# Virtual Welded-Joint Design—A Systematic Modeling Approach for High Performance Welds

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## Introduction

Weld fatigue strength is currently the bottleneck to design high performance and lightweight welded structures using advanced materials such as high strength steels. In order to achieve a high performance welded-joint it is necessary to manage the weld bead shape for maximum fatigue strength, produce preferable residual stress distribution, and obtain the desired microstructure for improved material toughness and strength. This is a systems challenge that requires the optimization of the welding process, the welding consumable, and the base material. This research intends to develop an integrated modeling and simulation tool for addressing these issues in a systems approach.

## Description of Modeling Approach

This research integrated existing modeling tools with further enhancement to develop a systematic microstructure-level modeling approach for the design of high performance welded-joints. The integrated modeling approach consists of five sub-models: (1) Weld Thermo-Fluid Model (WTFM), (2) Weld Microstructure Model (WMM), (3) Weld Material Property Model (WMPM), (4) Weld Structural Model (WSM), and (5) Weld Fatigue Model (WFM). The systematic modeling approach was thus based on interdisciplinary applied sciences including heat transfer, computational fluid dynamics, materials science, and engineering mechanics.

## Results and Discussion

Significant progress has been made in developing weld sub-models for Virtual Welded-Joint Design. A transient 3-dimensional model with free surface was developed to simulate heat transfer and fluid flow in Gas-Metal-Arc-Welding (GMAW) process. The unique behavior of the heat transfer and fluid flow in GMAW was considered by the incorporation of the driving forces in weld pool (surface tension gradient force, electromagnetic force, arc pressure, buoyancy force, and metal droplet impact force) and the heat source due to the metal droplets into the model. The model has been used to predict weld bead shape for both bead-on-plate welds and T-fillet welds. The predicted shapes were comparable with actual welds.

For weld microstructure model, the phase transformation model developed by H.K.D.H. Bhadeshia et al. [1] was adopted. Enhancement has been done to extend this model for predicting the spatial distribution of phases in both weld zone and heat-affected-zone (HAZ). The grain growth in the HAZ was simulated by the combination of thermal cycles and grain growth kinetics. It was found that the spatial distribution of grain size and phase volume fractions can be well predicted as functions of chemistry and cooling rates. For weld material property model, efforts has been made to predict yield strength and hardness in the weldment as functions of chemistry and cooling rates. The results show that welding induced material property change can be predicted based on the calculated microstructure using mixing law. For weld structural model, an avialable user material subroutine (UMAT) for welding process was adopted and modified to incorporate the effects of phase transformations. The structural model has been coupled with thermal and phase transformation models to predict weld residual stress. The results show that weld residual stress distribution can be manipulated by optimization of welding process and consumable composition. For Weld Fatigue Model, the structural stress method developing under JIP project has been identified as the solution to predict the life of welded-joints, due to its advantages in mesh insensitive and universal to different types of welds.

## Conclusions

The present work demonstrates the initial efforts and capabilities to simulate weld phenomena (heat transfer and fluid flow, grain growth, phase transformations, change of material property, and residual stress formation) using a systematic approach. The major findings can be summarized as following:

1. The developed 3D free surface weld thermo-fluid model can be used to predict the essential features of the weld bead shape.
2. The spatial distribution of grain size in HAZ due to different thermal cycles at various locations can be simulated by coupling the thermal model and grain growth kinetics.
3. The spatial distribution of phases in the weld zone and HAZ can be quantitatively predicted by coupling the thermal model, grain growth kinetics, and available phase transformation model.
4. Welding induced material property change can be predicted based on the calculated microstructure using mixing law.
5. Weld residual stresses can be simulated using the weld residual stress model.

The results indicate that welded-joint can be virtually designed based on a systematic approach. This computer-aided design (CAD) approach will integrate all of important welding variables such as alloy composition, welding parameters, and weld joint geometry into a systematic package. It will also output all of the essential results for welded-joint design such as weld bead shape, microstructure, material property, residual stress, and fatigue strength.