

# Thermo-Mechanical-Metallurgical Modeling of Cracking In Single Crystal Nickel-Base Superalloy Welds

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## Introduction

There is a need to repair and refurbish failed and used single crystal nickel-base superalloy components in the land base turbine industries for economic reasons. However, the welding process deteriorates the optimum microstructure that is achieved during prior heat treatment. It is also well known that changes in microstructure and residual stresses generated during welding process lead to cracking in weld metal (WM) and heat-affected zone (HAZ) of weldments. The cracking in the weldments is related to the interactions between thermal stresses, residual stresses and local strength variations that are influenced by local variations in weld thermal cycling and resultant microstructures. These interactions of thermal, mechanical and metallurgical changes govern the weldability of any structural alloy weld [1, 2]. The present work pertains to numerical modeling of these interactions for prediction of cracking tendencies in these alloys. Thermo-mechanical-metallurgical coupled analysis has been limited due to the size and complexity of the numerical calculation procedures for the following reasons: (a) the various cracking mechanisms in weldments often require transient analysis [3], and (b) current Finite Element Analysis (FEA) codes are limited in coupling thermal-metallurgical-mechanical analyses due to complex data transfer procedures [4] as well as the difficulty in describing the material microstructure evolution. In this work, a coupled FEA modeling procedure is introduced, using the SYSWELD® software. The coupled analysis is used to calculate residual stresses induced during the repair welding of a turbine blade of a single crystal Ni-base superalloy.

## Procedure

The repair welding process of Rene N5 (Ni-7.5Co-7.0Cr-1.5Mo-5.0W-3.0Re-6.5Ta-6.2Al (wt%)) single crystal plate with a groove has been modeled as a three-dimensional, transient problem. The weld process parameters are as follows: power=1000W, efficiency=0.7, speed=4.5mm/s. The simulation consists of two sub-models that are sequentially coupled, i.e., a thermal-metallurgical model and a mechanical model. Throughout the simulation, the same three-dimensional mesh was used. The base metal and the filler metal physical and metallurgical parameters were assumed to be identical in this preliminary research.

The thermal-metallurgical analysis was conducted first and the temperature history was then used as the thermal loading in the mechanical simulation. The history of metallurgical phase transformations was incorporated into the mechanical analysis, which determines the local mechanical properties with time and temperature.

As a first step, the latent heat effect from solidification (and not the solid-state transformation) has been considered. The kinetics of transformation from a  $\gamma+\gamma'$  mixture (68 % of cuboids of  $\gamma'$  in  $\gamma$  matrix) to  $\gamma$  during heating and the reverse transformation of  $\gamma$  to  $\gamma+\gamma'$  has been modeled using the data from thermodynamic calculations. To simulate deposition of a filler metal, an element activation/deactivation mode was used. Before

the filler metal addition, the elements in the weld metal are assumed to have zero mass. Thermodynamic and kinetics data for the alloys was obtained from ThermoCalc® and DICTRA® software [5, 6]. Temperature dependent mechanical properties from the literature [1, 3] were used in the calculations.

### Results and Discussion

In this coupled thermal-metallurgical modeling, solidification and solid-state phase transformation involving  $\gamma$  phase (fcc crystal structure) and  $\gamma'$  (L12 ordered crystal structure) are included. The above changes were captured during simulation. The temperature and phase fractions data at each node is stored at each time step. At the end of the thermal-metallurgical calculations, the data is transferred to the mechanical calculations through a robust data transfer algorithm. This eliminated the need for using subroutines and re-meshing process. This methodology is ideal for applying unified modeling procedure to various welding problems and complex geometries. In mechanical analysis, the deformation/strain/stress is calculated based on phase fractions as well as temperature stored at each node from the previous step. In the preliminary analysis, the simulations considered similar variations of yield strength, hardening coefficient and Young's modulus for  $\gamma$  phase region and the region containing  $\gamma + \gamma'$  phases. The typical results from the preliminary analysis are shown in Fig. 1. The spatial variation of temperature, liquid,  $\gamma-\gamma'$  region are shown in Fig. 1b to d, respectively. The transient transverse stress at that time is also shown Fig. 1e.

