Modeling of Friction Stir Welding Process for Fusion Energy Applications --

G. Aramayo, B. Radhakrishnan, S. A. David, G. Sarma and S. S. Babu (Oak Ridge National Laboratory)

OBJECTIVE

The objective of the research is to develop a process model for friction stir welding (FSW) to address the issues of coupling between the geometry of the welding tool, heat generation and plastic flow of the material, and the evolution of the material microstructure under the complex thermomechanical loading conditions experienced during welding In particular, the model will be applied to conduct parametric studies on the effect of process parameters and tool speed on the resulting temperature and strain distributions. The model will be applied to investigate optimum process parameters for fusion reactor materials, such as vanadium alloys and dispersion strengthened steels.

SUMMARY

The flow field in the work-piece in the vicinity of the tool during friction stir welding is modeled using two different approaches. In the first approach both the tool and the work-piece are modeled together using an arbitrary Eulerian Lagrangian (ALE) technique. In the second approach the work-piece is modeled separately assuming that it behaves like a viscous fluid. The current limitations in the analysis code DYNA are discussed, and preliminary computational results of flow modeling are presented.

INTRODUCTION

Vanadium alloys are excellent candidate materials for the fusion reactor first wall and the blanket structure due to their inherent low irradiation-induced activity, good mechanical properties, good compatibility with lithium, high thermal conductivity and good resistance to irradiation induced swelling and damage. Fabrication of large vanadium alloy structures for fusion reactor applications requires joining technologies without degrading the above properties. However, for joining technologies such as arc welding, electron beam welding and laser welding processes, the reactive nature of vanadium alloys leads to dissolution of oxygen and hydrogen into the liquid during welding that remain trapped as interstitial solid solution elements. This interstitial solid solution leads to embrittlement of the welds. Although techniques have been recently established to weld vanadium alloys in controlled atmosphere, there is no identified field welding technique for these alloys. Therefore, there is a need to explore an alternate joining technique.

Another potential problem related to fusion reactor materials is the repair welding of structural materials that have undergone excessive radiation damage. This damaged material contains helium bubbles. During arc welding, these bubbles coalesce at weld metal and heat-affected zone grain boundaries, due to stress and temperature gradients. This phenomenon leads to heat-affected-zone intergranular cracking and weld metal cracking. According to the current knowledge, the maximum allowable helium content in structural alloys is limited to ~ 1 appm in order to prevent micro-cracking during arc welding. This severely restricts the maximum allowable fluence for critical components such as the vacuum vessel. Therefore, alternative joining processes need to be considered to eliminate this problem.

One alternative joining process that has great potential is Friction Stir Welding (FSW), a newly developed solid-state joining process for fabrication of butt, lap, and circumferential joints in sheet

and plate material. In this process, the weld is formed by rotating a shouldered tool, that produces sufficient heat and force to move plasticized material to the rear of the joint, creating a dense, pore-free weld zone. Since there is no melting involved in this process, dissolution of gases will be minimal. In addition, due to low diffusivity in the solid state it offers the possibility of "step-change" increase in allowable helium for joining operations.

The interaction between the weld tool geometry and the generation of temperature and flow fields in the weld material are not well understood. Specifically, it is necessary to understand the influence of tool geometry and process parameters on the formation of microstructure and the temperature history of the weld metal. The objective of the proposed research is to develop such a process model.

COMPUTATIONAL MODELING EFFORTS

During the first year of the project, the existing computational resources in the lab were used to explore the possibility of modeling the flow filed and temperature field in the vicinity of the FSW tool. The finite element package LSDYNA was used for this purpose. Two analytical approaches were chosen. The first approach was based on a three-dimensional (3D) Arbitrary Lagrangian Eulerian (ALE) hydrodynamics formulation in which the geometry and kinematics of the FSW process are modeled. The advantage of this technique is the ability to model both the workpiece and the tool simultaneously, so that not only the flow and temperature fields in the work piece but also the stresses and strains and the temperature history of the tool can be calculated. The second approach was based on a computational fluid dynamics (CFD) approach in which the workpiece is modeled as a fluid with temperature-dependent viscosity. Here, the heat-flux and velocities are provided to the tool-workpiece interface as initial conditions, without actually modeling the tool. The advantage here is that it computationally much faster to achieve the steady-state temperature and velocity fields in the workpiece than in the ALE approach.

