2-D Stress Field and Interaction Forces of Spatial Crack Distributions in Finite Domains

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Abstract

We develop here analytical and Finite Element (FE) numerical methods of the analysis and computer simulation of the electron beam (E-beam) welding process. First, we develop an analytical solution to the heat transfer problem in e-beam welded joints based on the heat source method. The interaction between the e-beam and the welded joint is represented by a moving heat source at a constant speed, where the heat source is represented by a 3-D Gaussian distribution. The solution is applied to a tungsten circular patch configuration, whereby a central disk is welded to an external ring with a weld bead. FE simulations of the heat transfer process are then carried out and compared to the results of the analytical solution. To assess the development of residual stresses in the tungsten circular patch test, we show results of FE multiphysics simulations of coupled heat transfer and solid mechanics using temperature-dependent elastoplastic constitutive equations for solid tungsten. To understand the nature of crack susceptibility of the weld, a damage mechanics model based on phase-field is finally integrated into the suite of multiphysics models. Results of FE simulations are discussed and the influence of geometry and e-beam heating rates are determined.

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Contents

1. Introduction

Welding has been widely used as an important joining technique for metallic structures and components. A localized heat source is applied at the joining surfaces between two metal pieces, leading to melting and re-solidification of a small zone of the two pieces. Welding is distinct from brazing and soldering, which do not melt the base meta. A filler material is also added to the joint to form a pool of molten material (the weld pool) that cools to form the joint. The zone that has melted and solidified is known as the Heat Affected Zone (HAZ). Several types of energy sources are used for welding, such as gas flame, electric arc, friction, and ultrasound. Because of high temperature gradients as well as phase change and recrystallization in the HAZ, severe residual stresses are generated locally, leading to potential cracking of the weld and subsequent failure. The advent of energy beam heat sources, such as laser and electron beams, allowed more precise control of the HAZ and enabled welding applications that were not possible before with standard techniques. While laser beam welding employs a highly focused laser beam, electron beam welding is done in a vacuum. Both are very fast and have very high energy density, thus allowing deep weld penetration and minimizing the size of the HAZ. A major drawback of these energy beam techniques is their susceptibility to thermal cracking.

Because the residual stress field is highly-dependent on the weld geometry, environment, heating and cooling rates, as well as on evolving material properties within the HAZ, precise and general characterization of weld integrity is very difficult. Simulation tests attempt to reproduce some the welding conditions by applying external strain that can be easily quantified. The applied strain (or stress) is such that any restraint by the fixture and specimen is negligible. This approach allows metallurgical and compositional parameters to be isolated from the mechanical state of the weld. Nevertheless, the test conditions of these simulation tests are substantially different from actual welding environments and thus the results are difficult to apply to real weld conditions. To standardize the conditions for evaluations of weld-integrity, the Circular patch Test (CPT) and Circular Groove Test (CGT) have been widely used. The CPT consists of cutting a circular "patch" from the center of a plate and welding it back into its original position. The unique design of the CPT generates high residual stresses in the weld fusion zone and the HAZ to high stress. The magnitude of the residual stress increases with decreasing patch diameter. With this standardized method, it has become possible to evaluate weld integrity under very highly restrained conditions [1]. Studies of cracking in CPT have included Solidification and liquation cracking issues in welding [2], strain-age cracking characteristics [3], and finite element analysis [4].

The objective of the present investigation is to develop analytical and computational methods for assessment of weld integrity. These methods will be applied to the CPT of tungsten (W) sheets and plates. We first introduce the main parameters of e-beam welding in CPT in Section 2. Then we present an analytical solution to the transient heating and cooling problem during e-beam welding in Section**??**. Finally, we give a summary of the results and conclusions in section **??**.

2. Geometry Description

The input variables are:

1. Crack center vector $\mathbf{R_c}$.
2. Crack half width a.
3. Number of dislocation dipoles n_d.
4. Field point Q at $\mathbf{R_q}$.

