involves specification of the radius of the tool pin at the shoulder and at the tip, radius of tool shoulder and the length of the tool pin.



3. The welding parameters include the following parameters. The tool location denoted by (x,y) co-ordinates, tool's linear speed along the weld-centreline, its rotational velocity, axial pressure exerted by tool on the workpiece and tilt angle of the tool.

4. The numerical scheme parameters include the maximum number of iterations of heat, momentum and solute transport solution over the whole domain, under-relaxation for x-direction velocity (u), y-direction velocity (v), z-direction velocity (w), pressure (p) and temperature (T). It also contains the indexes for saving and loading file. If the index for saving file is 1, u, v, w, p, T and c values are saved for all grid points in file "tmp.sv" so that the calculation can be restarted from those values in case convergence hasn't been achieved within the specified maximum number of iterations. If it is zero, "tmp.sv" is not created. To restart from values in "tmp.sv", the index for loading file should be made 1, otherwise, it should be kept 0. It also contains the location of the thermo-couples to be employed to monitor the temperature at various locations. The total number of monitoring locations and their y and z co-ordinates must be specified by the user.

5. The boundary conditions contain the heat transfer coefficient at the 6 faces of the workpiece, the temperature at these faces, the initial temperature of the work-piece, ambient temperature and other terms describing the tool- workpiece interface as explained below.

The code has provision for three types of boundary conditions at the east, west, bottom, north and south surfaces. (I) surface temperature is given; (II) convective heat flux with h_c calculated using equation:

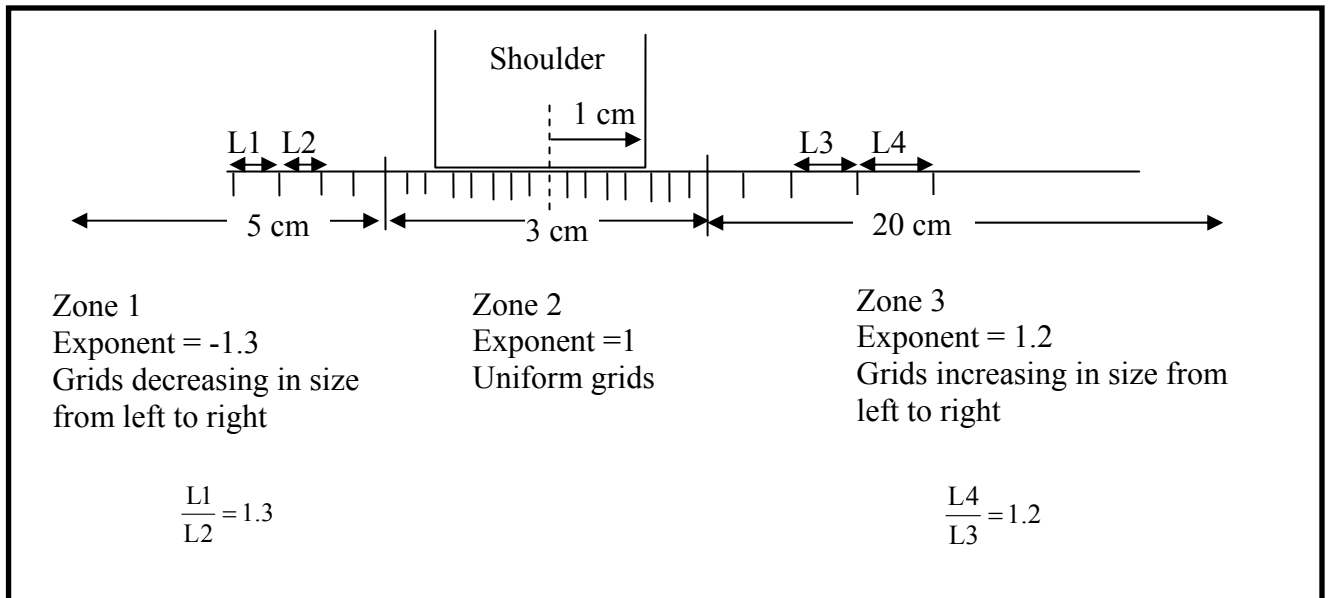
$$h_c = (1.3571 \times 10^{-5}) C' (1.8 \times \Delta T)^{0.25}$$

and (III) convective heat flux with h_c supplied by the user. This is done by determining the value of heat transfer co-efficient h_c in the input file as follows.

$$\text{If } \begin{cases} h_c > 20 \\ 0 < h_c < 20 \\ h_c < 0 \end{cases} \quad \text{then } \begin{cases} \text{(I)} \\ \text{(III)} \\ \text{(II)} \end{cases}$$

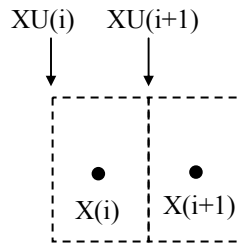
6) Fixed non-uniform rectangular grids are used in x, y and z directions. To facilitate generation of grids, the length(x-direction), width (y-direction) and depth (z-direction) are sub-divided into several zones. Since non-uniform grids are used, the user must specify the number of zones in each direction. For each zone, the length, number of control volumes and exponent must be specified. Grid generation is explained here. For example, consider a workpiece which is 18 cm long along the x-direction with the tool axis at 6.5 cm (from left), as specified in process parameters and tool shoulder radius of 1 cm. We define 3 zones. Note that grids are finer for the zone enclosing the tool shoulder. Also, the grids should be uniform for this zone.

```
3           !number of x-zones
5.0  3.0  20.0  !length of each x-zone (cm)
15   30  40     !number of control volumes in each x-zone
-1.3 1.0  1.2   !exponents to locate control volume interfaces
```



4. Description of a sample output file

a) The output file, output.txt, contains all the input parameters from input.txt. It also contains the x, y and z-grid locations in the domain eg. the positions of $x(i)$ and $xu(i)$ as shown in figure below.



A section of the output file is given below.

x-grid

```

i=      1      2      3      4      5      6      7
x=  0.000E+00 4.497E-02 1.338E-01 2.203E-01 3.044E-01 3.859E-01 4.645E-01
xu=  0.000E+00 0.000E+00 8.993E-02 1.776E-01 2.630E-01 3.458E-01 4.259E-01

```

The output file, output.txt, also contains the calculated parameters like peak temperature in the workpiece, the residual of calculated variables, the heat flux at each face, the maximum velocity in each direction, torque on the tool and the ratio of heat input to output at specified interval of iterations. A section of the output file is shown below:

```

iter      time/iter      res_enth      res_mass      res_u      res_v      res_w
  200         0.295         2.08E-04         2.24E-06         1.74E-03         1.72E-03         1.45E-03
Tmax      Tmax_tool      umax      vmax      wmax
1164.3      1141.2         6.7         6.6         0.8
vis_dis      shoulder      pin_ver      pin_hor      torque
  6.1         154.9         37.7         15.6         69.3
north  south  top  toploss  bottom  east  west  hout  hin  ratio
-1.6  -1.6  137.9  0.0  -94.0  -419.4  419.4  -97.2  198.7  0.49

```

b) A plotting data file “Tecout” contains following variables in ordered form, obtained after the final iteration: "X", "Y", "Z", "U", "V", "W", "T", "P", "VIS"

X, Y and Z are the co-ordinates (in mm) of grid points. U, V and W are the velocities (in mm/s) at the grid point in x, y and z-direction. T is the temperature in K, P is the pressure in dyne/cm^2 , and VIS is the viscosity in kg/m-s . This file can be directly opened using Tecplot plotting program. It is very important for visualization of results obtained.

c) The file “Tecmon.dat” contains the thermal cycle data for the various monitoring locations provided in input.txt. The data is in ordered form and can be plotted using any plotting software such as Tecplot®.

5. The main computational engine

5.1 Governing equations

Fixed non-uniform grids with co-ordinates attached to the moving tool axis were used. The origin of the co-ordinates and the directions are indicated in Fig. 1. As indicated in Fig. 1(b),

angle θ the angle with the negative x-axis in the counter-clockwise direction ($\theta = 0^\circ$ corresponds to plane $x < 0$).

The continuity equation for incompressible single phase flow in index notation for $i = 1, 2$ and 3 , representing x, y and z directions, respectively is given by:

$$\frac{\partial u_i}{\partial x_i} = 0 \quad [1]$$

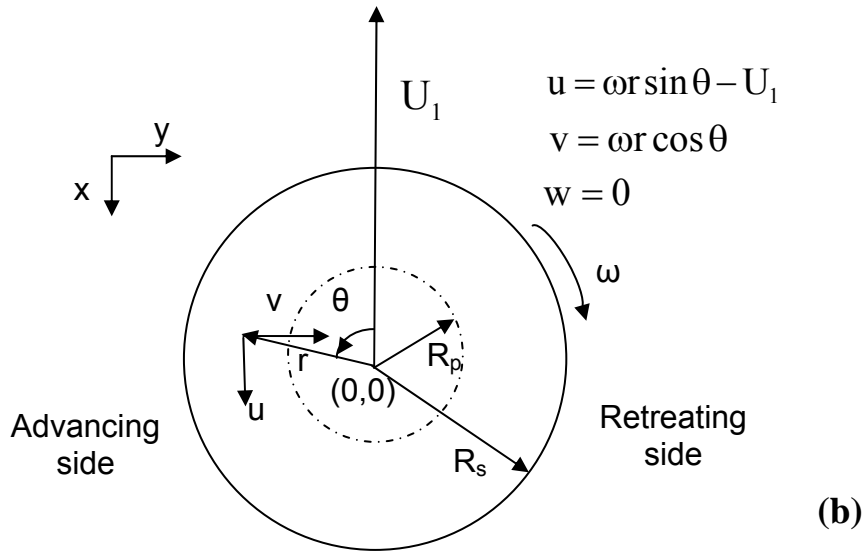
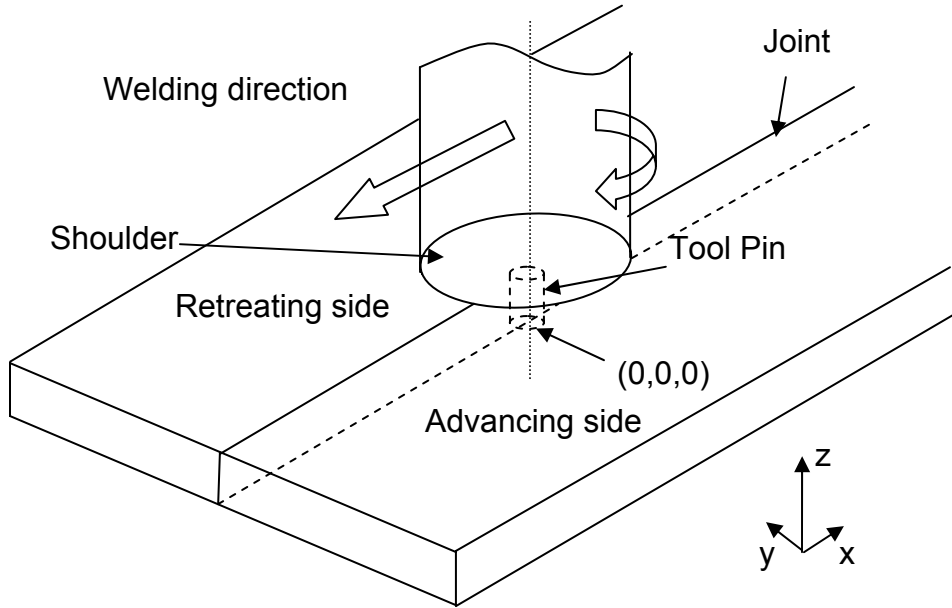


Fig. 1—(a) A schematic diagram of the FSW system considered in the model showing the thermal boundary conditions. (b) Top view of the tool showing tool velocity at the tool shoulder work piece interface. $\theta = 0$ corresponds to plane $x < 0$.

where u is the velocity of plastic flow. The steady single phase momentum conservation equations with reference to a co-ordinate system attached to the heat source in index form may be represented as:

$$\rho \frac{\partial u_i u_j}{\partial x_i} = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_i} \left(\mu \frac{\partial u_j}{\partial x_i} + \mu \frac{\partial u_i}{\partial x_j} \right) - \rho U_1 \frac{\partial u_j}{\partial x_i} \quad [2]$$

where ρ is the density and μ is the non-Newtonian viscosity and U_1 is the welding velocity, p is the pressure. The constitutive equations used here for viscosity calculation have been used for hot-working processes, particularly extrusion. Friction stir welding involves transfer of plasticized material from the front to the back of the tool pin as the tool traverses along the joint. It is basically an extrusion process followed by forging which joins the plates. Therefore, it is appropriate to use these equations for FSW. The calculation of viscosity requires local values of strain rate and temperature.

The steady thermal energy conservation equation is given by:

$$\rho C_p \frac{\partial (u_i T)}{\partial x_i} = -\rho C_p U_1 \frac{\partial T}{\partial x_i} + \frac{\partial}{\partial x_i} \left(k \frac{\partial T}{\partial x_i} \right) + S_{in} + S_b \quad [3]$$

where C_p is the specific heat and k is the thermal conductivity of the workpiece/tool. The term S_i represents the source term due to interfacial heat generation rate per unit volume at the tool pin-work piece interface and S_b is the heat generation rate due to plastic deformation in the workpiece away from the interface. The heat generated at the interface between vertical and horizontal surface of the tool pin and the workpiece, S_{in} , may be defined as:

$$S_{in} = [(1 - \delta)\eta\tau(\omega r - U_1 \sin \theta) + \delta\mu_f P_N] \frac{A_r}{V} \quad [4]$$

where, A_r is any small area on the tool pin-work piece interface, r is the radial distance of the center of the area from the tool axis, V is the control-volume enclosing the area A_r , τ is the maximum shear stress at yielding and θ is the angle with the negative x -axis in the counter-clockwise direction, η is the mechanical efficiency, *i.e.* the amount of mechanical energy converted to heat energy, δ denotes the spatially variable fractional slip between the tool and the workpiece interface, μ_f is the spatially variable coefficient of friction, ω is the angular velocity, P_N is the normal pressure on the surface and is equal P_V for the workpiece area in contact with the vertical surface of the pin and is equal to P_H for area below the horizontal surface of the tool. The velocity $(\omega r - U_1 \sin \theta)$ represents the local velocity of a point on tool with the origin fixed at the tool-axis.

In equation (4) The radial pressure is much smaller than the axial pressure and the value of P_V has been assumed to be zero. When δ is 0, full sticking is indicated and all the heat is generated by plastic deformation while heat is generated only by friction when $\delta = 1$. The variation of yield stress for mild steel alloy with temperature is shown in Fig. 3 based on data available in the literature.

