

Study patterns of microstructure formation during friction stir welding

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Abstract

Friction stir welding is a recently developed technology which is used in various branches of modern engineering. The basis of this technology is the friction of the rotating cylindrical or specially shaped tool between two metal plates brought together either to meet their ends of one above another with the overlap. When applying the FSW process in various economical sectors, the important task is to study the mechanisms and identify the physical laws and factors leading to formation of structural inhomogeneities and discontinuities in the weld seam. This paper analyzes the basic mechanisms behind the structural state generation in the material subjected to severe plastic deformation and heating. To investigate the atomic mechanisms of structural changes in FSW, the modeling at atomic scale has been carried out. Consistence between the results the simulation and experimental data has been achieved. Results of work can be a basis for new knowledge about the microstructure evolution of in FSW.

1 Introduction

Friction stir welding (FSW) is a relatively new method of obtaining non-detachable joints of materials (patented by The Welding Institute in UK (TWI), (UK) in 1991 [1]). Recent year studies have shown that FSW is an effective way to obtain high quality joints for structures of various dimensions and shapes, including sheets, 3D profile structures, and pipes. Also it was used to restore the worn parts or to modify and improve the microstructure of materials, for healing cracks and casting flaws. Possessing the broad technological capabilities for obtaining permanent joints of details or units, it can be used as an alternative to riveted joints, electric arc welding, electron beam and laser welding as well as for welding the dissimilar materials. Thus, FSW becomes a versatile technology that has a great potential in various industries [2].

When applying the FSW in different branches of economy, the important task is to study the mechanisms and identify the physical laws of a structural state generation and the factors leading to the formation of structural inhomogeneities and discontinuities in the weld seam. The aim of this work is to analyze the basic regularities and mechanisms of structural state formation in the material subjected to severe plastic deformation and elevated temperatures.

To investigate the atomic mechanisms of structural changes in FSW, the modeling at atomic scale has been carried out.

2 Experimental research

The objects of this experimental study were welds obtained by friction stir welding. Schematic illustration of the welding process is shown in Fig. 1. The microstructural evolution during FSW has been studied for different sets of FSW process parameters including those of normal operation mode which provided a quality joint and those obtained by varying the rotation rate of the tool, the feed rate and the plunge force.

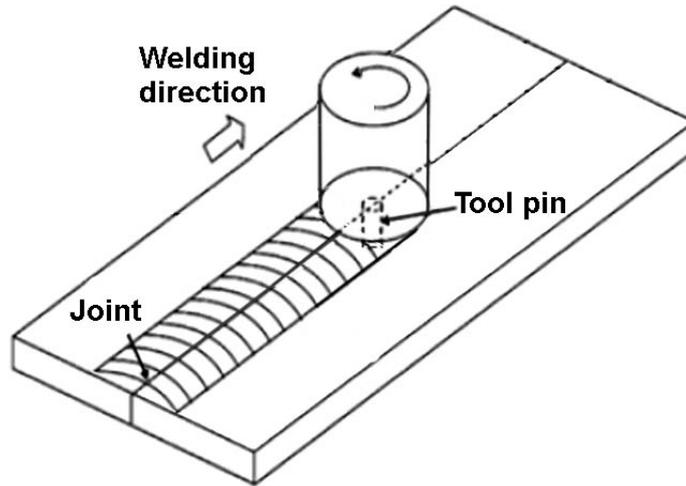


Figure 1: Schematic diagram of the FSW process

Metallographic analysis of the FSW joint macrostructure shows that the structure of the weld is generated by plastic flow and intense mass transfer of the material effected by the rotating tool. That such is true is supported by observing the vortical structures formed in the weld metal (Fig. 2) which become especially noticeable in the bottom zone of the weld near the root.

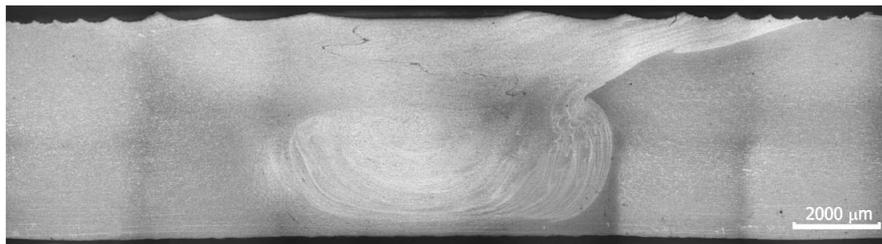


Figure 2: The cross section view of the FSW joint in aluminum sample.