ALE MODELLING EFFORT

The objective of the modeling effort is to capture the movement of the workpiece material form the front to the back of the rotating tool. In the current version of the analysis program there are several limitations. First, it is not possible to realistically incorporate the temperature field in the analysis of the workpiece deformation. Future versions of the code will have this capability. Therefore, in the initial phase of the research, the applicability of the ALE approach was investigated with several simplifying assumptions. The workpiece was assumed to be at a constant temperature. The material model (based on Johnson-Cook plasticity model) did not include the viscous nature of the workpiece.

The FE model of the workpiece and the tool are shown in fig. 1. In the simulations, the tool was given a rotational and a translational velocity and the velocity field in the workpiece in the vicinity of the tool was investigated. The movement of the material from the front to the back of the tool was also represented as a “volume fraction” map that shows the presence of the workpiece material in an initially void space.

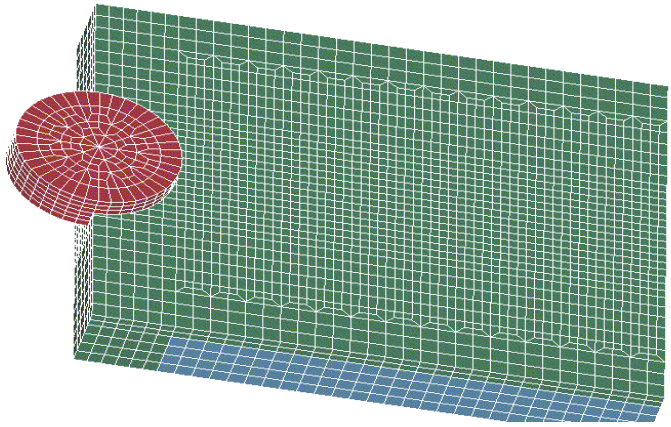

Fig1. Finite element model of the workpiece and the rotating tool.

