Thermal and Material Flow modelling of Friction Stir Welding using Comsol

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Abstract: Two Friction stir welding models are presented - a global thermal model using the temperature dependent heat source and a local material flow and heat generation model allowing for detailed investigation of different contact conditions. The two models are coupled into a larger local-global model. The flow model includes frictional dissipation from the contact between the workpiece and the tool as well as plastic dissipation.

Keywords: Friction Stir Welding, FEM, Heat Generation, CFD, Friction.

1 Introduction

Friction Stir welding (FSW) [2] is a solid state welding process where tool is inserted into the workpiece while rotating and moving along the joint line, see figure 1. Heat is generated in a combination with frictional and plastic/viscous dissipation due to the relative motion between the tool and workpiece. Under specific thermomechanical conditions, a shear layer establishes around the tool and by moving the tool along the joint line a weld is performed. The process parameter window is fairly narrow since the thermomechanical conditions are very sensitive to changing welding parameters. Aluminium and many other alloys that are Friction Stir welded are characterized as shear thinning - hence being non-Newtonian making this a highly non-linear problem to solve as well as truly multi-physical.

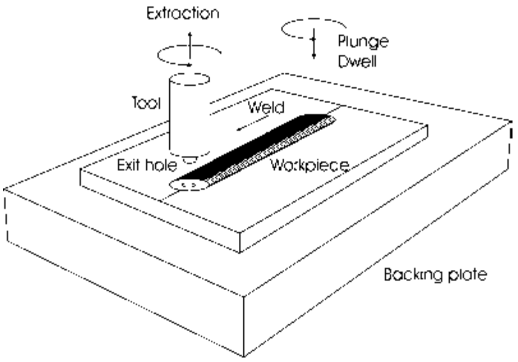

Figure 1: Schematic of Friction Stir Welding.

The presented FSW models are developed in COMSOL, and consist of two separate models that are sequentially coupled to each other. The thermal-pseudo mechanical model (TPM) [4, 3] is global model including workpiece, tool and backing plate - giving the heat generation and temperature distribution in a matter of seconds. The pseudo-frictional flow model (PFF) is a detailed local model analyzing the flow field around the tool, as well as the viscous and frictional heat generation. However the local flow model needs to have the "correct" inlet temperature from the global model. For this, the Comsol specific feature *Extrusion Boundary Coupling Variables* are used.

2 Numerical model

Figure 2 shows the schematic of the numerical models used for simulating the temperature fields, heat generation and material flow. The thermal-pseudo-mechanical model results in a detailed far-field temperature field - whereas the local model results in a detailed near-field temperature field. The thermal-pseudo-mechanical model is based on a heat generation driven by a temperature dependent flow stress, whereas the pseudo-frictional-flow model is based on a heat generation driven by a temperature and strain/shear rate dependent flow stress. The thermal-pseudo-mechanincal model does not account for different contact conditions - whereas the pseudo-frictional flow model can model contact conditions ranging from full sticking to nearly full sliding.

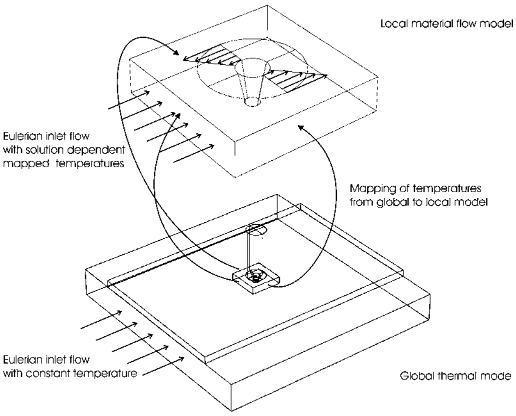

Figure 2: Schematic of local and global model with mapped temperatures between surfaces.

2.1 The thermal-pseudo mechanical model

The TPM model is based on a heat source where the temperature dependent yield shear stress is used as the driver in the local heat generation. The model assumes that the friction shear stress is in equilibrium with the deformation shear stress in the shear layer closest to the tool/matrix interface. The model could have been using Coulomb friction based on the local pressure distribution under the tool and the friction coefficient as function of the slip rate and temperature. The procedure using the yield shear stress indirectly assumes that some degree of sticking applies. The "real" constitutive material law depends on strain rate, strain and temperature, however the procedure chosen in the present work takes into account the first order effect of thermal softening.

