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Use of indicators for hot and warm cracking in welded structures

J Edberg[a,*], and J Andersson[b]

[a]*Luleå University of Technology, 971 87 Luleå, Sweden*
[b]*University West, Department of Engineering Science, 461 86 Trolhättan, Sweden*

Abstract

Weight reduction of mechanical components is becoming increasingly important as a way to provide more environment friendly production and operation of different equipment. This is true in almost any manufacturing industry, but is especially important to the aerospace industry. Casting has often been replaced by hot and cold metal working operations and welding, usually including an additional heat treatment. This gives components better material properties and provides components with less weight and cost but with increased strength and efficiency. This may even be true for rotating Ni- based superalloy components, and is enabled by welding methods. However, weld cracking of precipitation hardening Ni-based superalloys is a serious problem, both in manufacturing and overhaul since it endangers component life if cracks are allowed to propagate.
Cracks can appear in a weld and in it's surroundings. The triggering mechanisms depend on its location and when it is nucleated. Generally saying, weld cracking in precipitation hardening Ni-based superalloys consists of two different types of cracking, hot cracking and warm cracking which may be further divided into heat affected zone (HAZ) liquation cracking, solidification cracking and strain age cracking, respectively.
Finite element simulations of welding and heat treatment processes started in the seventies for small laboratory set-up cases and have today matured, and are now used on large-scale structures like aerospace components. But FE-based crack criteria that can predict the risk of cracking due to welding or heat treatments are rare. In a recent study both hot cracking and warm cracking have been investigated in Ni-based superalloys, and two FE-based indicators showing the risk of hot and warm cracks have been proposed. The objective of the investigation presented in this paper is to compare results from FE-simulations with experimental results from weldability tests, like the Varestraint test and the high temperature mechanical Gleeble test.

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Keywords: FEM; crack; indicator; superalloys

* Corresponding author. Tel.: +46-920-49-3433; fax: +46-920-49-1399.
E-mail address: Jonas.Edberg@ltu.se

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1. Introduction

Previously, no FE-based crack criteria, which can be used to predict cracking due to welding or heat treatment in precipitation hardening superalloys such as Alloy 718 have been available to the aerospace industry.

Cracking occurs during welding operation (hot cracking) [2, 3, 4], during the post weld heat treatment (warm cracking) [5, 6] or when carrying out repair work (hot cracking and/or warm cracking) [7]. It goes without saying that there is a strong desire to eliminate all cracking by proper and predictive process control.

Generally, it is accepted that cracking in precipitation hardening superalloys is due to stresses developed by shrinkage during solidification and cooling in association with re-precipitation of secondary phases, like the γ' phase during the cooling. Liquation of grain boundary constituents reduces ductility to almost zero and consequently even moderate stresses will cause cracking [8]. In a recent study [1], both hot cracking and warm cracking have been investigated in Ni-based superalloys, and two FE-based indicators showing the risk of hot and warm cracks have been proposed. These have been implemented in to the commercial finite element code MSC Marc and can be useful for designing weld and heat treatment procedures, with the aid of thermo-metallurgical-mechanical simulations. This would enable the manufacturer to avoid some of the time and cost consuming trial and error investigations and problem solving that are necessary today.

2. Theoretical analysis

A detailed description of the warm and the hot crack indicator can be found in [1]. The implemented hot crack criteria is based on the following assumptions:

- The material cannot carry any tensile stress above the coherent temperature.
- Cracks cannot form at temperatures above the coherent temperature.
- The material cannot carry any real load above the solidus temperature.
- Cracks form above the solidus temperature.
- Cracks only form when the temperature is decreasing.

Hot cracks will form if the material is subjected to plastic deformation within a critical temperature interval. The boundaries for this temperature interval are (in theory) the coherent temperature and the solidus temperature. In practice these temperatures are evaluated from crack investigations performed after a Varestaint tests. When plastic deformation reaches a critical value, then the hot crack indicator reach a value of 1.0.

The warm crack criteria are based on the idea that a material can withstand a limited amount of plastic work before a crack starts to develop. The following assumptions are made:

- The material will crack when a typical amount of plastic work is reached.
- Sensitivity to plastic deformation is temperature dependent due to metallurgical phenomena.

The plastic work is an essential contributor here. The plastic work is the effective stress times the effective plastic strain. Since plastic deformation only occurs when the yield stress is reached, the effective stress can be replaced with the current yield stress of the material. The plastic work is then multiplied with a function indicating the crack sensitivity due to metallurgical phenomena that occurs in the material. Finally the product of plastic work and the warm crack sensitivity function is summarized over all time steps in the simulation. The crack sensitivity function is evaluated from Gleeble tension tests within the temperature range of interest, so that the warm crack indicator reach the value 1.0 when warm cracks are likely to appear.

Both the value of the hot and warm crack indicator can be plotted at a specific time for the whole finite element model, or as a function of time for a selected point of interest after a successful simulation.