During FSW, mixing is not atomic as evident from the previous research on dissimilar metal joining. Here grains are deformed but efficient mixing of atoms does not occur. A rigorous calculation of heat generation due to viscous dissipation of momentum is difficult. A rough estimate of the viscous dissipation of momentum per unit volume, S_b , has been calculated as $f_m \mu \Phi$ where Φ is given by:

$$\Phi = 2 \left[\left(\frac{\partial u_1}{\partial x_1} \right)^2 + \left(\frac{\partial u_2}{\partial x_2} \right)^2 + \left(\frac{\partial u_3}{\partial x_3} \right)^2 \right] + \left(\frac{\partial u_1}{\partial x_2} + \frac{\partial u_2}{\partial x_1} \right)^2 + \left(\frac{\partial u_1}{\partial x_3} + \frac{\partial u_3}{\partial x_1} \right)^2 + \left(\frac{\partial u_3}{\partial x_2} + \frac{\partial u_2}{\partial x_3} \right)^2 \quad [5]$$

and f_m is an arbitrary constant that indicates the extent of molecular friction in the system. The value of f_m may tend to 1 for a well mixed system in molecular scale. In systems where the grains remain largely intact, the value of f_m may be very small.

5.2 Boundary conditions

Since the thermal conductivity of the tool material (tungsten) is around 4 times higher than steel, a significant amount of heat will be transported to the tool material. Therefore, the total heat generated at the shoulder/work piece interface has been partitioned between the work piece and the tool in the ratio given below:

$$f = \frac{J_w}{J_T} = \frac{\sqrt{(k\rho C_p)_w}}{\sqrt{(k\rho C_p)_T}} \quad [6]$$

where the subscript W and T denote the workpiece and the tool, respectively. The analytical expression is based on steady-state one dimensional heat transfer from point heat source located at the interface of dissimilar metals

A heat flux continuity at the shoulder matrix interface yields:

$$k \left. \frac{\partial T}{\partial z} \right|_{\text{top}} = \frac{J_w}{J_w + J_T} q_1 \quad \text{in the range } R_p \leq r \leq R_s \quad [7]$$

R_p and R_s represent the tool pin and shoulder radius, respectively and q_1 represents the rate of heat generation due to plastic work at the shoulder-work piece interface. It is given by

$$q_1 = \eta(1 - \delta)\tau(\omega r - U_1 \sin \theta) + \delta\mu_f P_T \quad [8]$$

The boundary condition for heat exchange between the top surface of the work piece and the surroundings beyond the shoulder involved consideration of both convective and radiative heat transfer as

$$-k \left. \frac{\partial T}{\partial z} \right|_{\text{top}} = \sigma\epsilon(T^4 - T_a^4) + h_t(T - T_a) \quad [9]$$

At the bottom surface, the heat transfer is given by

$$k \left. \frac{\partial T}{\partial z} \right|_{\text{bottom}} = h_b(T - T_a) \quad [10]$$

where h_b is the bottom heat transfer coefficient and T_a is the room temperature of 298 K. The heat transfer coefficient at the bottom face depends on the local temperature and is given by the following relation:

$$h_b = h_{b0}(T - T_a)^{0.25} \quad [11]$$

where h_{b0} is the heat transfer parameter for the bottom surface. As equation 11 shows, this parameter is a constant and it has a different unit than the heat transfer coefficient which is spatially variable.

Velocity at the tool pin periphery have been defined in terms of tool translation velocity and the tool pin angular velocity

$$\begin{aligned} u &= (1 - \delta)(\omega R_p \sin \theta - U_1) \\ v &= (1 - \delta)\omega R_p \cos \theta \\ w &= \kappa \frac{\omega}{2\pi} R_p \end{aligned} \quad [12]$$

where κ denotes the pitch of the threads on the cylindrical tool.

Similarly, at the shoulder contact, velocity condition may be written as:

$$\left. \begin{aligned} u &= (1 - \delta)(\omega r \sin \theta - U_1) \\ v &= (1 - \delta)\omega r \cos \theta \end{aligned} \right\} \text{ in the range } R_p \leq r \leq R_s \quad [13]$$

At all other surfaces, temperatures are set to ambient temperature and the velocities are set to zero.

The extent of slip was estimated from the following functional relationship determined from the reported experimental data of tool–workpiece interfacial slip in a flat-wedge cross-wedge rolling process. The trend of the reported data can be expressed by the following relation for FSW:

$$\delta = 1 - \exp\left(-\delta_0 \frac{\omega}{\omega_0} \frac{r}{R_s}\right) \quad [14]$$

where δ denotes the fraction-slip and δ_0 is a constant. The above equation was used for all interfaces, with r denoting the distance of the center of the area from the tool axis. It is constant at R_p for the vertical surface of the pin, varies from 0 to R_p for the horizontal surface and from R_p to R_s for the tool shoulder. A typical value of rotational speed, ω_0 , is used to non-dimensionalize the tool rotational speed of the tool, ω and R_s is the shoulder radius.

Values of friction coefficient were calculated considering the relative velocity between the tool and the workpiece guided by previous work in the field of friction welding of steel bars. The relative velocity increases from zero at the axis of rotation (static condition) to ωR_s at the periphery of the tool shoulder (dynamic condition). Friction coefficient, μ has the following form:

$$\mu_f = \mu_0 \exp(-\lambda \delta \omega r) \quad [15]$$

where δ is the percentage sticking and r is the radial distance from the tool axis for the point in consideration.

No flux boundary condition is used for elemental transport equation.

5.3 Solution methodology

Before discretizing the governing equations, the three equations of conservation of momentum and energy are rewritten in the following general form:

$$\frac{\partial}{\partial x_i} (\rho u_i \phi_j) = \frac{\partial}{\partial x_i} \left(\Gamma \frac{\partial \phi_j}{\partial x_i} \right) + S_j \quad [16]$$

where, ϕ is the general dependent variable, Γ is the diffusion coefficient, and S is the source term. The indices i or $j = 1, 2,$ and 3 represent the x, y and z direction respectively. Thus the governing momentum equation may be modified into the general form, as given by Eq. [16], to yield:

$$\frac{\partial}{\partial x_i} (\rho u_i u_j) = \frac{\partial}{\partial x_i} \left(\Gamma \frac{\partial u_j}{\partial x_i} \right) + S_{u_j} \quad [17]$$

where the source term for the momentum equations can be given as:

$$S_{u_j} = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_i} \left(\mu \frac{\partial u_i}{\partial x_j} \right) - \rho U \delta_{i1} \frac{\partial u_j}{\partial x_i} \quad [18]$$

Source due to welding velocity is only in the x -direction, hence it is multiplied by δ_{j1} which is non-zero only when $i = 1$.

Similarly, the heat transfer equation may be rewritten as:

$$\rho C_p \frac{\partial(u_i T)}{\partial x_i} = \frac{\partial}{\partial x_i} \left(k \frac{\partial T}{\partial x_i} \right) + S_h \quad [19]$$

$$\text{where } S_h = \left[\{S(\theta)A_r / V\} + \eta\Phi - \rho C_p U \delta_{ii} \frac{\partial T}{\partial x_i} \right] \quad [20]$$

The governing equations are discretized using the control volume method, where the workpiece is divided into small rectangular control volumes. Each control volume surrounds a grid point where the scalar variables are stored. Vectors such as the x, y, and z components of velocities are stored at grid points which are staggered with respect to those of scalar variables like pressure and temperature to ensure the stability of numerical calculation. Thus, the control volumes for scalars are different from those for the vectors. Discretized equations for a variable are formulated by integrating the corresponding governing equation over the control volumes using fully implicit hybrid power law scheme. The final discretized equation at a grid point ‘‘P’’ takes the following form:

$$a_p \phi_p = \sum_{nb} (a_{nb} \phi_{nb}) + a_p^0 \phi_p^0 + S_U \Delta V \quad [21]$$

where, ϕ represents a general variable such as velocity or enthalpy, ‘‘a’’ represents the coefficient of the variables calculated based on the power law scheme, subscript nb represents the neighbors of a the grid point P, ΔV is the volume of the control volume, a_p^0 and ϕ_p^0 are the coefficient and value of the general variable at the concerned grid point P at the previous time step, respectively. The coefficient of ϕ at the point P is defined in terms of neighboring grid points as follows:

$$a_p = \sum_{nb} a_{nb} + a_p^0 - S_p \Delta V \quad [22]$$

The terms S_U and S_p are the coefficients of the linearized source term, defined as:

$$S = S_U + S_p \phi \quad [23]$$

Among the velocity boundary conditions, the velocities are known on the shoulder surface. However, implementation of known fixed velocity boundary conditions (U_F) at the tool pin surface needs some discussion. Eq. [22] can be modified by assigning a large negative value to S_p , and S_p times U_F to S_U in eqn [21] such that the first term on the right hand side become negligible yielding $\phi_p = U_F$. The Implementation of heat flux at the top shoulder-workpiece interface also needs some discussion

$$\left(k \frac{dT}{dz} \right) \Big|_{z=z_{max}} = q_1(x_1, x_2) \quad [24]$$

Integrating this equation over the top most boundary control volume, the temperatures at the top most z-grids, nk, may be related to the temperature at the grid points at nk-1 as:

$$T_{i,j,nk} = T_{i,j,nk-1} + \frac{q_1(x_1, x_2)}{k_{i,j,nk}} \Delta z \quad [25]$$

where $k_{i,j,nk}$ and $C_{p,i,j,nk}$ represent the space dependent thermal conductivity and specific heat, respectively at the top most z-grids. Finally the equations at (nk-1) grid points can be obtained as follows:

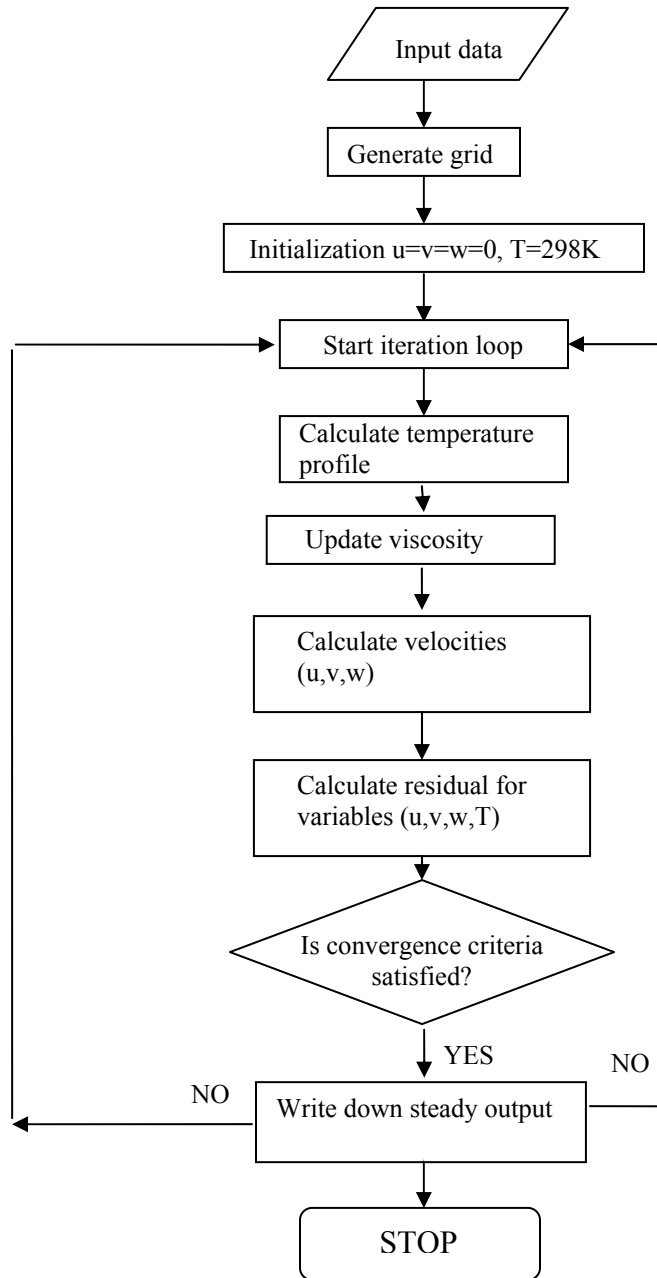
$$S_U = S_U + a_T \left[\frac{q_1(x_1, x_2)}{k_{i,j,nk} C_{p,i,j,nk}} \Delta z \right] \quad [26]$$

$$S_p = S_p + (a_T / \Delta V) \quad [27]$$

The boundary condition for the enthalpy at the bottom surface can be implemented as follows:

$$\left(k \frac{dT}{dz} \right) \Big|_{z=0} = h(T - T_a)$$

[28]



Summary of solution methodology

Integrating the equation over bottom control volume ($k=1$), the enthalpy may be expressed in terms of the grid point values at $k = 2$

$$h_{i,j,1} = \frac{(k_1 / \Delta z) h_{i,j,2} + h_c h_a}{\left(\frac{k_1}{\Delta z} - h_c \right)} = C_1 h_{i,j,2} + C_2 \quad [29]$$

where, $C_1 = \frac{(k_1 / \Delta z)}{[(k_1 / \Delta z) - h_c]}$ and $C_2 = \frac{h_c h_a}{[(k_1 / \Delta z) - h_c]}$

Finally, the equations at grid points for $k=2$, may be obtained, and Eq. [21] may be represented in terms of modified S_U and S_P as follows:

$$S_U = S_U + C_2 / \Delta V \tag{30}$$

$$S_P = S_P + (C_1 a_B / \Delta V) \tag{31}$$

Accurate calculation of temperature and velocity fields requires the use of very fine grid system. Spatially non-uniform grids are used for maximum resolution of variables. Finer grid spacing was used near the heat source.