The thermal model of a friction stir weld using the TPM heat source is more complex than using a traditional analytically prescribed heat source. The main advantage of TPM model is that it gives the total heat generation as output whereas a traditional thermal model calls for a total heat generation as input. The main reason for making the simulation to begin with was to estimate the heat generation and temperature field - which contradicts the reverse engineering approach of "guessing" the total Q that gives the best fit. Secondly, by giving Q as an input combined with a linear heat source distribution actually corresponds to prescribing a constant thermally indepent contact shear stress. The temperature dependent heat source in the TPM model makes the simulation highly non-linear and is solved using an iterative scheme. The solution time is 3 times longer for the TPM model than for the analytical model using the direct solvers in Comsol for both cases. The benefit though is that the TPM model can be used to explore welding conditions not supported by experimental measurements since it does not require torque or temperature data, which is normally the case for the analytical model. Some model parameters, e.g. heat transfer to backing plate and surroundings, can be tuned by obtaining a best fit between modelling and experimental thermal measurements. These model parameters are then reused for "new" process parameters, enabling exploration of "what if"-scenarios. One major drawback of the model is that if larger areas of the contact area (e.g. outer region of the tool shoulder) has close to sliding condition, the TPM model would overpredict the heat generation and hence the temperatures.

The thermal-pseudo-mechanical model (TPM) is developed using the *Heat transfer module* in Comsol, where the governing equations are the energy equations with convective terms, i.e.

$$\nabla k \nabla T = u \rho c_p \nabla T \tag{1}$$

The FSW specific boundary condition is the surface heat flux given by

$$q = \omega r \tau_{yield}(T) \tag{2}$$

where $\tau_{yield}(T)$ is the temperature dependent yield shear stress of the material at the contact interface, ω is the rotational speed in rad/s and r is the radial distance to the tool center. It is assumed that

$$\tau_{friction} = \tau_{yield}(T) \tag{3}$$

Figure 3 shows the shear yield stress for evaluated at strain rates of $\dot{\epsilon} = 10^{-3}$, since the model does not takes deformation rates into account.

2.2 The pseudo-frictional flow model

The pseudo-frictional flow model is based on the assumption of equilibrium between frictional stress at the interface and the viscous stress evaluated inside the shear layer closest to the contact surface. The viscous stress is then the driver for the frictional dissipation by applying a heat flux boundary condition at the tool/matrix surface defined as an boundary experession, see equation 9. This allows for simulating different contact conditions - and including the frictional heat generation. The temperature on the common/shared surfaces of the local and global model are mapped using Comsol's *Boundary Extrusion Variables* under *Extrusion Coupling Variables* by defining several variables, e.g. Tvar. The pseudo-frictional flow model (PFF) is developed using the *non-Newtonian module* and *Heat transfer module* where the governing equations are the Navier-Stokes equations, i.e. the momentum and continuity equations,

$$\rho u \nabla u = \nabla \left[-Ip + \eta \left(\nabla u + \nabla u^T \right) \right] \qquad (4)$$

$$\nabla u = 0 \qquad (5)$$

Due to the dominant viscous force, the inertia term can be neglected in FSW modeling, thus solving the Stokes equation. The following velocity vectors are applied as velovity boundary conditions at the contact interface,

$$u = -y\delta\omega \qquad (6)$$

$$v = x\delta\omega \qquad (7)$$

, where δ is the contact state variable describing the dimensionless degree of sticking, ω is the rotational speed in rad/s and r is the radial position. This corresponds to prescribing a counter-clockwise rotational flow with a tangential speed of $\delta\omega r$ as boundary condition at the contact interface. Additionally, the energy equation with volumetric heat source and convective terms are solved for, i.e.

$$\nabla k \nabla T = Q + u\rho c_p \nabla T \qquad (8)$$

where $Q = s_{ij}\epsilon_{ij}$ is the viscous dissipation in the shear layer. The following surface flux is applied as thermal boundary condition at the contact interface,

$$q = (1-\delta)\omega r \tau_{friction} \qquad (9)$$

, where $\tau_{friction}$ is the frictional stress which could be described by Coulomb friction. As mentioned above, the friction shear stress must be in equlibrium with the viscous shear stress just at the contact interface in steady-state conditions, thus it follows that

$$\tau_{friction} = \tau_{viscous} \qquad (10)$$

where $\tau_{viscous} = \sqrt{K_x^2 + K_y^2}$. The viscous stresses K_x and K_y at the boundaries are defined in *Equation System - Boundary Settings.* With axisymetrical tools there are rotational velocity boundary conditions in the xy-plane, only , resulting in neglectible flow in the z-direction. Therefore K_z is not accounted fore in this case.

