Analysis of Welding Residual Stress and Distortion in Large Fabricated Structures

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Introduction

Residual stresses and distortions are two of the major concerns in welded structures. The residual stresses in weld region are normally tensile and close to the material yield stress due to the shrinkage of the weld on cooling. Welding residual stresses not only cause distortion but also significantly affect the performance of welded structures specially for the failures occurring under low applied stresses such as brittle fracture, fatigue, and stress corrosion cracking. Welding induced distortion in large fabricated structures requires costly post-weld treatment such as machining or straightening.

Thermal-mechanical FEA of the welding process is an emerging and rapidly maturing technique. Computer aided design of the welding process is becoming an efficient and effective approach to achieve high quality weld products with reduced residual stress and distortion. A robust simulation package, Virtual Fabrication Technology (VFT^{TM}), has been developed by Caterpillar Inc. in collaboration with Battelle Memorial Institute to predict welding distortion and residual stress in large fabricated structures. Due to its accuracy and computation speed, VFT^{TM} has been routinely applied in welding process and product design in Caterpillar.

Procedure

Welding simulation in VFT^{TM} was done by sequentially coupling thermal and stress analysis. Either numerical or analytical solution can be taken for thermal analysis. Numerical solution is the commonly used approach in FEA thermal-mechanical analysis. However, it requires extensive manpower and computer resources to analyze large and complex weld structures. Analytical based thermal solution has been used in most cases for large structures. ABAQUS was used as a solver for the structural portion in weld residual stress analysis.

Among the codes and techniques in VFT^{TM}, Comprehensive Thermal Solution Procedure (CTSP) and UMAT-CAT for structural analysis have provided VFT^{TM} with unique and competitive advantages in welding simulation for large fabricated structures. CTSP is a high-speed analytical solution procedure used to obtain the temperature vs. time history in the structure being welded. In UMAT-CAT, the user material subroutine developed for welding simulation has taken the unique features into account. These features include material history annihilation (memory loss), melting effects, and temperature dependent material properties.

Results and Discussion

Traditional manufacturing processes were mainly established from trial-and-error experiments. Such trial-and-error procedure requires tremendous material, energy, labors, as well as produces significant waste, fumes and emissions. VFT™ on the other hand provides a paradigm-shift solution. Based on science and physics, VFT™ simulates an actual manufacturing process, thus the tests can be performed inside computer without resource waste and hazardous environment impact.

In the past 4 years, VFT™ has been applied in more than 20 large welded structures in Caterpillar to optimize manufacturing processes to achieve high performance product design. For example, the original design of 160H motor grader drawbar would use a steel plate thicker than the needed. To meet the design flatness criteria ($\pm$0.75 mm), straightening and machining processes have to be used to correct the significant distortions after welding. In order to design a more efficient process, more than 5 drawbars have to be tested and scraped in the shop before a possible process could be established, even not optimized though. Design and optimization using VFT™, on the other hand, allows engineer to reach optimized design much more efficiently and without hazardous impact to the environment. VFT™ was applied to design welding process using pre-cambering and optimized sequence, and weld fixture design. The simulation results using VFT™ was used in real manufacturing of drawbar and demonstrated “do it right at first time”. In addition, the original under-designed weld fixture, which otherwise had been scraped, was modified and reused based on the systematic simulation approach in VFT™. In the single practice for 160H drawbar, the design circle was reduced from 6 months to one month with cost avoidance of more than US$0.5M and eliminates associated waste, fumes and emissions.

VFT™ establishes a virtual design and manufacturing environment, which offers multi-million dollars benefit annually through avoidance of capital investment by eliminating unnecessary operations, such as machining center for large structure, cost avoidance in fixture design and rework, reduced cost of operation, reduced scrap and consumables and energy, as well as market benefits through product differentiation.

Conclusions

VFT™ uses computer modeling to predict the responses of fabricated structure, including distortion and residual stresses from welding processes. VFT™ has been developed based on science and physics and it provides a virtual environment for design and tests that were previously conducted in iron in shop. Welding induced residual stress and distortion in large fabricated structures can be reduced by optimized welding procedure based on simulation results. VFT™ is a generic manufacturing simulation tool, which can be diffused into other industries for similar benefits such as shipbuilding, automotives, nuclear piping, aerospace, railway and bridge construction, where metal fabrication play key role in the manufacturing.