Two criterions were used to test for convergence; magnitude of residuals of enthalpy and three velocities and the overall heat balance. The residuals for velocities and enthalpy are defined as:

$$R = \frac{\sum_{\text{domain}} \left| \frac{\sum_{\text{nb}} (a_{\text{nb}} \phi_{\text{nb}}) + a_p^0 \phi_p^0 + S_U \Delta V}{a_p} - \phi_p \right|}{\sum_{\text{domain}} |\phi_p|} \tag{31}$$

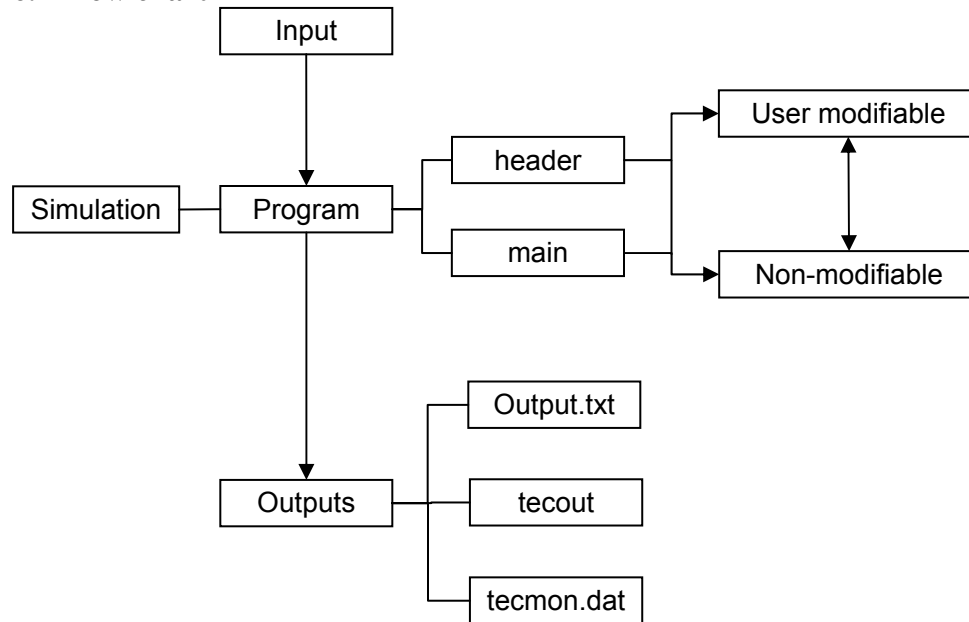
The residual values less than 5.0×10^{-5} were accepted as converged solution. Heat balance ratio is given by:

$$\theta = \left| \frac{\text{net heat input}}{\text{total heat out} + \text{heat accumulation}} \right| \tag{32}$$

The heat balance ratio θ within $0.99 \leq \theta \leq 1.01$ was accepted as converged solution. Several stricter convergence criteria did not change the final results.

6. Remarks about the computer code

6.1 Flow chart



Organization of the code

6.2 Description of user definable code

user.for

The user modifiable portion of the code is in a file named ‘user.for’. It contains the following subroutines:

1. Taskhandler – The main program that controls the sequence of operations
2. Initialize – Initializes the variables
3. Bound - Calculates the boundary values
4. Props - Updates the physical properties
5. Output - Generates output files and produces the required output

This file contains the values of the following five important variables that affect the calculations significantly.

a. del_0 is a constant which determines the slip at the tool-workpiece interface based on the following relation:

$$\delta = 1 - \exp\left(-\delta_0 \frac{\omega}{\omega_0} \frac{r}{R_s}\right) \quad [32]$$

where δ denotes the fraction-slip. The above equation was used for all interfaces, with r denoting the distance of the center of the area from the tool axis. It is constant at R_p for the vertical surface of the pin, varies from 0 to R_p for the horizontal surface and from R_p to R_s for the tool shoulder. A typical value of rotational speed, ω_0 , is used to non-dimensionalize the tool rotational speed of the tool, ω and R_s is the shoulder radius.

b. mu_0 is a constant which determines the friction coefficient, μ at the tool-workpiece interface, which has the following form:

$$\mu_f = \mu_0 \exp(-\lambda \delta \omega r) \quad [33]$$

where δ is the percentage sticking and r is the radial distance from the tool axis for the point in consideration. Values of friction coefficient were calculated considering the relative velocity between the tool and the workpiece guided by previous work in the field of friction welding of steel bars. λ is a constant whose value is taken as 1s/m. The relative velocity increases from zero at the axis of rotation (static condition) to ωR_s at the periphery of the tool shoulder (dynamic condition).

c. beta is used as an arbitrary constant in the estimate of viscous dissipation of momentum per unit volume, S_b . It is calculated as $beta \times \mu \Phi$ where Φ is given by:

$$\Phi = 2 \left[\left(\frac{\partial u_1}{\partial x_1} \right)^2 + \left(\frac{\partial u_2}{\partial x_2} \right)^2 + \left(\frac{\partial u_3}{\partial x_3} \right)^2 \right] + \left(\frac{\partial u_1}{\partial x_2} + \frac{\partial u_2}{\partial x_1} \right)^2 + \left(\frac{\partial u_1}{\partial x_3} + \frac{\partial u_3}{\partial x_1} \right)^2 + \left(\frac{\partial u_3}{\partial x_2} + \frac{\partial u_2}{\partial x_3} \right)^2 \quad [34]$$

Here $beta$ indicates the extent of atomic mixing. In systems where the grains remain largely intact, the value of $beta$ may be very small.

d. cf denotes the amount of plastic deformation work which is converted to heat at the tool-workpiece interface. It is the η in eqn. [4].

e. htck1 denotes the bottom heat transfer parameter h_{b0} in eqn. [11].

Also, since our calculation domain does not include the tool shoulder, we need to determine the fraction of heat generated at the tool shoulder-workpiece interface which enters the workpiece, so that this can be treated as heat flux into the workpiece. The fraction is denoted by *fracheat* and can be approximated as:

$$\text{fracheat} = \frac{J_w}{J_w + J_T} = \frac{1}{1 + \sqrt{(k\rho C_p)_T / (k\rho C_p)_W}} \quad [35]$$

where W denotes workpiece and T denotes tool. Representative value of this parameter for different workpiece-tool material combinations can be obtained from the references given.

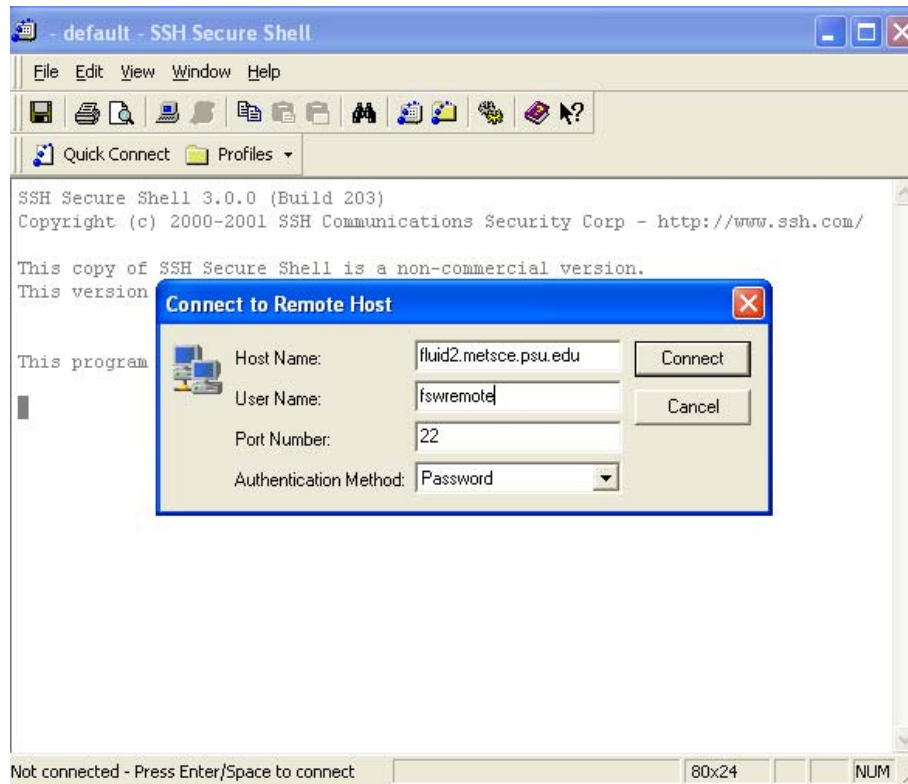
Representative values of these parameters for different workpiece-tool material combinations can be obtained from the references given.

Header.for

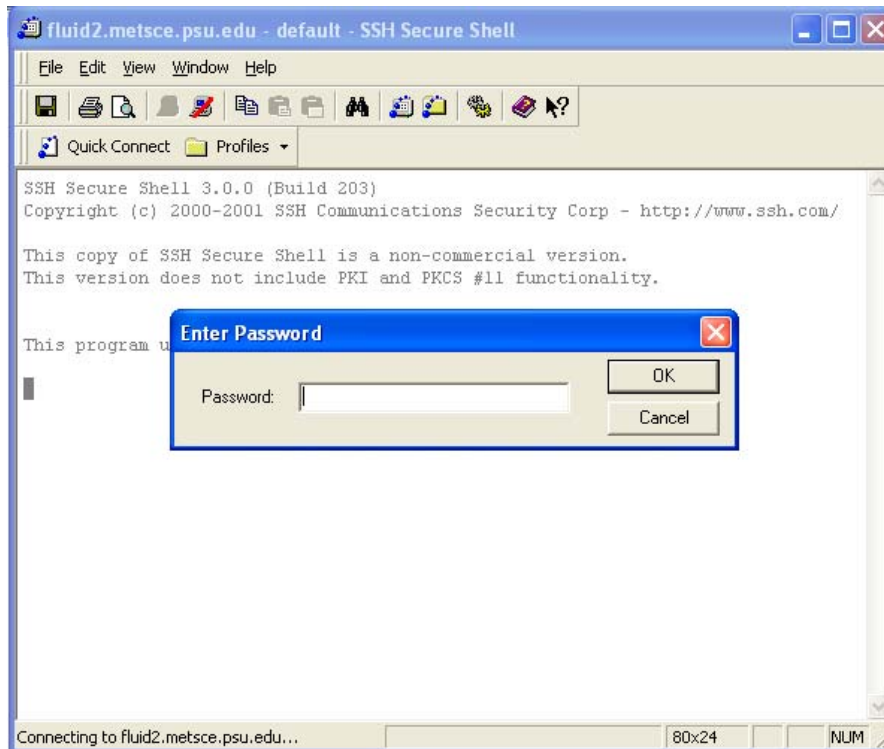
It is the resource file which stores all the variables shared between routines.

7. Connecting to the server to run the code

To run the code from a Windows-based computer, connect to host fluid2.metsce.psu.edu using SSH Secure Shell client. The User Name is obtained from Professor DebRoy (say 'fswremote'), Port Number is '22' and authentication method is 'Password'



Enter the password when prompted (say 'fsw1234')



To compile the code, type './compile.exe' and press enter at the command prompt. This creates an executable 'fsw.exe'. To execute the code, type './fsw.exe' and press enter.

8. Test Cases

8.1 Welding of AA6061-T6 using 304L stainless steel tool

input.txt

```

!-----Material selection-----
!1=AA6061,2=1018Steel,3=304L SS,6=Tungsten,8=Ti-6Al-4V
1          !Workpiece material on advancing side
2          !tool material
1          !Workpiece material on retreating side
!-----Tool geometry-----
0.95       !shoulder radius(cm)
0.3        !pin radius at shoulder (cm)
0.25       !pin radius at the tip (cm)
0.64       !pin length (cm)
0.1        !thread pitch (cm)
!-----Welding parameters-----
6.5        !x-location of the tool
10.0       !y-location of the tool
0.042      !welding velocity (cm/sec)
450.0      !rotational velocity (rpm)
65.9       !axial pressure (MPa)
2.0        !Tilt angle (degrees)
!-----Numerical scheme parameters-----
6000       !maximum number of iterations
0.8        !underrelaxation for u-velocity
0.8        !underrelaxation for v-velocity
0.8        !underrelaxation for w-velocity
0.8        !underrelaxation for pressure
0.95       !underrelaxation for temperature
0          !index for saving file (1 = save)
0          !index for loading file (1 = load)

```

```

6          !Number of monitoring locations
8.5  8.5  8.5  11.5  11.5  11.5  !y coordinates of monitoring locations
0.24 0.48 0.70 0.24 0.48 0.70  !z coordinates of monitoring locations
!-----Boundary conditions-----
100.      !heat transfer coefficient at west face (cal/cm2-s-K)
100.      !heat transfer coefficient at east face (cal/cm2-s-K)
100.      !heat transfer coefficient at north face (cal/cm2-s-k)
100.      !heat transfer coefficient at south face (cal/cm2-s-k)
0.0       !heat transfer coefficient at top face (cal/cm2-s-K)
298.0     !temperature at west face (K)
298.0     !temperature at east face (K)
298.0     !temperature at north face (K)
298.0     !temperature at south face (K)
298.0     !temperature at bottom face (K)
298.0     !preheat temperature (K)
298.0     !ambient temperature (K)
0.45      !fraction of energy entering the work-piece
!-----Grids-----
6          !number of x-zones
5.0  1.0  1.0  1.0  5.0  16.0  !length of each x-zone (cm)
12   20   30   20  12   15     !number of control volumes in each x-zone
-1.2 -1.1 1.0  1.1  1.2  1.3  !exponents to locate control volume interfaces
3          !number of y-zones
8.5  3.0  8.5      !length of each y-zone (cm)
15   65   15       !number of control volumes in each y-zone
-1.3 1.0  1.3     !exponents to locate control volume interfaces
1          !number of z-zones
0.72      !length of each z-zone (cm)
15        !number of control volumes in each z-zone
1.0       !exponents to locate control volume interfaces

```

Output.txt

Friction Stir Welding

```

Advancing side : AA 6061
Tool           : 1018 C-Mn Steel
Retreating side: AA 6061

```

Process parameters

```

Starting x-location of the power source      6.5000E+00
Starting y-location of the power source      1.0000E+01
Welding velocity (cm/sec)                   4.2000E-02
RPM (rad/s)                                 4.5000E+02
Contact pressure due to axial load (MPa)     6.5900E+01

```

advancing side material properties

```

Density (gm/cm3)                            2.7000E+00
Solidus temperature (K)                     8.5500E+02
Specific heat (cal/gm-K)                    2.0860E-01
Thermal cond. (cal/cm-sec-K)                3.2917E-01
Emissivity of the material                   0.0000E+00

```

tool material properties

```

Density (gm/cm3)                            7.8600E+00
Solidus temperature (K)                     1.7450E+03
Specific heat (cal/gm-K)                    1.1344E-01
Thermal cond. (cal/cm-sec-K)                1.2291E-01
Emissivity of the material                   0.0000E+00

```

retreating side material properties

```

Density (gm/cm3)                            2.7000E+00
Solidus temperature (K)                     8.5500E+02
Specific heat (cal/gm-K)                    2.0860E-01
Thermal cond. (cal/cm-sec-K)                3.2917E-01