The stress distribution [see Fig. 1e] shows that the portions of the HAZ region are under tensile stress ( $> 200$  MPa). It is important to note that these tensile stresses also overlap with the regions that show less  $\gamma'$  that strengthens the alloys. Since the strength of the HAZ is lower than that of

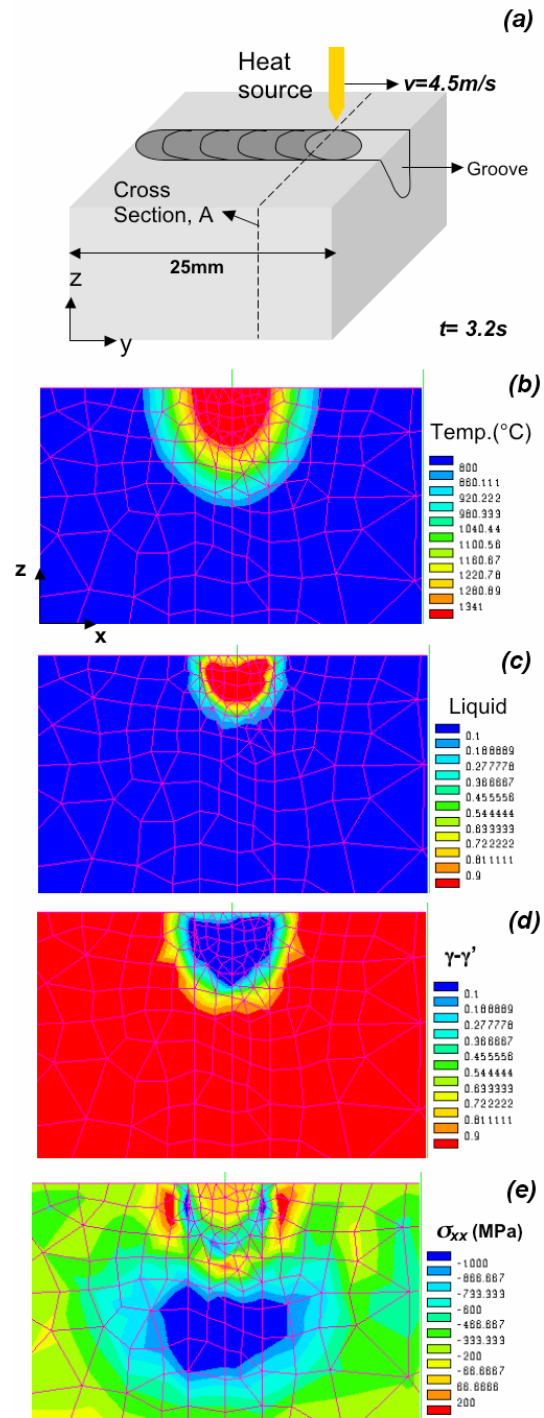


Fig. 1 (a) Schematic of repair welding of a single-crystal ReneN5 depositing filler metal on plate with a groove (at welding time,  $t=3.2\text{s}$  with welding velocity,  $v=4.5\text{m/s}$ ). On the cross section A, contours of (b) temperature, (c) liquid phase fraction, (d)  $\gamma-\gamma'$  phase fraction, (e) transverse residual stress ( $\sigma_{xx}$ ).

base metal in these regions, there can be an increasing probability of weld cracking. Current research is focusing on parametric studies to investigate the effect of heat input and preheat temperature. Another important variable is to change the initial microstructure of the base metal, which may evolve differently during weld thermal cycle in comparison to microstructure that is obtained through standard heat treatment. This is expected to change the mechanical response of the HAZ region and thereby change the cracking tendencies. These results will be compared with ongoing comprehensive experimental weldability research for different repair welding geometries.

Moreover, ongoing research is focused on developing robust kinetic models to consider the precipitation of  $\gamma'$  phase in the  $\gamma$  phase. The phase and temperature dependent mechanical properties are being collected and will be considered in the simulations. Other important microstructural changes that affect the mechanical soundness of weldments include the columnar-to-equiaxed dendrite transition (CET), segregation, liquation of carbides, and grain growth. These changes will be described using phenomenological models similar to other published research [2, 7].

### Summary and Conclusion

A FEA analysis procedure, based on a commercial FEA code, unifying thermal-metallurgical-mechanical modeling has been applied to describe cracking during repair welding of single crystal nickel-base superalloys. This methodology, by incorporating the detailed thermodynamics, kinetics, and mechanical properties of various phases, allow for the accurate thermal-mechanical behavior of weldments under various welding processes, parameters and geometries to be predicted. Preliminary results show that tensile stresses develop in the HAZ where there is a reduction of  $\gamma'$  phase fraction that strengthens the alloys, which suggests that HAZ can be more vulnerable regions to cracking than weld metal regions. Future research is considering the effects of welding process parameters and filler metal properties.

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