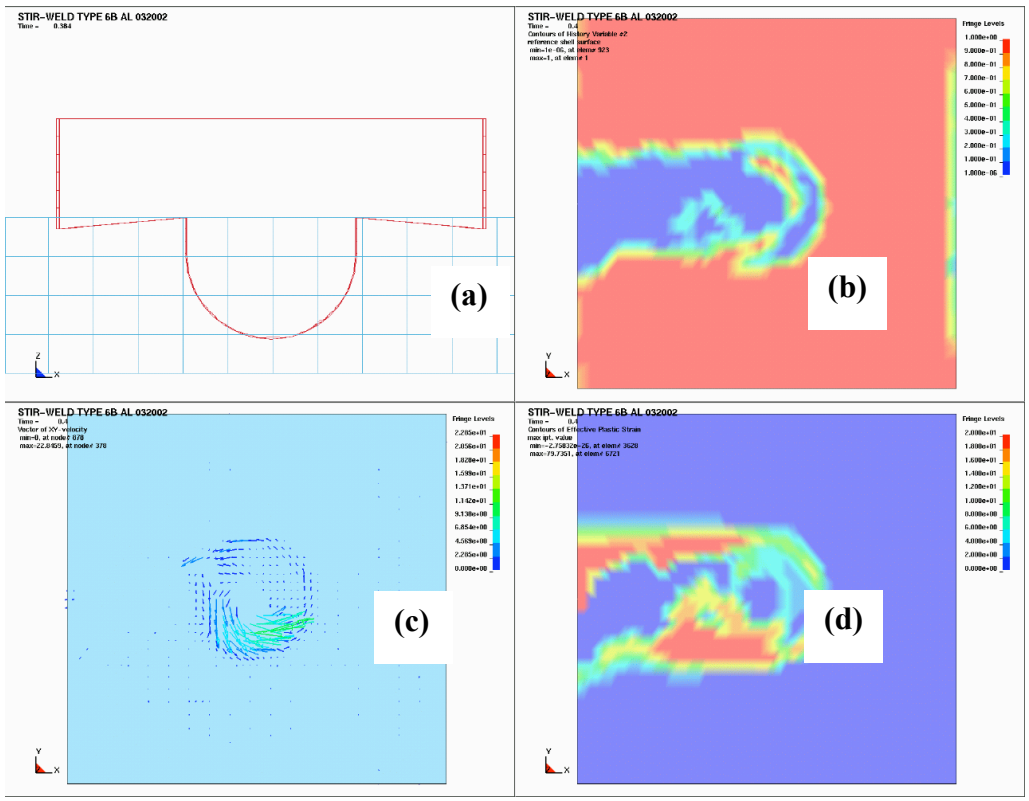

Fig. 2. Computational modeling of the FSW process using the ALE approach showing (a) position of the tool, (b) volume fraction of work piece material (red = full, blue = void), (c) velocity vectors and (d) contour of plastic strain in the workpiece material.

Fig. 2 shows a typical result from the ALE simulations that shows the location of the tool, the contours of volume fraction of workpiece material behind the rotating tool, the flow vectors and the contours of plastic strain. The current effort using the ALE approach will be expanded to real materials incorporating the temperature and flow fields when the newer versions of the analysis package become available. However, the initial results look quite encouraging and the approach is very useful in solving coupled tool-workpiece effects.

CFD MODELING

In this approach the workpiece is treated as a viscous fluid. The velocity boundary conditions are given to the interface between the tool and workpiece, while the tool itself is not explicitly modeled. The objective is to calculate the steady-state velocity and temperature fields in the work piece. Again, there is a limitation in the current CFD version that precludes coupling of the velocity and temperature fields. Therefore, simplifying assumptions were again used, with the objective of exploring the applicability of this technique for modeling FSW process. Fig.3 shows the computed steady-state velocity profile on the top surface of the workpiece when the tool is rotated and translated at the same time. The radial asymmetry in the velocity profile is a function of the ratio of rotational and translational velocities. However, the translational velocity that was used in the current simulations is very small compared to the rotational part. Therefore, significant deviations are not observed. However, the CFD approach provides a fast and efficient way to compute the effect of tool geometry and process parameters on the velocity profile in the workpiece, and will be explored further in the future.

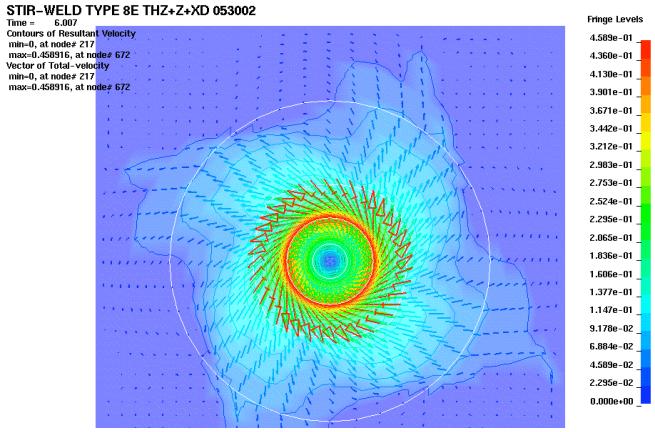

Fig. 3. Computational modeling of FSW process using CFD approach within LSDYNA showing the steady-state velocity profile in the vicinity of a rotating and translating tool.

CONCLUSIONS

The currently available FE analysis packages in the laboratory have been used to model the flow behavior of workpiece material in the vicinity of the rotating and translating FSW tool. Both the ALE and CFD packages currently available with the LSDYNA finite element package can capture the flow fields. However, there are limitations in terms of coupling the flow fields with the temperature fields generated by friction, and in using material models that incorporate temperature dependent stress-strain-strain rate and viscosity effects. Future versions of the analysis package will incorporate these features and will provide the basis for further process modeling activities in order to achieve the objectives set forth in the proposed research.