```



```

Emissivity of the material                0.0000E+00
-----
Numerical scheme parameters
-----
Maximum number of iterations              6000
Time step                                1.0000E+20
Maximum time                              0.0000E+00
Underrelaxation for u-velocity            8.0000E-01
Underrelaxation for v-velocity            8.0000E-01
Underrelaxation for w-velocity            8.0000E-01
Underrelaxation for pressure              8.0000E-01
Underrelaxation for temperature           9.5000E-01
-----
Boundary conditions
-----
Heat transfer coeff at west face (cal/cm2-s-K) 1.0000E+02
Heat transfer coeff at east face (cal/cm2-s-K) 1.0000E+02
Heat transfer coeff at north face (cal/cm2-s-K) 1.0000E+02
Heat transfer coeff at south face (cal/cm2-s-K) 1.0000E+02
Heat transfer coeff at bottom face (cal/cm2-s-K) 1.2000E-02
Heat transfer coeff at top face (cal/cm2-s-K) 0.0000E+00
Temperature at west face (K)               2.9800E+02
Temperature at east face (K)               2.9800E+02
Temperature at north face (K)              2.9800E+02
Temperature at south face (K)              2.9800E+02
Temperature at bottom face (K)             2.9800E+02
Preheat temperature (K)                   2.9800E+02
Ambient temperature (K)                   2.9800E+02
Fraction of heat entering work-piece      4.5000E-01
Parameter for slip                        3.0000E+00
Parameter for friction coefficient         3.5000E-01
Parameter for viscous dissipation         3.0000E-03
-----
Geometrical parameters
-----
x direction
number of zones                           6
zone( 1) length                           0.5000E+01
zone( 1) number of control volumes (CV)    12
zone( 1) exponent to locate CV interfaces  -.1200E+01
zone( 2) length                           0.1000E+01
zone( 2) number of control volumes (CV)    20
zone( 2) exponent to locate CV interfaces  -.1100E+01
zone( 3) length                           0.1000E+01
zone( 3) number of control volumes (CV)    30
zone( 3) exponent to locate CV interfaces  0.1000E+01
zone( 4) length                           0.1000E+01
zone( 4) number of control volumes (CV)    20
zone( 4) exponent to locate CV interfaces  0.1100E+01
zone( 5) length                           0.5000E+01
zone( 5) number of control volumes (CV)    12
zone( 5) exponent to locate CV interfaces  0.1200E+01
zone( 6) length                           0.1600E+02
zone( 6) number of control volumes (CV)    15
zone( 6) exponent to locate CV interfaces  0.1300E+01
y direction
number of zones                           3
zone( 1) length                           0.8500E+01
zone( 1) number of control volumes (CV)    15
zone( 1) exponent to locate CV interfaces  -.1300E+01
zone( 2) length                           0.3000E+01
zone( 2) number of control volumes (CV)    65
zone( 2) exponent to locate CV interfaces  0.1000E+01
zone( 3) length                           0.8500E+01
zone( 3) number of control volumes (CV)    15

```

```

zone( 3) exponent to locate CV interfaces          0.1300E+01
z direction
number of zones                                  1
zone( 1) length                                  0.7200E+00
zone( 1) number of control volumes (CV)          16
zone( 1) exponent to locate CV interfaces        0.1000E+01

Number of grid points in x-direction (length)    111
Number of grid points in y-direction (width)     97
Number of grid points in z-direction (depth)     18
length of the specimen (cm)                     2.9000E+01
Width of the specimen (cm)                      2.0000E+01
Height of the specimen (cm)                    7.2000E-01

```

x-grid

```

i=      1      2      3      4      5      6      7
x= 0.000E+00 2.479E-01 7.391E-01 1.221E+00 1.693E+00 2.154E+00 2.603E+00
xu= 0.000E+00 0.000E+00 4.957E-01 9.825E-01 1.460E+00 1.926E+00 2.381E+00

i=     106     107     108     109     110     111
x= 2.307E+01 2.433E+01 2.563E+01 2.696E+01 2.831E+01 2.900E+01
xu= 2.244E+01 2.369E+01 2.497E+01 2.628E+01 2.763E+01 2.900E+01

```

y-grid

```

j=      1      2      3      4      5      6      7
y= 0.000E+00 3.646E-01 1.086E+00 1.792E+00 2.480E+00 3.151E+00 3.803E+00
yv= 0.000E+00 0.000E+00 7.292E-01 1.443E+00 2.140E+00 2.820E+00 3.482E+00

j=     92     93     94     95     96     97
y= 1.685E+01 1.752E+01 1.821E+01 1.891E+01 1.964E+01 2.000E+01
yv= 1.652E+01 1.718E+01 1.786E+01 1.856E+01 1.927E+01 2.000E+01

```

z-grid

```

k=      1      2      3      4      5      6      7
z= 0.000E+00 2.250E-02 6.750E-02 1.125E-01 1.575E-01 2.025E-01 2.475E-01
zw= 0.000E+00 0.000E+00 4.500E-02 9.000E-02 1.350E-01 1.800E-01 2.250E-01

k=      8      9     10     11     12     13     14
z= 2.925E-01 3.375E-01 3.825E-01 4.275E-01 4.725E-01 5.175E-01 5.625E-01
zw= 2.700E-01 3.150E-01 3.600E-01 4.050E-01 4.500E-01 4.950E-01 5.400E-01

k=     15     16     17     18
z= 6.075E-01 6.525E-01 6.975E-01 7.200E-01
zw= 5.850E-01 6.300E-01 6.750E-01 7.200E-01

```

Date: 2007-12-18 time: 16 :21 :14

```

iter   time/iter   res_enth   res_mass   res_u      res_v      res_w
100    0.340        5.75E-05   2.16E-01   2.50E-02   5.16E-02   1.89E-01
Tmax   Tmax_tool     umax       vmax       wmax
468.7  476.0         4.7        4.7        2.9
vis_dis  shoulder     pin_ver    pin_hor    torque
1.2    220.5        136.9     22.7      56.1
north  south   top   toploss  bottom  east   west   hout   hin   ratio
-6.6   -6.6   146.9  0.0    -105.1 -101.5 101.5 -118.3 381.2 0.31

```

```

iter   time/iter   res_enth   res_mass   res_u      res_v      res_w
1000   0.322        5.85E-06   2.21E-01   5.87E-02   1.08E-01   9.00E-01
Tmax   Tmax_tool     umax       vmax       wmax
514.9  519.4         4.7        4.7        2.2
vis_dis  shoulder     pin_ver    pin_hor    torque
0.9    178.0        72.3      14.5     41.9

```

north	south	top	toploss	bottom	east	west	hout	hin	ratio
-7.6	-7.6	158.8	0.0	-186.0	-101.5	98.3	-204.3	265.6	0.77

iter	time/iter	res_enth	res_mass	res_u	res_v	res_w
2000	0.322	2.16E-06	2.19E-01	5.73E-02	1.06E-01	8.32E-01
Tmax	Tmax_tool	umax	vmax	wmax		
519.7	523.8	4.7	4.7	1.0		
vis_dis	shoulder	pin_ver	pin_hor	torque		
0.9	173.5	66.2	13.7	40.5		

north	south	top	toploss	bottom	east	west	hout	hin	ratio
-3.9	-3.9	168.8	0.0	-213.6	-101.5	95.2	-227.6	254.3	0.89

iter	time/iter	res_enth	res_mass	res_u	res_v	res_w
3000	0.321	1.17E-06	2.24E-01	5.93E-02	1.14E-01	8.66E-01
Tmax	Tmax_tool	umax	vmax	wmax		
520.7	524.8	4.7	4.7	2.4		
vis_dis	shoulder	pin_ver	pin_hor	torque		
0.8	172.5	64.9	13.6	40.2		

north	south	top	toploss	bottom	east	west	hout	hin	ratio
-2.3	-2.3	170.8	0.0	-222.3	-101.5	94.2	-234.2	251.8	0.93

iter	time/iter	res_enth	res_mass	res_u	res_v	res_w
4000	0.321	1.25E-06	2.08E-01	5.83E-02	1.04E-01	8.10E-01
Tmax	Tmax_tool	umax	vmax	wmax		
521.0	525.1	4.7	4.7	1.1		
vis_dis	shoulder	pin_ver	pin_hor	torque		
0.9	172.2	64.5	13.5	40.1		

north	south	top	toploss	bottom	east	west	hout	hin	ratio
-1.7	-1.7	171.5	0.0	-225.3	-101.5	93.9	-236.3	251.2	0.94

iter	time/iter	res_enth	res_mass	res_u	res_v	res_w
5000	0.321	8.94E-07	2.07E-01	5.85E-02	1.02E-01	8.83E-01
Tmax	Tmax_tool	umax	vmax	wmax		
521.1	525.2	4.7	4.7	2.4		
vis_dis	shoulder	pin_ver	pin_hor	torque		
0.8	172.2	64.4	13.5	40.1		

north	south	top	toploss	bottom	east	west	hout	hin	ratio
-1.5	-1.6	170.5	0.0	-226.3	-101.5	93.8	-237.1	250.9	0.94

iter	time/iter	res_enth	res_mass	res_u	res_v	res_w
6000	0.321	1.06E-06	2.28E-01	5.90E-02	1.12E-01	8.16E-01
Tmax	Tmax_tool	umax	vmax	wmax		
521.1	525.2	4.7	4.7	1.7		
vis_dis	shoulder	pin_ver	pin_hor	torque		
0.9	172.1	64.4	13.5	40.1		

north	south	top	toploss	bottom	east	west	hout	hin	ratio
-1.5	-1.5	173.3	0.0	-226.4	-101.5	93.8	-237.1	250.9	0.95

Some important calculated parameters at the end of heating cycle

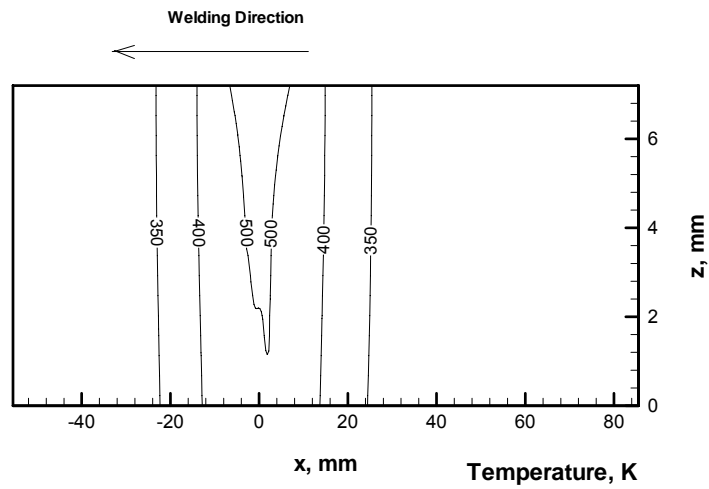
Peak temperature	(K)	5.2115E+02
Maximum u-velocity	(cm/s)	4.7037E+00
Maximum v-velocity	(cm/s)	4.6922E+00
Maximum w-velocity	(cm/s)	1.6545E+00
Deformational heat in workpiece	(cal/s)	0.8616E+00 (0.3 %)
Heat at tool shoulder	(cal/s)	0.1721E+03 (68.6 %)
Heat at tool pin's vertical surface	(cal/s)	0.6437E+02 (25.7 %)
Heat at tool pin's bottom surface	(cal/s)	0.1351E+02 (5.4 %)
Rate of heat input	(cal/s)	2.5087E+02
Rate of heat output	(cal/s)	-2.3713E+02
Ratio of heat input to heat output		9.4522E-01

Date: 2007-12-18 time: 16:53:21

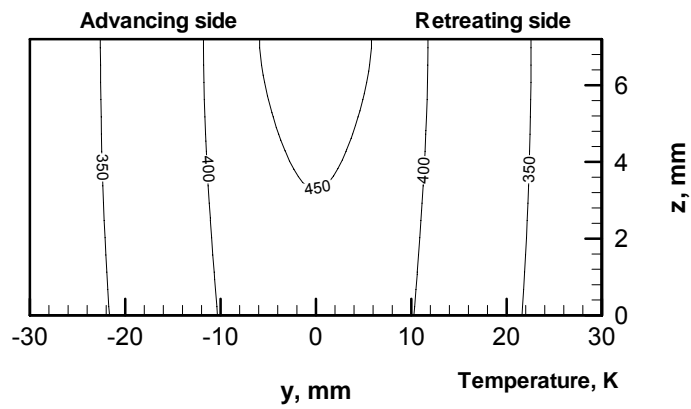
Total time used: 0 hr 32 m 7 s

Plots

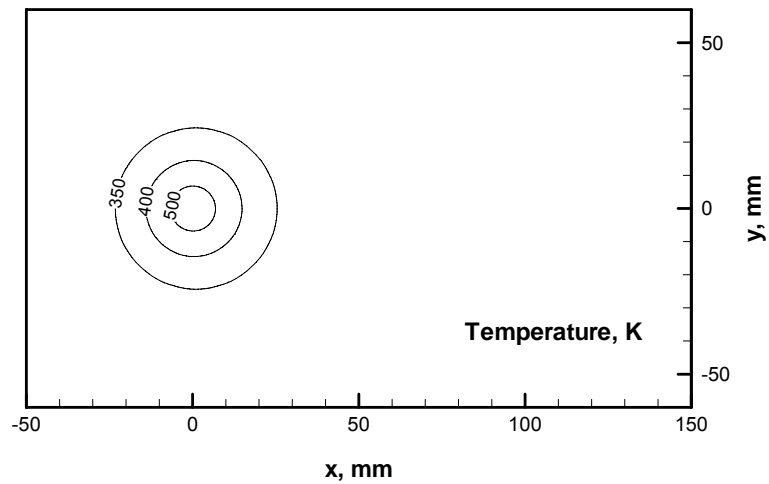
a



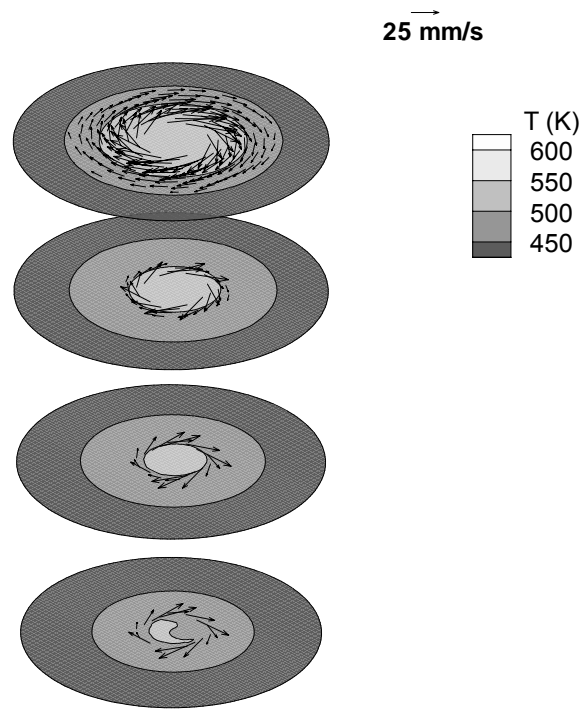
b



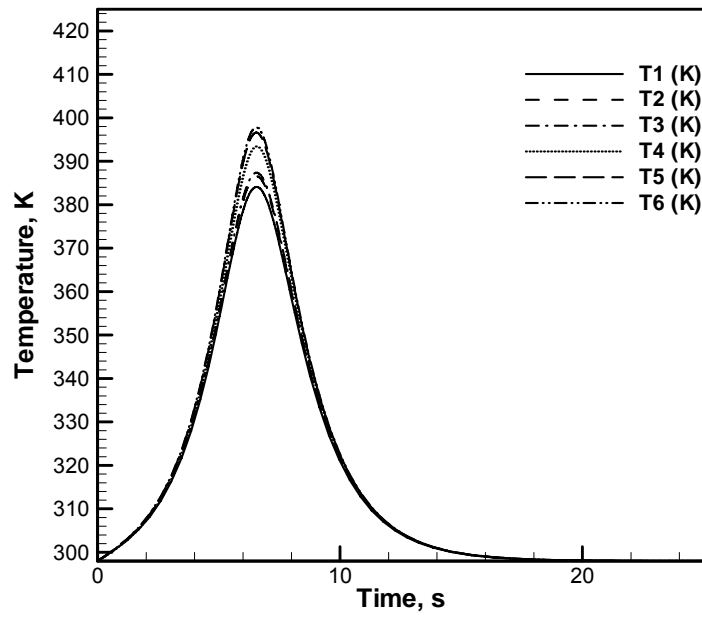
c



Computed temperature profiles(K) in (a) $y=0$ (xz plane), (b) $x=0$ (yz plane) and (c) $z=7.2$ mm (xy) i.e. the top surface of the workpiece.



