

Notes on: “Back of the envelope calculations in friction stir welding - velocities, peak temperature, torque, and hardness”

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Analytical calculations of the material flow fields, peak temperature, torque, and weld hardness for friction stir welding are available in the following paper:

A. Arora, T. DebRoy, H.K.D.H. Bhadeshia, *Back-of-the-envelope calculations in friction stir welding – Velocities, peak temperature, torque, and hardness, Acta Materialia 59(2011) 2020-2028. doi:10.1016/j.actamat.2010.12.001*

In order to facilitate these calculations, links to several downloadable files are provided at the end of this document. Both the source code and the executable file for the calculation of velocities are available for download. For the calculation of peak temperature, torque and weld hardness excel spreadsheets are provided. The following notes give descriptions of the files and the calculation procedures.

Velocity field

Velocity field during friction stir welding (FSW) can be calculated using the accompanying executable file named *velocity.exe* or the Fortran source code file named *velocity.for*. The executable file can be used on any Microsoft Windows® operating system. Upon execution the user will be asked to select the workpiece material and values of a few welding parameters. The source code can be compiled using any standard Fortran compiler. The source code has two subroutines named *grid* and *fgh*.

The subroutine *grid* creates a computational domain with length (x) and width (y) equal to the tool shoulder radius (r_s) and depth (z) equal to the pin length (pl). The length and width of computational domain is divided into 100 equal divisions each and depth is divided into 40 divisions. An inverted cone shaped computational domain defined by $rh(k)$ is considered with radius at the top surface equal to the tool shoulder radius and at the bottom equal to the pin radius (rp).

The subroutine *fg* computes the values of function F, G and H which are then used to compute the velocity components u_t , v_t , w_x in the r , θ and z directions in cylindrical coordinate system. These velocities are then converted to cartesian coordinate system (u_x , v_x and w_x). The velocities are written to a file entitled “output.txt” for plotting using a commercial software such as *Tecplot*®. A detailed description of the equations used can be obtained in the manuscript entitled “*Back of the envelope calculations in friction stir welding - velocities, peak temperature, torque, and hardness*”.

Using the default variable values in the program *velocity.exe* the following stream traces were generated. The stream traces show that the computed velocities display the flow asymmetry characteristic of FSW where most of the material flows through the retreating side. The analytically computed velocity fields can be further used to compute strain and strain rates in FSW.

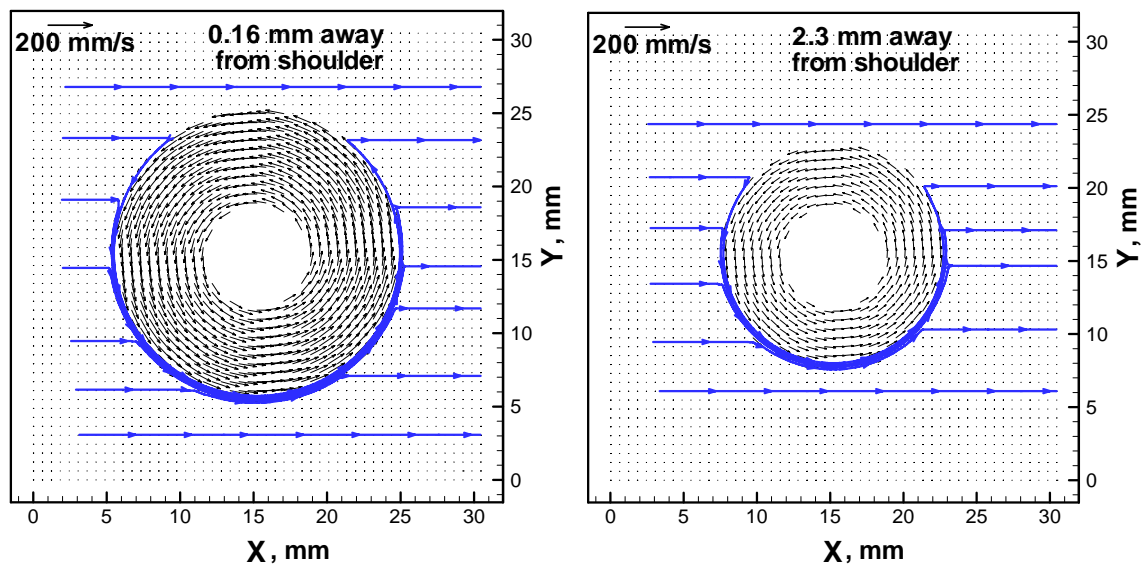


Figure 1 Analytically computed velocity fields and stream traces in FSW at two planes parallel to the tool shoulder workpiece interface. The planes are 0.16 and 2.3 mm away from the tool shoulder.

Peak Temperature, Torque and TMAZ hardness:

Three spreadsheets are provided to calculate the peak temperature, torque and TMAZ hardness in FSW. The spreadsheet entitled “*Peak temperature.xls*” can be used to calculate the peak temperature in friction stir welding. The data used for the derivation of dimensionless correlation are available in the spreadsheet. The variable names and units

are mentioned in the first cell of every column. Further details about the estimation of peak temperature in FSW can be found in the manuscript entitled “*Back of the envelope calculations in friction stir welding - velocities, peak temperature, torque, and hardness*”.

The torque in FSW can be analytically calculated using spreadsheet entitled “*Torque.xls*”. The calculated torque values for AA2524 and Ti-6A-4V are provided in the spreadsheet. The variables used with the units are shown on the top of every column. For the formulas and description of methodology please refer to the manuscript entitled “*Back of the envelope calculations in friction stir welding - velocities, peak temperature, torque, and hardness*”.

The TMAZ hardness in friction stir welding of aluminum alloys can be estimated analytically as a function of the concentration of the alloying elements. The analytically estimated hardness values for various aluminum alloys is shown in spreadsheet named “*Aluminum Hardness.xls*”. The reference numbers given in the spreadsheet correspond to the references in the manuscript entitled “*Back of the envelope calculations in friction stir welding - velocities, peak temperature, torque, and hardness*”.

List of files accompanying this document:

1. [velocity.exe](#)
2. [velocity.for](#)
3. [Peak temperature.xls](#)
4. [Torque.xls](#)
5. [Aluminum Hardness.xls](#)