The aluminium alloy of Al 7075-T6 used in this FSW is treated as a non-Newtonian fluid using the power law expression with a strain rate and temperature dependent viscosity. The constitutive law is implemented in Comsol using the *Power law viscosity model* and the model parameters are based on experimental data from [1] for Friction Stir Processed A7075-T6 material.

$$\tau = \eta\dot{\gamma}^n = \eta\dot{\gamma}^{n-1}\dot{\gamma} \qquad (11)$$

where $\eta_{eff} = \eta\dot{\gamma}^{n-1}$ is the effective viscosity dependent on strain rate and temperature. The effective viscousity is found from

$$\tau_{ref}(T) = \eta_{eff,ref}(T)\dot{\gamma}_{ref} \qquad (12)$$

$$\eta_{eff,ref}(T) = \frac{\tau_{ref}(T)}{\dot{\gamma}_{ref}} = \frac{\tau_{ref}(T)}{\sqrt{3}\dot{\epsilon}_{ref}} \qquad (13)$$

where $\dot{\epsilon}_{ref}$ and $\tau_{ref}(T)$ are reference values from [1]. Equation 13 is given as input in m-value field and the n-value is set to 0.2 in *Subdomain Settings - Power Law coefficients.*

2.3 Local-global coupling

The models are weekly coupled, meaning that the temperature field at the corresponding local-global interface are mapped from the TPM model to the PFF model model. The heat transfer coefficient at the bottom surface of the PFF model is tuned such that the total heat generation of the two models are similar. This results in a more realistic temperature field in the local model. The heat generation and the local distribution at the tool/matrix interface and shear layer obtained in the local model could be mapped back to the TPM model. However since the local model already has utilized the temperature at the overlapping (shared) surfaces the local/global models once, this proceedure has not been used.

The coupling is from the global to the local, which enables the two sub-models to be solved sequentially. Especially the local model, i.e the pseudo-frictional-flow model calls for the full use of the CPU-resources, since the highly non-linear characteristic of the model.

3 Results

Figure 3 shows the temperature dependent shear yield stress used in both the TPM and pseudo-frictional flow model.

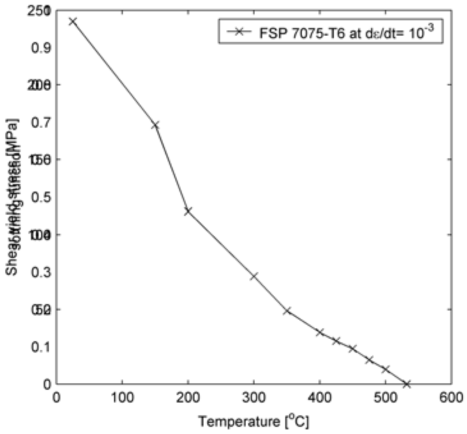

Figure 3: Temperature dependent yield shear stress, from [1, 4].

Figure 4 shows the temperature profiles from the experiment of 7075 T6 welds compared to the model with welding speed of 0.67 mm/s and rotational speed of 535 RPM, giving rise to a total heat generation of 1.9 kW. The model has been calibrated by adjusting the different heat transfer coefficients in the model, and not by adjusting the heat input as in traditional models.

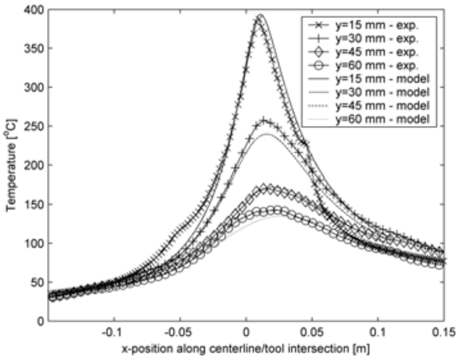

Figure 4: Comparison between experimentaly measured temperature profiles and numerical results, from [1, 4].

Figure 5 shows the temperature distribution in the tool, workpiece and backing plate. The TPM-model calls for an iterative solver because the heat source is part of the solution itself (temperature dependent) however it is still much less computational demanding that a full thermo-mechanical model. The temperature dependent yield shear stress leads to a self-stabilizing heat generation giving temperatures below the solidus temperature, which in the case of A7075-T6 is 532 ^oC, [3].