Plot of temperature contours (K) and velocity vectors at $z=2.02, 3.82, 5.62,$ and 7.2mm planes.



Thermal cycles at the 6 different locations indicated in input.txt

8.2 Welding of Ti-6Al-4V using tungsten tool

input.txt

```
!-----Material selection-----
!1=AA6061,2=1018Steel,3=304L SS,6=Tungsten,8=Ti-6Al-4V
8      !Workpiece material on advancing side
6      !tool material
8      !Workpiece material on retreating side
!-----Tool geometry-----
0.95   !shoulder radius(cm)
0.3    !pin radius at shoulder (cm)
0.3    !pin radius at the tip (cm)
0.64   !pin length (cm)
0.0    !thread pitch (cm)
!-----Welding parameters-----
6.5    !x-location of the tool
10.0   !y-location of the tool
0.16   !welding velocity (cm/sec)
275.0  !rotational velocity (rpm)
60.0   !axial pressure (MPa)
0.0    !Tilt angle (degrees)
!-----Numerical scheme parameters-----
2000   !maximum number of iterations
0.8    !underrelaxation for u-velocity
0.8    !underrelaxation for v-velocity
0.8    !underrelaxation for w-velocity
0.8    !underrelaxation for pressure
0.8    !underrelaxation for temperature
0      !index for saving file (1 = save)
0      !index for loading file (1 = load)
6      !Number of monitoring locations
8.8 11.2 9.7 10.3 8.0 12.0 !y coordinates of monitoring locations
0.70 0.70 0.02 0.02 0.3 0.3 !z coordinates of monitoring locations
!-----Boundary conditions-----
100.   !heat transfer coefficient at west face (cal/cm2-s-K)
100.   !heat transfer coefficient at east face (cal/cm2-s-K)
100.   !heat transfer coefficient at north face (cal/cm2-s-k)
100.   !heat transfer coefficient at south face (cal/cm2-s-k)
0.0    !heat transfer coefficient at top face (cal/cm2-s-K)
298.0  !temperature at west face (K)
298.0  !temperature at east face (K)
298.0  !temperature at north face (K)
298.0  !temperature at south face (K)
298.0  !temperature at bottom face (K)
298.0  !preheat temperature (K)
298.0  !ambient temperature (K)
!-----Grids-----
4      !number of x-zones
5.0 3.0 5.0 16.0 !length of each x-zone (cm)
12 70 12 15 !number of control volumes in each x-zone
-1.2 1.0 1.2 1.3 !exponents to locate control volume interfaces
3      !number of y-zones
8.5 3.0 8.5 !length of each y-zone (cm)
20 70 20 !number of control volumes in each y-zone
-1.3 1.0 1.3 !exponents to locate control volume interfaces
1      !number of z-zones
0.72   !length of each z-zone (cm)
25     !number of control volumes in each z-zone
1.0    !exponents to locate control volume interfaces
```

output.txt

```
Friction Stir Welding
  Advancing side : Ti-6Al-4V
  Tool           : Tungsten
  Retreating side: Ti-6Al-4V
-----
Process parameters
-----
Starting x-location of the power source      6.5000E+00
Starting y-location of the power source      1.0000E+01
Welding velocity (cm/sec)                   1.6000E-01
RPM (rad/s)                                 2.7500E+02
Contact pressure due to axial load (MPa)     6.0000E+01
-----
advancing side material properties
-----
Density (gm/cm3)                            4.4200E+00
Solidus temperature (K)                     1.9330E+03
Specific heat (cal/gm-K)                    1.3007E-01
Thermal cond. (cal/cm-sec-K)                1.5724E-02
Emissivity of the material                   0.0000E+00
-----
tool material properties
-----
Density (gm/cm3)                            1.9400E+01
Solidus temperature (K)                     3.6830E+03
Specific heat (cal/gm-K)                    3.3110E-02
Thermal cond. (cal/cm-sec-K)                3.6000E-01
Emissivity of the material                   0.0000E+00
-----
retreating side material properties
-----
Density (gm/cm3)                            4.4200E+00
Solidus temperature (K)                     1.9330E+03
Specific heat (cal/gm-K)                    1.3007E-01
Thermal cond. (cal/cm-sec-K)                1.5724E-02
Emissivity of the material                   0.0000E+00
-----
Numerical scheme parameters
-----
Maximum number of iterations                 2000
Time step                                   1.0000E+20
Maximum time                                 0.0000E+00
Underrelaxation for u-velocity              8.0000E-01
Underrelaxation for v-velocity              8.0000E-01
Underrelaxation for w-velocity              8.0000E-01
Underrelaxation for pressure                8.0000E-01
Underrelaxation for temperature             8.0000E-01
-----
Boundary conditions
-----
Heat transfer coeff at west face (cal/cm2-s-K) 1.0000E+02
Heat transfer coeff at east face (cal/cm2-s-K) 1.0000E+02
Heat transfer coeff at north face (cal/cm2-s-K) 1.0000E+02
Heat transfer coeff at south face (cal/cm2-s-K) 1.0000E+02
Heat transfer coeff at bottom face (cal/cm2-s-K) 1.0000E-02
Heat transfer coeff at top face (cal/cm2-s-K) 0.0000E+00
Temperature at west face (K)                 2.9800E+02
Temperature at east face (K)                 2.9800E+02
Temperature at north face (K)                2.9800E+02
Temperature at south face (K)                2.9800E+02
Temperature at bottom face (K)               2.9800E+02
Preheat temperature (K)                     2.9800E+02
Ambient temperature (K)                     2.9800E+02
Fraction of heat entering work-piece         4.5000E-01
Parameter for slip                           2.8420E+00
Parameter for friction coefficient            7.0000E-01
Parameter for viscous dissipation            1.0000E-01
-----
Geometrical parameters
-----
x direction
  number of zones                            4
  zone( 1) length                            0.5000E+01
  zone( 1) number of control volumes (CV)     12
  zone( 1) exponent to locate CV interfaces   -.1200E+01
  zone( 2) length                            0.3000E+01
```

```

zone( 2) number of control volumes (CV)          70
zone( 2) exponent to locate CV interfaces        0.1000E+01
zone( 3) length                                  0.5000E+01
zone( 3) number of control volumes (CV)         12
zone( 3) exponent to locate CV interfaces        0.1200E+01
zone( 4) length                                  0.1600E+02
zone( 4) number of control volumes (CV)         15
zone( 4) exponent to locate CV interfaces        0.1300E+01
y direction
number of zones                                  3
zone( 1) length                                  0.8500E+01
zone( 1) number of control volumes (CV)         20
zone( 1) exponent to locate CV interfaces        -.1300E+01
zone( 2) length                                  0.3000E+01
zone( 2) number of control volumes (CV)         70
zone( 2) exponent to locate CV interfaces        0.1000E+01
zone( 3) length                                  0.8500E+01
zone( 3) number of control volumes (CV)         20
zone( 3) exponent to locate CV interfaces        0.1300E+01
z direction
number of zones                                  1
zone( 1) length                                  0.7200E+00
zone( 1) number of control volumes (CV)         26
zone( 1) exponent to locate CV interfaces        0.1000E+01

Number of grid points in x-direction (length)    111
Number of grid points in y-direction (width)     112
Number of grid points in z-direction (depth)     28
length of the specimen (cm)                     2.9000E+01
Width of the specimen (cm)                      2.0000E+01
Height of the specimen (cm)                    7.2000E-01

```

x-grid

i=	1	2	3	4	5	6	7
x=	0.000E+00	2.479E-01	7.391E-01	1.221E+00	1.693E+00	2.154E+00	2.603E+00
xu=	0.000E+00	0.000E+00	4.957E-01	9.825E-01	1.460E+00	1.926E+00	2.381E+00
i=	8	9	10	11	12	13	14
x=	3.037E+00	3.457E+00	3.857E+00	4.235E+00	4.582E+00	4.873E+00	5.021E+00
xu=	2.824E+00	3.251E+00	3.662E+00	4.053E+00	4.418E+00	4.747E+00	5.000E+00
i=	15	16	17	18	19	20	21
x=	5.064E+00	5.107E+00	5.150E+00	5.193E+00	5.236E+00	5.279E+00	5.321E+00
xu=	5.043E+00	5.086E+00	5.129E+00	5.171E+00	5.214E+00	5.257E+00	5.300E+00
i=	22	23	24	25	26	27	28
x=	5.364E+00	5.407E+00	5.450E+00	5.493E+00	5.536E+00	5.579E+00	5.621E+00
xu=	5.343E+00	5.386E+00	5.429E+00	5.471E+00	5.514E+00	5.557E+00	5.600E+00
i=	29	30	31	32	33	34	35
x=	5.664E+00	5.707E+00	5.750E+00	5.793E+00	5.836E+00	5.879E+00	5.921E+00
xu=	5.643E+00	5.686E+00	5.729E+00	5.771E+00	5.814E+00	5.857E+00	5.900E+00
i=	36	37	38	39	40	41	42
x=	5.964E+00	6.007E+00	6.050E+00	6.093E+00	6.136E+00	6.179E+00	6.221E+00
xu=	5.943E+00	5.986E+00	6.029E+00	6.071E+00	6.114E+00	6.157E+00	6.200E+00
i=	43	44	45	46	47	48	49
x=	6.264E+00	6.307E+00	6.350E+00	6.393E+00	6.436E+00	6.479E+00	6.521E+00
xu=	6.243E+00	6.286E+00	6.329E+00	6.371E+00	6.414E+00	6.457E+00	6.500E+00
i=	50	51	52	53	54	55	56
x=	6.564E+00	6.607E+00	6.650E+00	6.693E+00	6.736E+00	6.779E+00	6.821E+00
xu=	6.543E+00	6.586E+00	6.629E+00	6.671E+00	6.714E+00	6.757E+00	6.800E+00
i=	57	58	59	60	61	62	63
x=	6.864E+00	6.907E+00	6.950E+00	6.993E+00	7.036E+00	7.079E+00	7.121E+00
xu=	6.843E+00	6.886E+00	6.929E+00	6.971E+00	7.014E+00	7.057E+00	7.100E+00
i=	64	65	66	67	68	69	70
x=	7.164E+00	7.207E+00	7.250E+00	7.293E+00	7.336E+00	7.379E+00	7.421E+00
xu=	7.143E+00	7.186E+00	7.229E+00	7.271E+00	7.314E+00	7.357E+00	7.400E+00
i=	71	72	73	74	75	76	77
x=	7.464E+00	7.507E+00	7.550E+00	7.593E+00	7.636E+00	7.679E+00	7.721E+00
xu=	7.443E+00	7.486E+00	7.529E+00	7.571E+00	7.614E+00	7.657E+00	7.700E+00
i=	78	79	80	81	82	83	84

x=	7.764E+00	7.807E+00	7.850E+00	7.893E+00	7.936E+00	7.979E+00	8.127E+00
xu=	7.743E+00	7.786E+00	7.829E+00	7.871E+00	7.914E+00	7.957E+00	8.000E+00
i=	85	86	87	88	89	90	91
x=	8.418E+00	8.765E+00	9.143E+00	9.543E+00	9.963E+00	1.040E+01	1.085E+01
xu=	8.253E+00	8.582E+00	8.947E+00	9.338E+00	9.749E+00	1.018E+01	1.062E+01
i=	92	93	94	95	96	97	98
x=	1.131E+01	1.178E+01	1.226E+01	1.275E+01	1.324E+01	1.382E+01	1.457E+01
xu=	1.107E+01	1.154E+01	1.202E+01	1.250E+01	1.300E+01	1.347E+01	1.417E+01
i=	99	100	101	102	103	104	105
x=	1.542E+01	1.635E+01	1.735E+01	1.840E+01	1.950E+01	2.065E+01	2.184E+01
xu=	1.497E+01	1.587E+01	1.684E+01	1.786E+01	1.894E+01	2.007E+01	2.124E+01
i=	106	107	108	109	110	111	
x=	2.307E+01	2.433E+01	2.563E+01	2.696E+01	2.831E+01	2.900E+01	
xu=	2.244E+01	2.369E+01	2.497E+01	2.628E+01	2.763E+01	2.900E+01	