More careful study of the microstructure of the weld metal clearly revealed a layered structure formed by a rotating the tool in the plasticized metal (Fig. 3). It is an alternation of metal rings, which repeat the tool geometry and being separated by the boundaries that are etched in metallographic studies.

As noted in [3], such a layered (onion) structure has been observed in the subsurface layers of ductile metals in sliding. It is generated during successive shear of thin layers when shear stress from friction force exceeds the yield strength of the material. During friction stir welding, sliding is realized between the base metal and plunged tool. Since a substantial amount of metal becomes involved in the plastic flow, we can assume that the interaction in this case is of adhesion nature. Also this is confirmed by the fact that

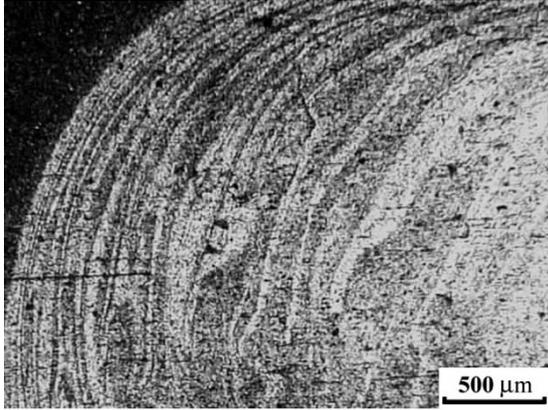


Figure 3: The layered (onion) structure of the weld metal (cross section)

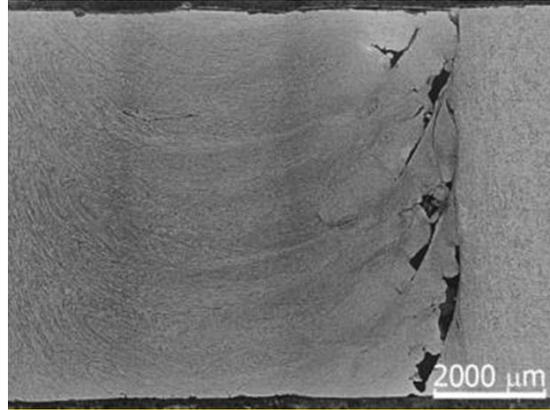


Figure 4: Void near the boundary between the nugget and base metal in the sample of aluminum alloy at high tool feed speed

aluminum sticks to the instrument during welding. Another feature of the FSW is vortical structures in the weld generated mainly owing to special form of the tool [1]. In addition, the deformation incompatibility between the weld metal and the adjacent base material is responsible for formation of such a structure in FSW. The latter is the reason behind the weld flaw generation between the base metal and the deformed layer (Fig. 4). It is especially evident on samples obtained at the process parameters different from the normal operation mode ones.

Analysis of the material deformation in sliding friction [4] indicates that the flow of metal is not by a crystallographic mechanisms and occurs as a result of mass transfer, which is characterized by the movement of fragments of different scale levels that represent the basic plastic flow carriers. According to this research, the plasticized layer has an ultrafine subgrain structure being inherent to the severely deformed material. The same fine structure has been found in the weld zone.

Thus, our investigations helped us to reveal common features between microstructural evolution in FSW seams and that of subsurface metal layers generated in sliding experiments.

3 Numerical model of the process

In order to study the implementation of possible atomic mechanisms in the loading conditions identical to those used in FSW, we carried out modeling the FSW by a rotating tool in the form of rigid cylinder that moves along the boundary between two grains. Schematic representation of the simulated sample is shown in Figure 5. The study was conducted in the framework of molecular dynamics method using the software package LAMMPS [5]. The interaction between atoms is described within the embedded atom method [6]. Modeled sample was considered as NVE ensemble that maintains the number of particles N , the occupied volume V and the energy of the system E . Velocity-Verlet integrator was used. The equations of motion were integrated with a time step $\Delta t = 0.001ps$.

The two metal crystallites' sizes (Me1 and Me2) were $10.8 \times 21.7 \times 2.9nm$. The part of atoms shaped in $3.6nm$ diameter cylinder were simulating a tool rotating at constant angular velocity ω . Also this cylinder was moved along the boundary at feeding rate V .