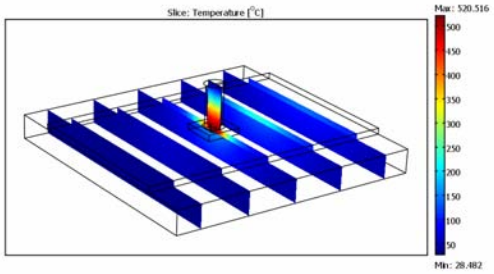

Figure 5: Temperture field in the global thermal model using the TPM heat source.

The TPM model is used for a parameter study of welding speeds ranging from 1 to 10 mm/s and rotational speeds ranging from 100 to 1000 RPM. The heat generation is shown in figure 7 and the peak temperature is shown in figure 6. Notice how the temperature stabilizes just below the melting temperature for high RPM / low welding speed combinations, which is due to the loss for flow stress at elevated temperatures. As a consequence of stabilizing the peak temperatures, the heat generation "saturates" as well.

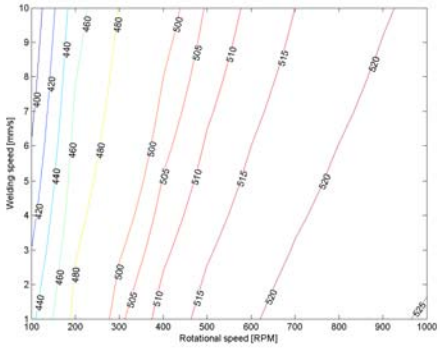

Figure 6: Contour plot of the maximum temperature as function of rotational speed and welding speed[3].

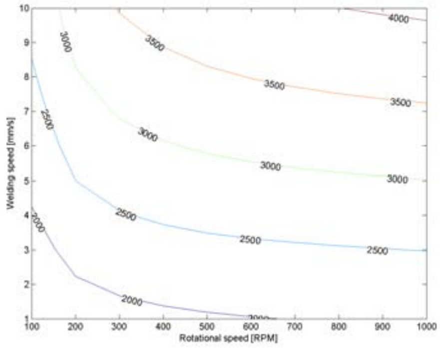

Figure 7: Contour plot of the maximum heat generation as function of rotational speed and welding speed[3].

Figure 8 shows the 3D flow field under the tool shoulder and around the tool probe obtained using the pseudo-frictional flow model coupled to the global TPM. The non-Newtonian material behaviour leads to a narrow shear layer. The flow field is shown with a contact condition of $\delta = 0.2$ using the pseudo-frictional flow model. The total heat is generated by $\sim$ 20% plastic dissipation and $\sim$80% frictional dissipation.

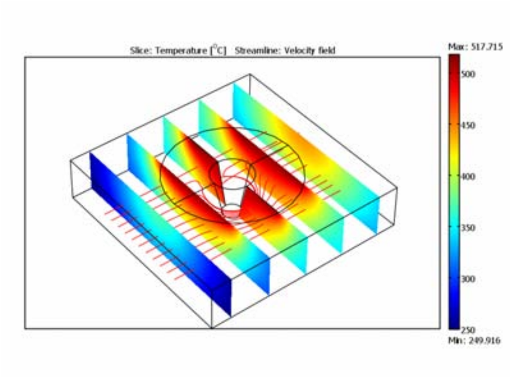

Figure 8: Material flow and temperture field in the local flow model using the pseudo-frictional heat source.

Figure 9 shows the heat generation obtained using the pseudo-frictional flow model with contact conditions varying from 0.1 to 1 with increments of 0.1. The boundary conditions are simplified with adiabatic conditions at the sides and bottom, and inlet convective flow with temperature of 200 ^oC - hence the model is not coupled to the TPM model in this case. Due to the counter action between the heat generation obtained by frictional and plastic dissipation, the total heat generation is only slightly dependent of delta. The total heat generation is lowest at sliding conditions because the deformation rate is lowest, i.e. the shear rate in the shear layer is lower that at higher degree of sticking. Even though the temperature is slightly lower, which could lead to recovery of the material strength, the temperature dependence of the flow stress (viscosity) is not dominant compared to the rate dependence, hence the shear stress in the shear layer and close to the contact interface is lower as well. As a consequence, the total heat generation is varying between $\sim$ 800 Watts for $\delta = 0.1$ (sliding condition) to $\sim$ 1050 Watts for $\delta = 1.0$ (full sticking condition) in a standard case where the welding speeds is 2 mm/s and the rotational speed is 400 RPM. Based on the pseudo-frictional flow model, it is concluded that the heat generation "only" changes around 20-25% dependent on the contact conditions, which is also qualitatively supported by experimental findings that the sliding condition produces less heat than the sticking conditions.