y-grid

j=	1	2	3	4	5	6	7
y=	0.000E+00	2.742E-01	8.182E-01	1.353E+00	1.880E+00	2.396E+00	2.903E+00
yv=	0.000E+00	0.000E+00	5.483E-01	1.088E+00	1.619E+00	2.140E+00	2.652E+00
j=	8	9	10	11	12	13	14
y=	3.399E+00	3.885E+00	4.359E+00	4.820E+00	5.269E+00	5.703E+00	6.123E+00
yv=	3.154E+00	3.645E+00	4.125E+00	4.593E+00	5.048E+00	5.490E+00	5.917E+00
j=	15	16	17	18	19	20	21
y=	6.526E+00	6.911E+00	7.275E+00	7.615E+00	7.926E+00	8.200E+00	8.413E+00
yv=	6.329E+00	6.723E+00	7.098E+00	7.451E+00	7.778E+00	8.074E+00	8.327E+00
j=	22	23	24	25	26	27	28
y=	8.521E+00	8.564E+00	8.607E+00	8.650E+00	8.693E+00	8.736E+00	8.779E+00
yv=	8.500E+00	8.543E+00	8.586E+00	8.629E+00	8.671E+00	8.714E+00	8.757E+00
j=	29	30	31	32	33	34	35
y=	8.821E+00	8.864E+00	8.907E+00	8.950E+00	8.993E+00	9.036E+00	9.079E+00
yv=	8.800E+00	8.843E+00	8.886E+00	8.929E+00	8.971E+00	9.014E+00	9.057E+00
j=	36	37	38	39	40	41	42
y=	9.121E+00	9.164E+00	9.207E+00	9.250E+00	9.293E+00	9.336E+00	9.379E+00
yv=	9.100E+00	9.143E+00	9.186E+00	9.229E+00	9.271E+00	9.314E+00	9.357E+00
j=	43	44	45	46	47	48	49
y=	9.421E+00	9.464E+00	9.507E+00	9.550E+00	9.593E+00	9.636E+00	9.679E+00
yv=	9.400E+00	9.443E+00	9.486E+00	9.529E+00	9.571E+00	9.614E+00	9.657E+00
j=	50	51	52	53	54	55	56
y=	9.721E+00	9.764E+00	9.807E+00	9.850E+00	9.893E+00	9.936E+00	9.979E+00
yv=	9.700E+00	9.743E+00	9.786E+00	9.829E+00	9.871E+00	9.914E+00	9.957E+00
j=	57	58	59	60	61	62	63
y=	1.002E+01	1.006E+01	1.011E+01	1.015E+01	1.019E+01	1.024E+01	1.028E+01
yv=	1.000E+01	1.004E+01	1.009E+01	1.013E+01	1.017E+01	1.021E+01	1.026E+01
j=	64	65	66	67	68	69	70
y=	1.032E+01	1.036E+01	1.041E+01	1.045E+01	1.049E+01	1.054E+01	1.058E+01
yv=	1.030E+01	1.034E+01	1.039E+01	1.043E+01	1.047E+01	1.051E+01	1.056E+01
j=	71	72	73	74	75	76	77
y=	1.062E+01	1.066E+01	1.071E+01	1.075E+01	1.079E+01	1.084E+01	1.088E+01
yv=	1.060E+01	1.064E+01	1.069E+01	1.073E+01	1.077E+01	1.081E+01	1.086E+01
j=	78	79	80	81	82	83	84
y=	1.092E+01	1.096E+01	1.101E+01	1.105E+01	1.109E+01	1.114E+01	1.118E+01
yv=	1.090E+01	1.094E+01	1.099E+01	1.103E+01	1.107E+01	1.111E+01	1.116E+01
j=	85	86	87	88	89	90	91
y=	1.122E+01	1.126E+01	1.131E+01	1.135E+01	1.139E+01	1.144E+01	1.148E+01
yv=	1.120E+01	1.124E+01	1.129E+01	1.133E+01	1.137E+01	1.141E+01	1.146E+01
j=	92	93	94	95	96	97	98
y=	1.159E+01	1.180E+01	1.207E+01	1.239E+01	1.273E+01	1.309E+01	1.347E+01
yv=	1.150E+01	1.167E+01	1.193E+01	1.222E+01	1.255E+01	1.290E+01	1.328E+01
j=	99	100	101	102	103	104	105
y=	1.388E+01	1.430E+01	1.473E+01	1.518E+01	1.564E+01	1.612E+01	1.660E+01

```

yv= 1.367E+01 1.408E+01 1.451E+01 1.495E+01 1.541E+01 1.588E+01 1.636E+01
j= 106 107 108 109 110 111 112
y= 1.710E+01 1.760E+01 1.812E+01 1.865E+01 1.918E+01 1.973E+01 2.000E+01
yv= 1.685E+01 1.735E+01 1.786E+01 1.838E+01 1.891E+01 1.945E+01 2.000E+01

```

z-grid

```

k= 1 2 3 4 5 6 7
z= 0.000E+00 1.385E-02 4.154E-02 6.923E-02 9.692E-02 1.246E-01 1.523E-01
zw= 0.000E+00 0.000E+00 2.769E-02 5.538E-02 8.308E-02 1.108E-01 1.385E-01

k= 8 9 10 11 12 13 14
z= 1.800E-01 2.077E-01 2.354E-01 2.631E-01 2.908E-01 3.185E-01 3.462E-01
zw= 1.662E-01 1.938E-01 2.215E-01 2.492E-01 2.769E-01 3.046E-01 3.323E-01

k= 15 16 17 18 19 20 21
z= 3.738E-01 4.015E-01 4.292E-01 4.569E-01 4.846E-01 5.123E-01 5.400E-01
zw= 3.600E-01 3.877E-01 4.154E-01 4.431E-01 4.708E-01 4.985E-01 5.262E-01

k= 22 23 24 25 26 27 28
z= 5.677E-01 5.954E-01 6.231E-01 6.508E-01 6.785E-01 7.062E-01 7.200E-01
zw= 5.538E-01 5.815E-01 6.092E-01 6.369E-01 6.646E-01 6.923E-01 7.200E-01

```

Date: 2008- 1- 8 time: 10 :39 :10

iter	time/iter	res_enth	res_mass	res_u	res_v	res_w			
100	0.700	4.64E-04	6.10E-05	2.09E-03	2.26E-03	1.43E-03			
Tmax	Tmax_tool	umax	vmax	wmax					
1233.8	1071.6	4.6	5.1	0.5					
vis_dis	shoulder	pin_ver	pin_hor	torque					
338.5	170.9	267.8	35.6	102.9					
north	south	top	toploss	bottom	east	west	hout	hin	ratio
-2.4	-2.4	105.9	0.0	-102.0	-394.7	394.7	-106.9	812.9	0.13

iter	time/iter	res_enth	res_mass	res_u	res_v	res_w			
500	0.636	8.91E-05	2.50E-06	5.81E-04	5.91E-04	6.90E-04			
Tmax	Tmax_tool	umax	vmax	wmax					
1476.8	1367.3	4.6	5.1	0.5					
vis_dis	shoulder	pin_ver	pin_hor	torque					
291.1	148.9	10.1	10.9	51.0					
north	south	top	toploss	bottom	east	west	hout	hin	ratio
-2.5	-2.5	129.2	0.0	-274.4	-394.7	394.7	-279.3	461.0	0.61

iter	time/iter	res_enth	res_mass	res_u	res_v	res_w			
1000	0.603	2.63E-05	7.74E-07	5.70E-04	5.80E-04	6.59E-04			
Tmax	Tmax_tool	umax	vmax	wmax					
1545.1	1448.6	4.6	5.1	0.5					
vis_dis	shoulder	pin_ver	pin_hor	torque					
276.8	148.6	2.6	6.7	49.1					
north	south	top	toploss	bottom	east	west	hout	hin	ratio
-1.4	-1.4	140.6	0.0	-359.3	-394.7	394.7	-362.0	434.7	0.83

iter	time/iter	res_enth	res_mass	res_u	res_v	res_w			
1500	0.589	1.00E-05	2.99E-07	5.61E-04	5.71E-04	6.49E-04			
Tmax	Tmax_tool	umax	vmax	wmax					
1568.2	1476.9	4.6	5.1	0.4					
vis_dis	shoulder	pin_ver	pin_hor	torque					
272.0	148.5	2.2	6.4	49.0					
north	south	top	toploss	bottom	east	west	hout	hin	ratio
-0.7	-0.7	145.0	0.0	-396.3	-394.7	394.7	-397.7	429.1	0.93

iter	time/iter	res_enth	res_mass	res_u	res_v	res_w			
2000	0.577	4.10E-06	1.25E-07	5.58E-04	5.67E-04	6.45E-04			
Tmax	Tmax_tool	umax	vmax	wmax					
1577.1	1488.1	4.6	5.1	0.4					
vis_dis	shoulder	pin_ver	pin_hor	torque					
270.2	148.5	2.1	6.4	49.0					
north	south	top	toploss	bottom	east	west	hout	hin	ratio
-0.4	-0.4	146.9	0.0	-413.4	-394.7	394.7	-414.2	427.2	0.97

Some important calculated parameters at the end of heating cycle

Peak temperature (K) 1.5771E+03

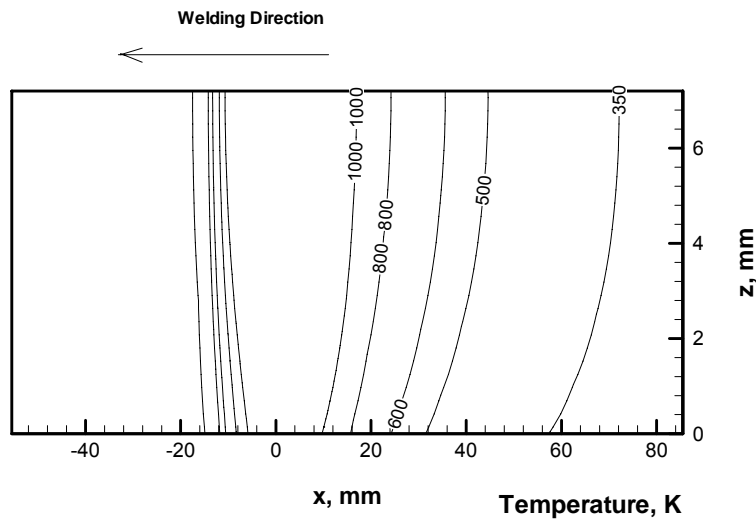
Maximum u-velocity	(cm/s)	4.6328E+00
Maximum v-velocity	(cm/s)	5.0712E+00
Maximum w-velocity	(cm/s)	4.4864E-01
Deformational heat in workpiece	(cal/s)	0.2702E+03 (63.2 %)
Heat at tool shoulder	(cal/s)	0.1485E+03 (34.8 %)
Heat at tool pin's vertical surface	(cal/s)	0.2089E+01 (0.5 %)
Heat at tool pin's bottom surface	(cal/s)	0.6438E+01 (1.5 %)
Rate of heat input	(cal/s)	4.2720E+02
Rate of heat output	(cal/s)	-4.1416E+02
Ratio of heat input to heat output		9.6946E-01

