Hot Tap Welding Model

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1 Problem Statement

Consider a stainless steel pipe with density ρ, specific heat capacity c_P , and thermal conductivity k. A repair sleeve is welded onto a cylindrical pressurized pipe filled with some flowing process fluid. This is an axisymmetric cross section about a horizontal axis of rotation. The heat input due to welding is modeled by using a time-dependent volumetric heat source term, $f(r, z, t)$, where r is the radial coordinate, z is the longitudinal coordinate and t is time.The heat transfer on the inside and outside surfaces of the pipe are modeled by assuming a standard Neumann boundary condition, where the heat flux is proportional to the difference between the surface temperature and some reference temperature. On the outer G-Ambient surface, the heat transfer coefficient and reference temperature are denoted by $h_{ambient}$ and $T_{ambient}$, respectively. On the inner G-Process surface, they are $h_{process}$ and $T_{process}$. The schematic is shown in Figure 1.

Objective: To determine the thermal history during welding within the metal for 0≤t≤10 seconds

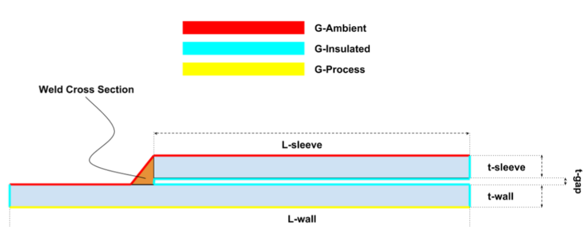

Figure 1: Illustration of the axi-symmetric sleeve geometry (Source: E^2G)

2 Assumptions

- The weld bead is the entire triangular region in Figure 1, which is assumed to be an isosceles right triangle. We denote this region as W.
- The heat source $f(r,z,t)$ is sinusoidal in time, uniform within W, and zero everywhere else. Specifically, consider $f(r,z,t) = 2700\frac{1}{2}(1+cos((t+5)(\frac{\pi}{5})))$ BTU/s-in^3 $\forall x \in W$ and $f(r,z,t) = 0$ BTU/s-in^3 $\forall x \notin W$.
- $T_{process} = 325°F$ and $h_{process} = 48$ BTU/hr-ft^2-F.
- $T_{ambient} = 70°F$ and $h_{ambient} = 9$ BTU/hr-ft2-F.
- Boundaries indicated by G-Insulated are insulated.
- The geometry is characterized by the dimensions in Figure 1. Specifically, assume that $t-sleeve = t-wall = 0:188$ in, $L-wall = 1.5(L-sleeve)$, $L-sleeve = 10(t-wall)$, and $t-gap = 0.02in$.
- The material properties are constant. Assume that $\rho = 0.284$ lb/in^3, $c_P = 0.119$ BTU/lb-F, and $k = 31.95$ BTU/hr-ft-F.

3 Model Formulation

The response of the metal (steel) in the current study is formulated by defining the problem using the partial differential equation (PDE) for transient heat conduction defined as

$$\rho c_P \frac{\partial T}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(-kr\frac{\partial T}{\partial r}) + \frac{\partial}{\partial z}(-k\frac{\partial T}{\partial z}) = f(r,z,t). \tag{1}$$

The convective heat transfer boundary conditions due to air flow and process fluid flow are assumed to act at the sleeve-ambient (and pipe-ambient) interfaces and the pipe-process interface respectively and they are evaluated as

$$-k\frac{\partial T(r_i,z,t)}{\partial x} = h_i(T_i - T(r_i,z,t)), \tag{2}$$

such that

- $r_i = t-wall$, $T_i = T_{ambient}$, $h_i = h_{ambient}$ for sleeve-ambient interface,
- $r_i = -z + L - sleeve + t - wall + t - gap + t - sleeve$, $T_i = T_{ambient}$, $h_i = h_{ambient}$ for weld-ambient interface,
- $r_i = t - wall + t - sleeve + t - gap$, $T_i = T_{ambient}$, $h_i = h_{ambient}$ for pipe-ambient interface and
- $r_i = 0$, $T_i = T_{process}$, $h_i = h_{process}$ for pipe-process interface.

Additionally, the heat flow is zero across all the boundaries labelled as insulated.