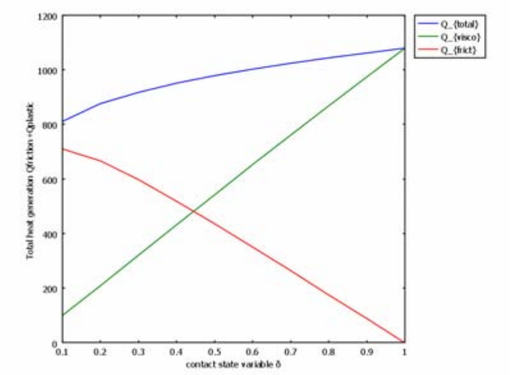

Figure 9: Total, frictional and viscous heat generation for contact state variable δ varying from 0.1 (close to full sliding) to 1.0 (full sticking)

In the following two preliminary models are presented. Figure 10 shows the flow around a FSW tool with threaded probe. The model uses element sizes of 0.2 mm at the thread surface, which can be related to the thread spacing of 2 mm. This fine mesh, see 11, results in close to 1 million dof's using second order elements. This problem is highly non-linear since the power coefficient of n=0.1 is used. The solution is obtained using the parametric solver in Comsol with n-values ramped from 1, i.e. full Newtonian down to 0.1, i.e. higly shear thinning behaviour reprentative for aluminium. Notice how the shear layer localizes within the tread cavaties. The boundary condition for this model is prescribed "manually" at each surfaces, ensuring that the flow is tangential to the surfaces. The calculation time is $\sim$ 3 million seconds using a 2 x 3.0 GHz Intel Xeon Quad processors (8 CPUs) - 16GB RAM workstation using its full capacity.

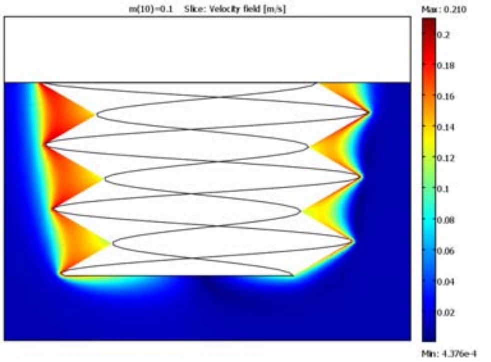

Figure 10: 3D flow around a FSW tool with threaded probe.

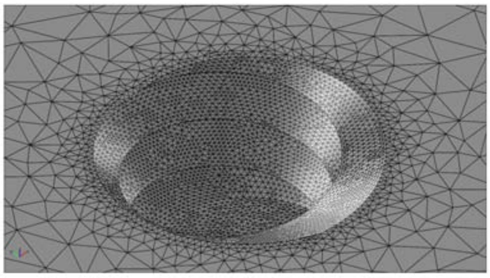

Figure 11: Mesh used in the model for the 3D flow around a FSW tool with threaded probe.

Figure 12 shows the flow around a FSW tool with threaded probe and scroll shoulder. The scroll and thread features influence the flow by dragging the material inwards and downwards. However, the rotational flow is dominant and the material flow in the z-direction is much less than normaly anticipated. The velocity boundary conditions along the tool/matrix interface is prescribed using the *Moving wall boundary condition*.

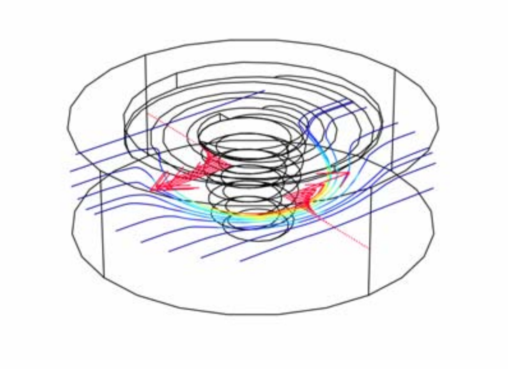

Figure 12: 3D flow around a FSW tool with threaded probe and scroll shoulder.

4 Conclusion

This paper demonstrates the powerful capabilities of Comsol to couple a highly detailed local CFD model of the flow around the Friction Stir Welding tool to a global thermal model. Each sub-model represents some of the most advanced models of each field allowing for both predictions of heat generation, temperatures, material flow for different degees of sticking at the tool matrix interface.

References

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