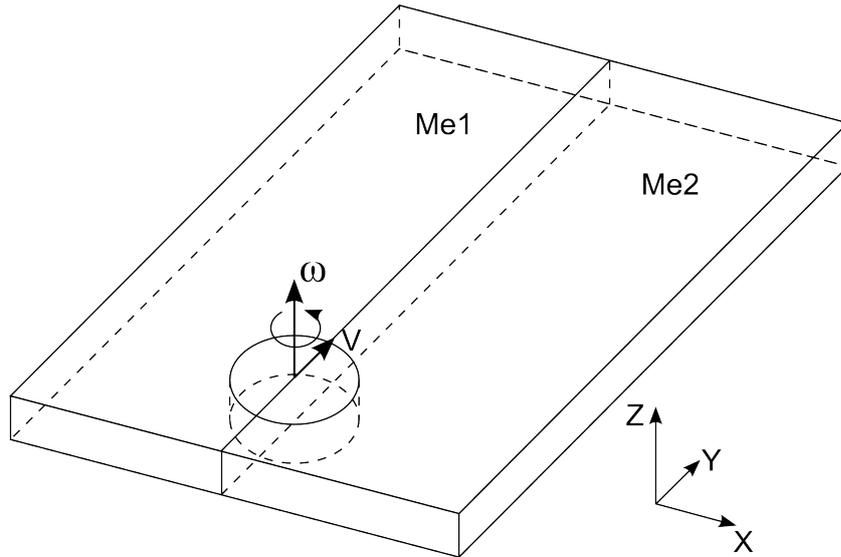


Figure 5: Schematic representation of the simulated sample.

4 The simulation results

Originally we modeled the process which reproduced at the atomic scale the loading conditions used in FSW of two ideal copper crystallites. The rotation rate and feeding rate of the tool were chosen $V = 50m/s$ and $\omega = 0,1ps^{-1}$, respectively. Heat removal from the sample was realized by introducing the artificial viscosity of atoms belonging to two buffer layers on the edges of both fragments. Periodic boundary conditions were set in all directions to account for extended sizes of the simulated sample.

Analysis of the structure of the sample showed the intermixing and stirring of dissimilar atoms as a result the FSW tool pass at the inter-crystallite boundary. Fig. 6a shows the mapping of atoms on the plane XoY for a moment of time corresponding to the working tool pass along the entire length of the boundary between two metals. Differently shaded are the gray atoms originally belonged to either Me1 or Me2 crystallites. It is seen that the trace of passing instrument consists of two parts. The area with the crystal lattice irregularities has been found directly behind the tool. Atoms of Me1 and Me2 fragments present in it in approximately equal proportions. The thickness of this area is comparable with the size of the rotating tool. When tool passes far along the boundary at a distance comparable with its diameter, there formed a region where atoms start occupy the original position of the crystal lattice due to relaxation in the nodes. The specificity of this area is the gradient distribution of atoms belonging to grains Me1 and Me2. Analysis of the crystal lattice structure by using the atomic bond local topology search algorithm [7] revealed the structural defects. However, their volume fraction relative to the total number of atoms is negligible.

By increasing the feed rate of the tool along the edge of the “trail” we can generate a number of structural defects such as nanopores with their location being identical to the results of experimental studies when FSW has been carried out with breaching the normal operation parameters. (compare Fig. 6b with 4). The results showed that the final atomic lattice structure in the weld formed after passing the tool also corresponds to fcc lattice. A distinctive feature of this “trace” is a large number of structural defects (vacancies, nanopores, dislocations and stacking faults). The event of generation of a nanopore is clearly visible in the figure above.