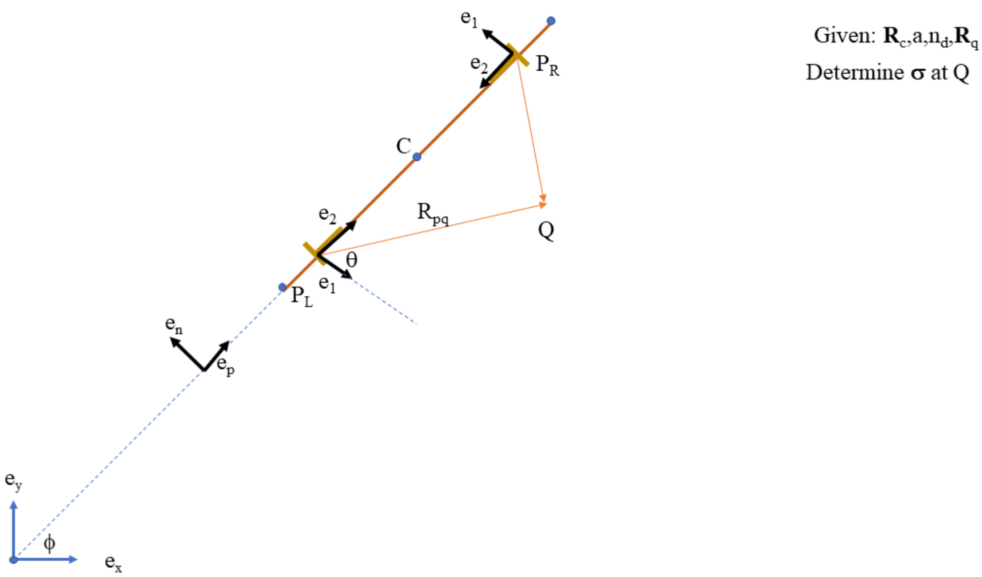

Figure 1: Crack geometry and coordinate systems.

Denote the following unit vectors, as shown in Figure 1:

- $\mathbf{e}_x$=[1 0 0].
- $\mathbf{e}_y$=[0 1 0].
- $\mathbf{e}_z$=[0 0 1].
- $\mathbf{e}_p = [\cos\phi \;\; \sin\phi \;\; 0]$.
- $\mathbf{e}_n = [-\sin\phi \;\; \cos\phi \;\; 0]$.

Let's have n_d on the crack line. Dislocations are numbered as $j = 1, 2, ..., 2n_d$. Dislocations will come in pairs at j, and $2n_d + 1 - j$. Thus, "left (L)" dislocations will be numbered $j = 1, 2, ..., n_d$, and "Right (R)" dislocations will be numbered $2n_d, 2n_d - 1, 2n_d - 2, ..., n_d + 1$. The local coordinate unit vectors for the "L" and "R" dislocations will be: Denote the following unit vectors, as shown in Figure 1:

- $\mathbf{e}_1^L = -\mathbf{e}_n$.
- $\mathbf{e}_2^L = \mathbf{e}_p$.
- $\mathbf{e}_1^R = \mathbf{e}_n$.
- $\mathbf{e}_2^R = -\mathbf{e}_p$.
- $\mathbf{e}_3^L = \mathbf{e}_3^R = \mathbf{e}_z$.

The crack is an object $C(i)$, with $i = 1, 2, ..., n_C$, containing dislocations $C(j)$ with $j = 1, 2, 3.., 2n_d$ and $jj = 2n_d, 2n_d - 1, .., n_d + 1$. Any property of a dislocation is contained in the crack-dislocation object, thus, for example, $\mathbf{e}_1$ is written as a doublet: $C(i).D(j).\mathbf{e}_1$ and $C(i).D(jj).\mathbf{e}_1$.

The crack half-length is a. The initial distance between dislocations is $d = a/n_d$. The "Left" crack tip will be taken as a local origin to locate dislocations on the crack face. The position vector of the "Left" tip is $\mathbf{R}_L$, and the position vector of dislocations (P) indexed j and jj are given by:

- $\mathbf{R}_L = \mathbf{R}_c - a\mathbf{e}_p$.
- $\mathbf{R}_P(j) = \mathbf{R}_L + d(j-1)\mathbf{e}_p$.
- $\mathbf{R}_P(jj) = \mathbf{R}_L + d(jj-1)\mathbf{e}_p$.

The filed point Q is defined by its position vector $\mathbf{R}_Q$ at an angle θ_Q, while the position vector of dislocation P is defined by its position vector $\mathbf{R}_P(j)$ at an angle ϕ in the global coordinate system. Now the local position vector between the source point P and the field point Q is given by :

- $\mathbf{R}_{PQ} = \mathbf{R}_Q - \mathbf{R}_P(j)$.
- $\theta = \pi/2 + \theta_{PQ} - \phi$.

Let $K = \frac{\mu b}{2\pi|\mathbf{R}_{PQ}|}$. The stress field of dislocation j at point Q is given by:

$$\sigma/K = -(\sin\theta(2+\cos\theta))\mathbf{e}_1\otimes\mathbf{e}_1 + (\sin\theta\cos 2\theta)\mathbf{e}_2\otimes\mathbf{e}_2 \quad (1)$$

$$-(2\nu\sin\theta)\mathbf{e}_3\otimes\mathbf{e}_3 + (\cos\theta\cos 2\theta)(\mathbf{e}_1\otimes\mathbf{e}_2 + \mathbf{e}_2\otimes\mathbf{e}_1) \quad (2)$$

Acknowledgments

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