Date: 2008- 1- 8 time: 10:58:30

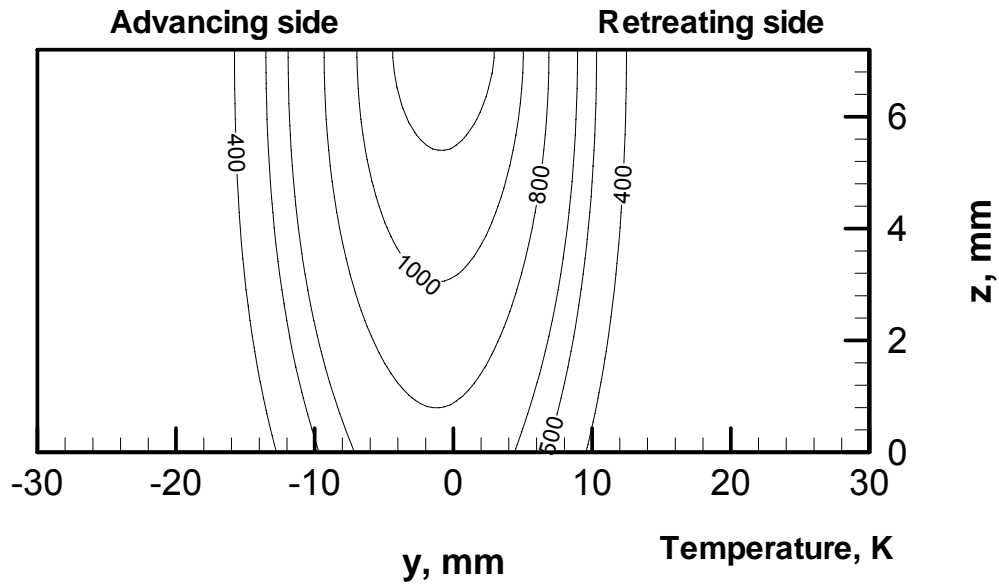
Total time used: 0 hr 19 m 20 s

Plots

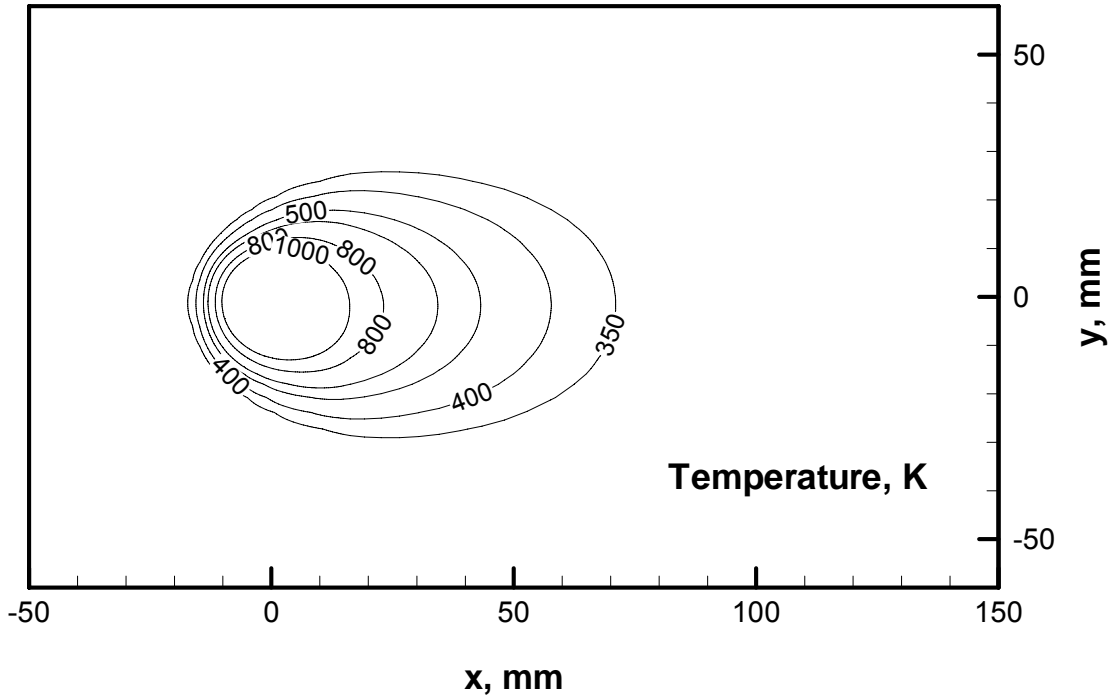
a



b

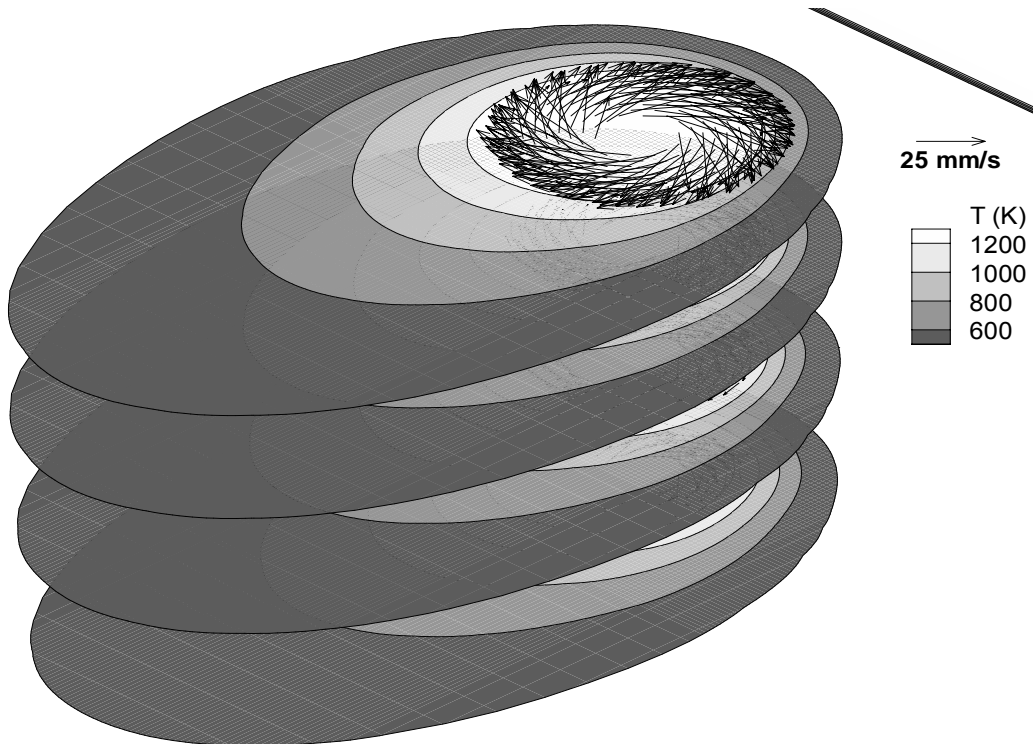


c



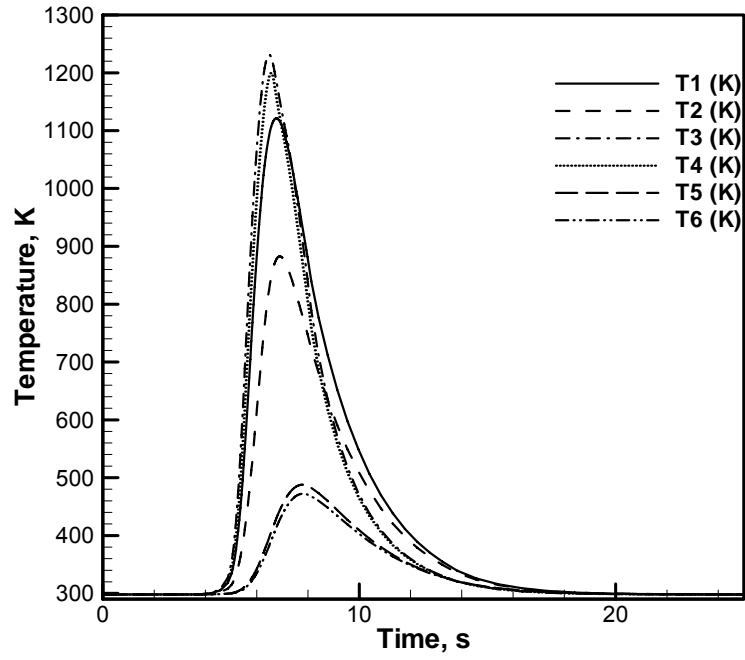
Computed temperature profiles(K) in (a) $y=0$ (xz plane), (b) $x=0$ (yz plane) and (c) $z=7.2$ mm (xy) i.e. the top surface of the workpiece.

d



Plot of temperature contours (K) and velocity vectors at $z=2.02$, 3.82 , 5.62 , and 7.2 mm planes.

e



Thermal cycles at the 6 different locations indicated in input.txt

8.3 Welding of 304L Stainless steel using tungsten tool

input.txt

```
!-----Material selection-----
!1=AA6061,2=1018Steel,3=304L SS,6=Tungsten,8=Ti-6Al-4V
3          !Workpiece material on advancing side
6          !tool material
3          !Workpiece material on retreating side
!-----Tool geometry-----
0.95      !shoulder radius(cm)
0.3       !pin radius at shoulder (cm)
0.25      !pin radius at the tip (cm)
0.64      !pin length (cm)
0.1       !thread pitch (cm)
!-----Welding parameters-----
6.5       !x-location of the tool
10.0      !y-location of the tool
0.042     !welding velocity (cm/sec)
450.0     !rotational velocity (rpm)
65.9      !axial pressure (MPa)
2.0       !Tilt angle (degrees)
!-----Numerical scheme parameters-----
14000     !maximum number of iterations
0.8       !underrelaxation for u-velocity
0.8       !underrelaxation for v-velocity
0.8       !underrelaxation for w-velocity
0.8       !underrelaxation for pressure
0.7       !underrelaxation for temperature
0         !index for saving file (1 = save)
0         !index for loading file (1 = load)
6         !Number of monitoring locations
8.5  8.5  8.5  11.5 11.5 11.5  !y coordinates of monitoring locations
0.24 0.48 0.70 0.24 0.48 0.70  !z coordinates of monitoring locations
!-----Boundary conditions-----
100.      !heat transfer coefficient at west face (cal/cm2-s-K)
100.      !heat transfer coefficient at east face (cal/cm2-s-K)
100.      !heat transfer coefficient at north face (cal/cm2-s-k)
100.      !heat transfer coefficient at south face (cal/cm2-s-k)
0.0       !heat transfer coefficient at top face (cal/cm2-s-K)
298.0     !temperature at west face (K)
298.0     !temperature at east face (K)
298.0     !temperature at north face (K)
298.0     !temperature at south face (K)
298.0     !temperature at bottom face (K)
298.0     !preheat temperature (K)
298.0     !ambient temperature (K)
0.45      !fraction of energy entering the work-piece
!-----Grids-----
6         !number of x-zones
5.0 1.0 1.0 1.0 5.0 16.0  !length of each x-zone (cm)
12  20  30  20 12  15  !number of control volumes in each x-zone
-1.2 -1.1 1.0 1.1 1.2  1.3  !exponents to locate control volume interfaces
3         !number of y-zones
8.5 3.0  8.5  !length of each y-zone (cm)
15  65  15  !number of control volumes in each y-zone
-1.3 1.0 1.3  !exponents to locate control volume interfaces
1         !number of z-zones
0.72     !length of each z-zone (cm)
15       !number of control volumes in each z-zone
1.0      !exponents to locate control volume interfaces
```

output.txt

```
Friction Stir Welding
  Advancing side : 304L stainless steel
  Tool           : Tungsten
```

Retreating side: 304L stainless steel

Process parameters

Starting x-location of the power source 6.5000E+00
Starting y-location of the power source 1.0000E+01
Welding velocity (cm/sec) 4.2000E-02
RPM (rad/s) 4.5000E+02
Contact pressure due to axial load (MPa) 6.5900E+01

advancing side material properties

Density (gm/cm3) 7.8000E+00
Solidus temperature (K) 1.6970E+03
Specific heat (cal/gm-K) 1.1056E-01
Thermal cond. (cal/cm-sec-K) 3.5777E-02
Emissivity of the material 0.0000E+00

tool material properties

Density (gm/cm3) 1.9400E+01
Solidus temperature (K) 3.6830E+03
Specific heat (cal/gm-K) 3.3110E-02
Thermal cond. (cal/cm-sec-K) 3.6000E-01
Emissivity of the material 0.0000E+00

retreating side material properties

Density (gm/cm3) 7.8000E+00
Solidus temperature (K) 1.6970E+03
Specific heat (cal/gm-K) 1.1056E-01
Thermal cond. (cal/cm-sec-K) 3.5777E-02
Emissivity of the material 0.0000E+00

Numerical scheme parameters

Maximum number of iterations *****
Time step 1.0000E+20
Maximum time 0.0000E+00
Underrelaxation for u-velocity 8.0000E-01
Underrelaxation for v-velocity 8.0000E-01
Underrelaxation for w-velocity 8.0000E-01
Underrelaxation for pressure 8.0000E-01
Underrelaxation for temperature 7.0000E-01

Boundary conditions

Heat transfer coeff at west face (cal/cm2-s-K) 1.0000E+02
Heat transfer coeff at east face (cal/cm2-s-K) 1.0000E+02
Heat transfer coeff at north face (cal/cm2-s-K) 1.0000E+02
Heat transfer coeff at south face (cal/cm2-s-K) 1.0000E+02
Heat transfer coeff at bottom face (cal/cm2-s-K) 1.2000E-02
Heat transfer coeff at top face (cal/cm2-s-K) 0.0000E+00
Temperature at west face (K) 2.9800E+02
Temperature at east face (K) 2.9800E+02
Temperature at north face (K) 2.9800E+02
Temperature at south face (K) 2.9800E+02
Temperature at bottom face (K) 2.9800E+02
Preheat temperature (K) 2.9800E+02
Ambient temperature (K) 2.9800E+02
Fraction of heat entering work-piece 4.5000E-01
Parameter for slip 4.0000E-01
Parameter for friction coefficient 4.3000E-01
Parameter for viscous dissipation 1.0000E-02

Geometrical parameters

x direction
number of zones

6

```

zone( 1) length                0.5000E+01
zone( 1) number of control volumes (CV)      12
zone( 1) exponent to locate CV interfaces    -.1200E+01
zone( 2) length                0.1000E+01
zone( 2) number of control volumes (CV)      20
zone( 2) exponent to locate CV interfaces    -.1100E+01
zone( 3) length                0.1000E+01
zone( 3) number of control volumes (CV)      30
zone( 3) exponent to locate CV interfaces    0.1000E+01
zone( 4) length                0.1000E+01
zone( 4) number of control volumes (CV)      20
zone( 4) exponent to locate CV interfaces    0.1100E+01
zone( 5) length                0.5000E+01
zone( 5) number of control volumes (CV)      12
zone( 5) exponent to locate CV interfaces    0.1200E+01
zone( 6) length                0.1600E+02
zone( 6) number of control volumes (CV)      15
zone( 6) exponent to locate CV interfaces    0.1300E+01
y direction
number of zones                 3
zone( 1) length                0.8500E+01
zone( 1) number of control volumes (CV)      15
zone( 1) exponent to locate CV interfaces    -.1300E+01
zone( 2) length                0.3000E+01
zone( 2) number of control volumes (CV)      65
zone( 2) exponent to locate CV interfaces    0.1000E+01
zone( 3) length                0.8500E+01
zone( 3) number of control volumes (CV)      15
zone( 3) exponent to locate CV interfaces    0.1300E+01
z direction
number of zones                 1
zone( 1) length                0.7200E+00
zone( 1) number of control volumes (CV)      16
zone( 1) exponent to locate CV interfaces    0.1000E+01

Number of grid points in x-direction (length)  111
Number of grid points in y-direction (width)   97
Number of grid points in z-direction (depth)   18
length of the specimen (cm)                   2.9000E+01
Width of the specimen (cm)                    2.0000E+01
Height of the specimen (cm)                   7.2000E-01

```

x-grid

```

i=      1      2      3      4      5      6      7
x=  0.000E+00  2.479E-01  7.391E-01  1.221E+00  1.693E+00  2.154E+00  2.603E+00
xu=  0.000E+00  0.000E+00  4.957E-01  9.825E-01  1.460E+00  1.926E+00  2.381E+00

i=    106    107    108    109    110    111
x=  2.307E+01  2.433E+01  2.563E+01  2.696E+01  2.831E+01  2.900E+01
xu=  2.244E+01  2.369E+01  2.497E+01  2.628E+01  2.763E+01  2.900E+01

```

y-grid

```

j=      1      2      3      4      5      6      7
y=  0.000E+00  3.646E-01  1.086E+00  1.792E+00  2.480E+00  3.151E+00  3.803E+00
yv=  0.000E+00  0.000E+00  7.292E-01  1.443E+00  2.140E+00  2.820E+00  3.482E+00

j=     92     93     94     95     96     97
y=  1.685E+01  1.752E+01  1.821E+01  1.891E+01  1.964E+01  2.000E+01
yv=  1.652E+01  1.718E+01  1.786E+01  1.856E+01  1.927E+01  2.000E+01

```

z-grid

```

k=      1      2      3      4      5      6      7
z=  0.000E+00  2.250E-02  6.750E-02  1.125E-01  1.575E-01  2.025E-01  2.475E-01
zw=  0.000E+00  0.000E+00  4.500E-02  9.000E-02  1.350E-01  1.800E-01  2.250E-01

k=      8      9     10     11     12     13     14

```



```

z= 2.925E-01 3.375E-01 3.825E-01 4.275E-01 4.725E-01 5.175E-01 5.625E-01
zw= 2.700E-01 3.150E-01 3.600E-01 4.050E-01 4.500E-01 4.950E-01 5.400E-01

k= 15 16 17 18
z= 6.075E-01 6.525E-01 6.975E-01 7.200E-01
zw= 5.850E-01 6.300E-01 6.750E-01 7.200E-01

```

Date: 2007-12-18 time: 17 :54 :17

```

iter    time/iter    res_enth    res_mass    res_u    res_v    res_w
100     0.490         5.04E-04    5.39E-02    2.74E-02  5.52E-02  7.65E-01
Tmax    Tmax_tool      umax        vmax        wmax
996.1   771.7         18.1        18.1        1.3
vis_dis  shoulder      pin_ver     pin_hor     torque
59.5    372.0         378.7       33.8        164.7
north   south   top    toploss  bottom  east   west   hout   hin   ratio
-0.7    -0.7   341.0  0.0     -45.6   -155.4 155.4  -47.0  844.0 0.06

```

```

iter    time/iter    res_enth    res_mass    res_u    res_v    res_w
1000    0.425         5.44E-05    1.41E-01    3.37E-02  8.29E-02  8.90E-01
Tmax    Tmax_tool      umax        vmax        wmax
1139.1  1123.3        19.5        19.4        6.7
vis_dis  shoulder      pin_ver     pin_hor     torque
31.7    159.0         102.6       12.4        56.5
north   south   top    toploss  bottom  east   west   hout   hin   ratio
-0.5    -0.5   156.8  0.0     -235.2 -155.4 155.4  -236.2 305.8 0.77