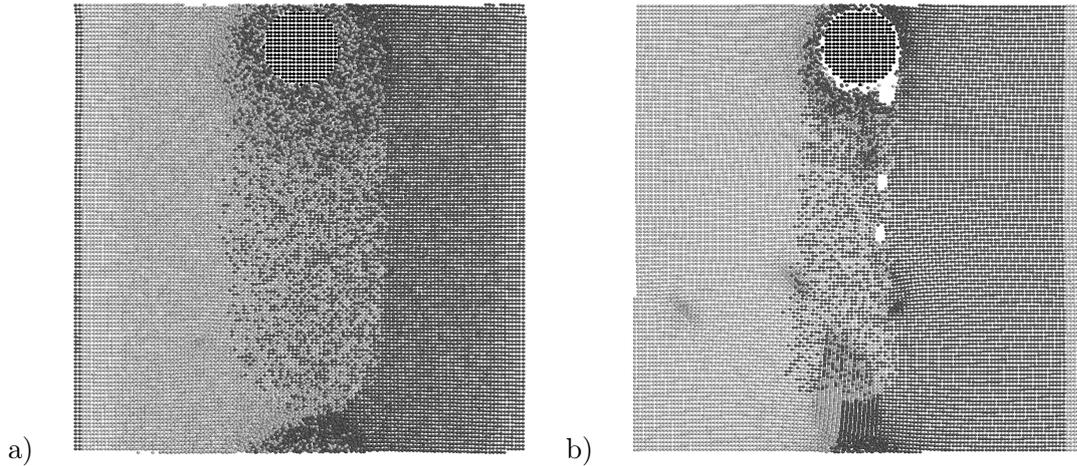


Figure 6: Projection of atoms on the plane XoY after the passage tool in conjugate pair Cu – Cu at different speeds tool: a) $50m/s$ and $\omega = 0,1ps^{-1}$; b) $100m/s$ and $\omega = 0,1ps^{-1}$.

At the next stage of the research we reproduced at the atomic scale the loading conditions used in FSW of dissimilar material crystallites such as Cu (Me1) and α -Fe (Me2). Along the Y and Z directions periodic conditions were simulated. In the X direction the hard boundary conditions were set up. As in the previous case, the interaction was computed using a model of embedded atom method. Sizes of simulated fragments of Me1 and Me2 were equal to $21,7 \times 21,7 \times 2,9nm$. Initial crystallographic orientation of both crystallites was chosen as $[100]$ $[010]$ and $[001]$ along the respective axes. Tool speed was $V = 50m/s$ and $\omega = 0,1ps^{-1}$. As before, the removal of heat from the specimen is realized by introducing an artificial viscosity of atoms belonging to the two buffer layers peripheral with respect to the plane of coupling of both crystallites.

Simulation results showed that after the passage of the rotating tool along the boundary, we can see there a complex configuration comprising the intermix of copper and iron atoms. The detailed analysis of the resultant structure showed some Cu-atoms substituted Fe ones in the α -Fe bcc lattice in the vicinity of initial joint interface and vice versa iron atoms substituted copper ones in the fcc lattice.

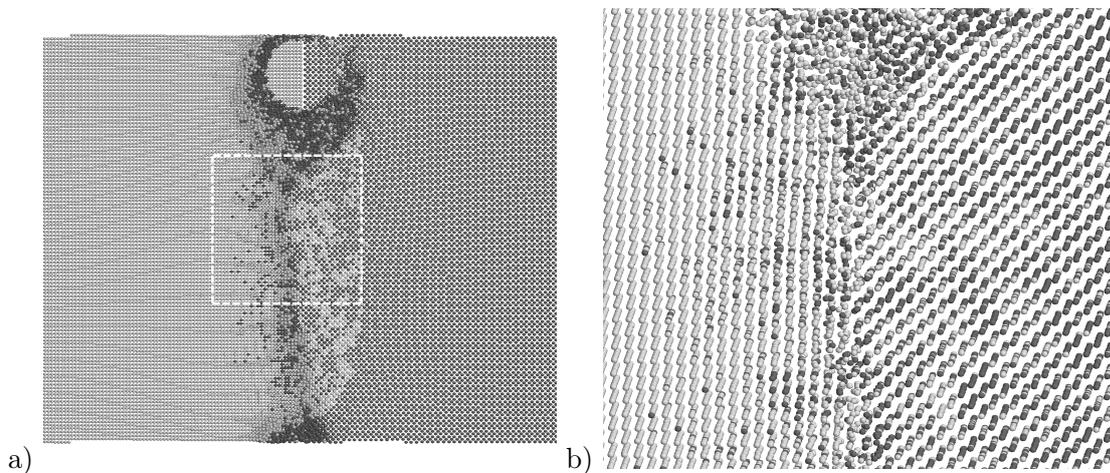


Figure 7: Projection of atoms on the plane XoY after the passage tool in conjugate pair Cu – α -Fe. Image (b) corresponds to the fragment framed in (a).

As previously, the gradient character of atom substitution zone in both metals has been observed but the width of this zone is less in comparison with the results obtained for the Cu–Cu interface. This can be explained by the differences in crystal lattice structures. This also explains the presence of numerous structural defects along the boundary obtained after passing the instrument.

5 Conclusions

On the basis of the research results the conclusions can be made as follows. In spite of the fundamental differences in characteristic spatial and temporal parameters, computer simulation results are in good qualitative agreement with those of experimental studies. Computer model may be a test bed serving for better understanding the basic laws of structural inhomogeneity origin in FSW. The simulation results obtained can be those of practical importance. They allow to discover new ways and mechanisms to obtain non-equilibrium states in the crystal lattice due to the initiation of the mechanically activated metal interdiffusion at the atomic level.

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