4 Solution Procedure

The formulated problem is numerically evaluated using the technique of finite element analysis with the help of the open source PDE solver FreeFEM (Hecht 2012). The domain is created based on the details provided for the geometry of the set-up. This is followed by generation of simple triangular element based mesh. The finite element formulation is developed for the problem given by Equation (1) by assuming

$$T = T_h^e(r, z, t) = \sum_{j=1}^{n} T_j^e w_j^e(r, z, t), \tag{3}$$

where T_h^e is the approximate solution for T, T_j^e is the approximate solution at the node j and w_j^e is the approximation (interpolation or shape) function for the chosen finite element type, which is linear for the current study. Then, the weak form is developed for the PDE which can be expressed as

$$\int_{\Omega_e} \left(\frac{1}{\alpha} w \frac{\partial T}{\partial t} + \frac{\partial w}{\partial r}\frac{\partial T}{\partial r} + \frac{\partial w}{\partial z}\frac{\partial T}{\partial z} - wf\right) r dr dz - \oint_{\Gamma_e} w\left(\frac{\partial T}{\partial r} n_r + \frac{\partial T}{\partial z} n_z\right) ds = 0, \tag{4}$$

where α is the thermal diffusivity of the metal which can be expressed as $\alpha = \frac{k}{\rho c_P}$. This can be re-written as

$$\int_{\Omega_e} \left(\frac{1}{\alpha} w\left(\frac{T - T_{old}}{\Delta t}\right) + \frac{\partial w}{\partial r}\frac{\partial T}{\partial r} + \frac{\partial w}{\partial z}\frac{\partial T}{\partial z} - wf\right) r dr dz - \oint_{\Gamma_e} w\left(\frac{\partial T}{\partial r} n_r + \frac{\partial T}{\partial z} n_z\right) ds = 0, \tag{5}$$

where T is the temperature in the current time step, T_{old} is the temperature in the previous time step and Δt is the chosen time interval. Using time interval of 0.1 seconds, the PDE is numerically solved using the convective and the insulated boundary conditions.

5 Results

The peak temperature distribution in and around the weld region is as shown in Figure 2. The variation of temperature at a point very close to the weld region on the sleeve pipe is shown in Figure 3. It shows that the regions around the weld region would be subjected to very high temperatures, which could affect the microstructure and mechanical behavior of the metal. The sinusoidal nature of the heat source could also lead to rapid fluctuations in the thermal behavior of the metal.

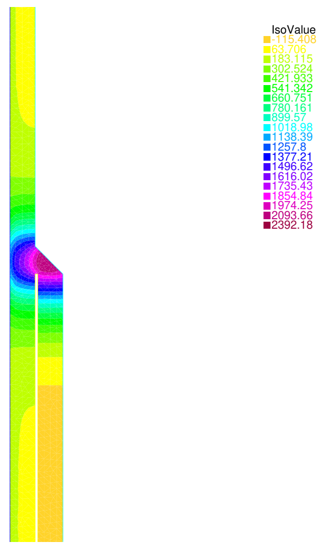

Figure 2: Peak temperature distribution close to the weld region

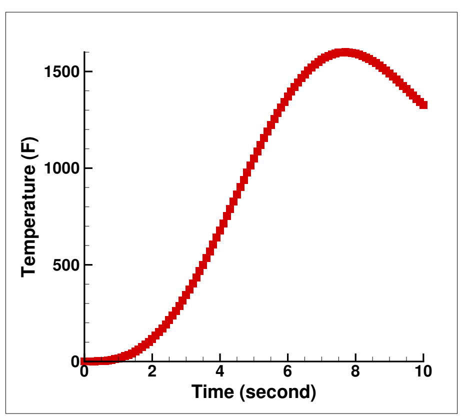

Figure 3: Variation of temperature at a point close to the weld region over time

6 Additional Information

- *The current model is 2D axisymmetric, but in reality the geometry of the component that is welded onto the live pipe is not able to be modeled axisymmetrically. Thus, how would you extend your model to 3D and demonstrate some geometry extensions that would require a 3D model?*

  The 2D axisymmetric model might not be able to predict the response accurately if the welding is between two dissimilar metals which could make the weld surface asymmetrical and hence would have to be modeled in 3D (Phanikumar, Chattopadhyay, and Dutta 2011). Additionally, the attachment of the hot-tap fitting and the valve to the sleeve would restrict the possibility of using a 2D axisymmetric model. One more inherent assumption made while using the 2D axisymmetric model is that the process of welding is carried out across the entire circumference at the same time (Bang et al. 2002). The model can be extended to 3D by bringing in the dependence of the θ (azimuth) term to the governing PDE and the heat source term.