```

```

iter    time/iter    res_enth    res_mass    res_u    res_v    res_w
2000    0.423         5.86E-05    1.28E-01    3.35E-02  9.68E-02  8.39E-01
Tmax    Tmax_tool      umax        vmax        wmax
1151.4  1136.1        19.6        19.4        4.2
vis_dis  shoulder      pin_ver     pin_hor     torque
31.0    154.5         96.7        11.7        54.3
north   south   top    toploss  bottom  east   west   hout   hin   ratio
0.2     0.2   156.8  0.0     -289.1 -153.5 155.4  -286.8 294.0 0.98

```

```

iter    time/iter    res_enth    res_mass    res_u    res_v    res_w
2045    0.423         4.57E-05    1.30E-01    3.39E-02  9.68E-02  8.87E-01
Tmax    Tmax_tool      umax        vmax        wmax
1151.6  1136.2        19.5        19.4        6.6
vis_dis  shoulder      pin_ver     pin_hor     torque
30.8    154.4         96.7        11.7        54.2
north   south   top    toploss  bottom  east   west   hout   hin   ratio
0.3     0.3   153.9  0.0     -295.9 -152.9 155.4  -292.8 293.6 1.00

```

Some important calculated parameters at the end of heating cycle

```

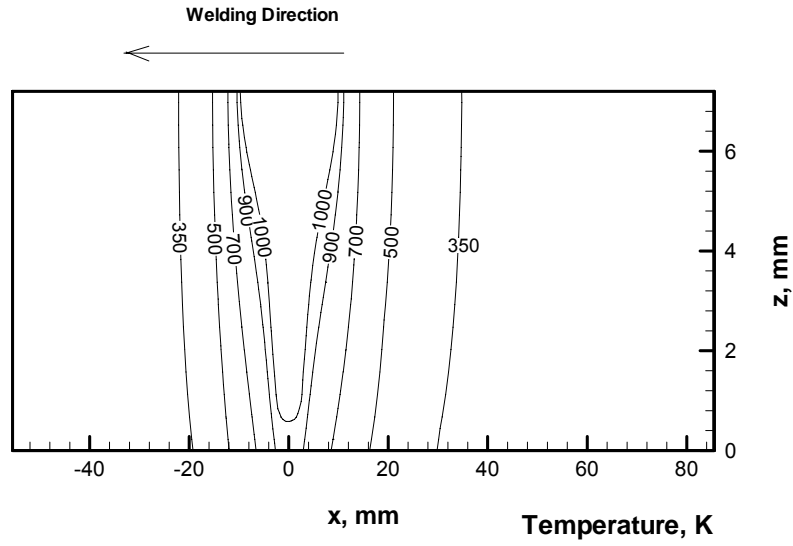
Peak temperature      (K)                1.1516E+03
Maximum u-velocity    (cm/s)            1.9543E+01
Maximum v-velocity    (cm/s)            1.9428E+01
Maximum w-velocity    (cm/s)            6.6459E+00
Deformational heat in workpiece (cal/s) 0.3076E+02 (10.5 %)
Heat at tool shoulder (cal/s) 0.1544E+03 (52.6 %)
Heat at tool pin's vertical surface (cal/s) 0.9672E+02 (32.9 %)
Heat at tool pin's bottom surface (cal/s) 0.1170E+02 ( 4.0 %)
Rate of heat input    (cal/s) 2.9361E+02
Rate of heat output    (cal/s) -2.9282E+02
Ratio of heat input to heat output 9.9731E-01

```

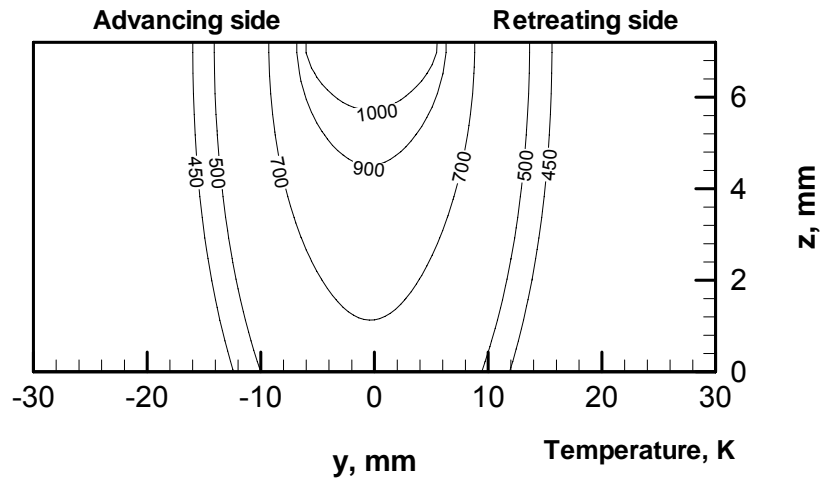
Date: 2007-12-18 time: 18: 8:52

Total time used: 0 hr 14 m 35 s

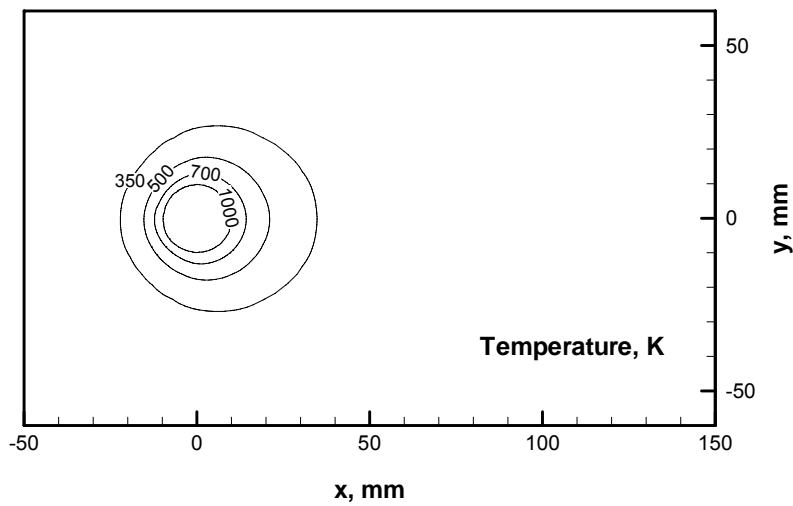
a



b

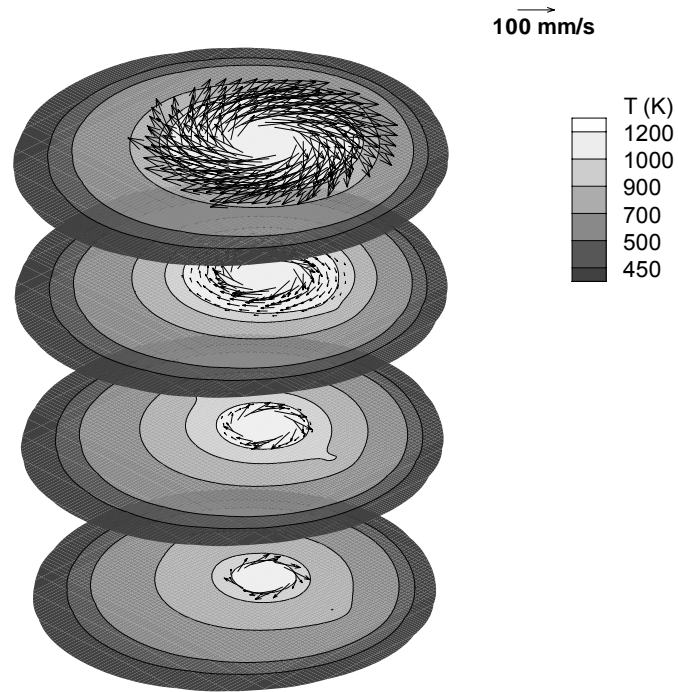


c



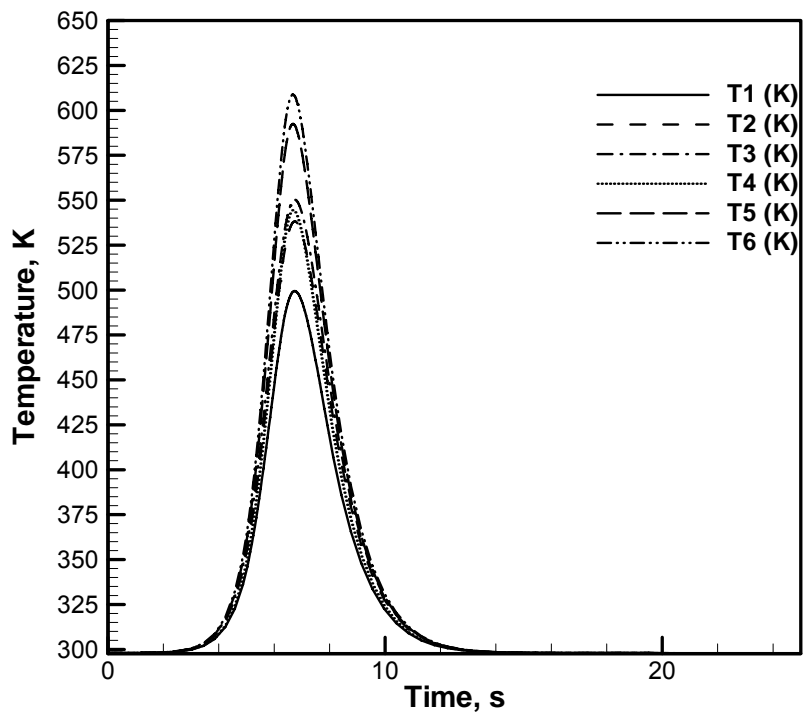
Computed temperature profiles(K) in (a) $y=0$ (xz plane), (b) $x=0$ (yz plane) and (c) $z=7.2$ mm (xy) i.e. the top surface of the workpiece.

d



Plot of temperature contours (K) and velocity vectors at $z=2.02, 3.82, 5.62,$ and 7.2mm planes.

e



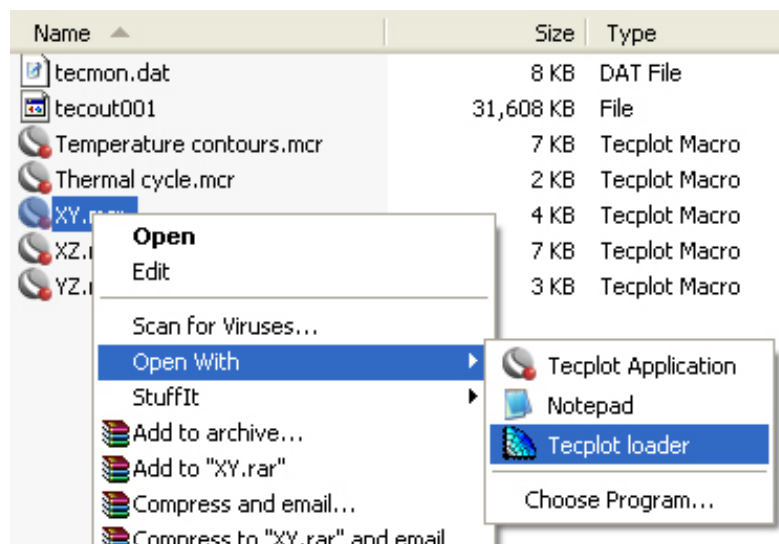
Thermal cycles at the 6 different locations indicated in input.txt

9. Plotting results using Tecplot®

The results generated from the code can be plotted using a commercially available software Tecplot®. Various types of plots can be generated using Tecplot® to analyze the results, some of those are shown in the test cases given above. Tecplot® also gives an option to automate the plot generation process. Macros can be designed to generate any specific kind of plots. There are five macro (.mcr) files provided to generate five types of plots which are shown in the test cases in section 8.

Steps to use the macro files:

1. Put the all the files (all .mcr files, tecout001 and tecmon.dat) in one folder.
2. Open XY.mcr file with “Tecplot loader” as shown in the screenshot below
3. Once the macro is loaded, a new layout file (XY.lay) would be generated in the same directory. Now exit Tecplot®.
4. Repeat step 2-3 for rest of the macro files (YZ.mcr, XZ.mcr, Thermal Cycle.mcr and Temperature contours.mcr)
5. In the end there would be 6 new files would be generated in the folder (5 layout file and one dataset for temperature contours)
6. These layout files can be used for further analysis of the results.



10. Concluding remarks

The results obtained are sensitive to the values of input variables μ_0 , del_0 , β and cf . These parameters determine the boundary conditions for heat and momentum transfer. These parameters could be optimized so as to achieve thermal cycles similar to those obtained from thermocouple measurements and torque values measured using a dynamometer for samples being joined by FSW.

Physical considerations guide that ' cf ' and ' fr_{heat} ' should always be less than 1. A small value of ' del_0 ' indicates less sticking at the tool workpiece interface. ' del_0 ' can be higher than 1, with higher values indicating greater sticking. The parameter ' β ' should be small enough so that, heat generating due to plastic work within the workpiece is not higher than the heat generated at the tool shoulder, as several experiments have indicated that heat generation is

primarily below the shoulder for commonly welded alloys in practical welding conditions. The heat transfer coefficient at the bottom plate is enhanced to account for the backing plate and a small value of this parameter will result in insufficient heat loss from the workpiece, resulting in non-convergence.

The under-relaxation factor can also be tweaked to achieve better convergence. In fact, it could be greater than 1 (over-relaxed) in certain cases.

The grids containing the tool pin should be uniformly fine; else it could lead to errors in integration of the heat generated at the tool pin's cylindrical surface. Also, the workpiece should be big enough, so that edge effect is not felt by the temperature contours.

Users might face problems of non-convergence or NaN (not a number) in the output in some cases. It could be due to incorrect specification of input parameters or as is true for all large and complex codes, there might be undetected bugs. If the problem is not resolved using any of the suggestions given above, the user may like to contact the code-writers for help. Their email addresses are listed below:

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Amit Arora
Dr. T. DebRoy

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amitarora at psu dot edu
debroy at psu dot edu

REFERENCES

The following papers contain results obtained using the FSW code and their discussion. They can be accessed from <http://www.matse.psu.edu/modeling/>.

1) R. Nandan, G. G. Roy and T. DebRoy, "Numerical Simulation of Three-Dimensional Heat Transfer and Plastic Flow During Friction Stir Welding": *Metal. Mater. Trans. A*, 2006, vol. 37(4) pp. 1247-1259.

2) R. Nandan, G. G. Roy, T. J. Lienert and T. DebRoy, "Numerical modelling of 3D plastic flow and heat transfer during friction stir welding of stainless steel": *Sci. Technol. Weld. Joining*, 2006, vol. 11(5), pp. 526-537.

3) R. Nandan, G. G. Roy, T. J. Lienert and T. DebRoy, "Three Dimensional Heat and Material Flow during Friction Stir Welding of Mild Steel": *Acta Materialia*, 2007, vol. 55(3), pp. 883-895.