- *In the current model, we specify the inner G-Process surface boundary condition directly. Explain how you would improve the model to explicitly include fluid flow inside the pipe for gas, liquid, or multi-phase flow that could be either laminar or turbulent, and how would this effect the temperature on the process side of the pipe?*

  Instead of using a G-Process boundary condition, the fluid flow within the pipe can be incorporated into the model by determining the heat transfer coefficient ($h_{process}$) for laminar and turbulent flows using the relations given by equations (6) and (7) respectively (Subramanian 2015).

$$\frac{h_{process}D}{k} = 3.66 + \frac{0.065RePr\frac{D}{L}}{1 + 0.04(RePr\frac{D}{L})} \tag{6}$$

$$\frac{h_{process}}{\rho c_P V} = 0.023Re^{-0.2}Pr^{\frac{-2}{3}}(\frac{\mu_b}{\mu_w})^{0.14} \tag{7}$$

  Here, D is the inside diameter of the pipe, k is the thermal conductivity of the fluid, Re is the Reynolds' number defined as $\frac{DV\rho}{\mu_b}$, V is the average velocity of the fluid, Pr is the Prandtl number defined as $\frac{\mu_b c_P}{k}$, L is the length of the pipe, ρ is the density of the fluid, c_P is the specific heat capacity of the fluid at constant pressure, μ_b is the viscosity of the fluid in the bulk and μ_w is the viscosity of the fluid next to the wall. The temperature on the process side is going to be a function of the radius of the pipe, with a maximum at the wall and a minimum at the center of the pipe.

- *In the current model, we assume that the welding process can be modeled as a volumetric heat source term. In reality, the welding process is much more complex than this. Do a quick literature review on welding simulations and* *modeling this process numerical, and then describe how you would modify the existing model to include a more sophisticated welding simulation for the source term.*

A double ellipsoidal heat source model proposed by Goldak et al. is usually employed to simulate the welding process in 3D (Goldak, Chakravarti, and Bibby 1984) (Farias, Teixeira, and Vilarinho 2021) (Kik 2020) (Wang et al. 2013). According to this model, the heat source is defined as a combination of two ellipsoidal sources. One half of the source is the quadrant of one ellipsoidal source and the other half is the quadrant of the second ellipsoid. Based on this, the power density distribution in both the halves can be expressed as

$$f(x,y,z,t) = \frac{6\sqrt{3}g_1 Q}{abc\pi\sqrt{\pi}} e^{\frac{-3x^2}{a^2}} e^{\frac{-3y^2}{b^2}} e^{\frac{-3z^2}{c^2}} \tag{8}$$

and

$$f(x,y,z,t) = \frac{6\sqrt{3}g_2 Q}{abc\pi\sqrt{\pi}} e^{\frac{-3x^2}{a^2}} e^{\frac{-3y^2}{b^2}} e^{\frac{-3z^2}{c^2}} \tag{9}$$

respectively, where g_1 and g_2 are the fractions of the heat deposited in each of the halves such that $g_1 + g_2 = 2$. Here, Q is the energy input rate, a, b, c are the semi-axes of the ellipsoid in the directions x, y, z respectively. If we would like to consider a 2D axisymmetric model, the heat source could be defined using the Gaussian distribution as

$$f(r) = f(0)e^{-Cr^2}, \tag{10}$$

where $f(r)$ is the surface flux at radial distance r from the heat (weld) source, $f(0)$ is the maximum flux at the center of the heat source, C is the concentration coefficient (higher the value of C, the more concentrated the heat flux is). $f(0)$ can be defined as a function of thermal efficiency, electric current and the voltage of the weld source.

- *In the current model, we use empirical data that is correlated to cooling time to determine the propensity for the material to crack post welding. In reality, as the material is heated up the microstructure transforms, and depending on how the material cools determines the resulting microstructure and corresponding material properties of the cooled metal. Harder and more brittle materials upon post weld cooling are typically more prone to cracking. How would we go about modeling the microstructural changes of the weld process directly?*

  The evolution of the weld microstructure can be modeled using a combination of kinetic modeling approaches (for decomposition of austenite) and a heat transfer model (Novotnỳ and Ivančo 2014).

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