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Influence of Vibrational Treatment on Thermomechanical Response of Material under Conditions Identical to Friction Stir Welding

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Abstract. A molecular dynamics model was constructed to describe material loading on the atomic scale by the mode identical to friction stir welding. It was shown that additional vibration applied to the tool during the loading mode provides specified intensity values and continuous thermomechanical action during welding. An increase in additional vibration intensity causes an increase both in the force acting on the workpiece from the rotating tool and in temperature within the welded area.

INTRODUCTION

A relatively new and efficient industrial method of producing permanent joints in various structures is friction stir welding [1, 2]. It allows joining materials with strongly different chemical composition and mechanical properties. The application of additional ultrasonic treatment during friction stir welding of materials facilitates the welding process, reduces tool wear [3, 4], and improves the produced weld quality [5]. Today, there is still no comprehensive understanding of the ultrasonic treatment role in the evolution of material structure in the weld affected zone and in the dynamics of processes occurring in the friction stir welded material. Experimental investigation of these aspects is complicated due to multiple scales (spatial and temporal) and mutual influence of physical and mechanical processes occurring in the material during friction stir welding. Computer simulation methods can therefore be an effective tool for solving such problems. Previous investigation results reported elsewhere [6] show that computer simulation helps to disclose the main mass transfer mechanisms occurring in the weld zone.

In this paper, computer simulation was performed to study on the atomic scale the influence of additional vibration on intensive mass transfer in the material and thermomechanical action exerted on the material under conditions identical to friction stir welding.

COMPUTER EXPERIMENT

Calculations were carried out using a molecular dynamics method with the potentials calculated on the basis of a modified embedded atom method [7]. Loading was simulated by the motion of a rotating absolutely rigid cone-

shaped tool along the interface between two identical crystallites measured 12.2×38.9×2.1 nm (Fig. 1a). The atomic structure of the crystallites corresponded to the structure of aluminum alloy 2024. It was given by randomly replacing 5% of Al atoms in a perfect fcc lattice by Cu atoms that correspond to the intermetallic phase. The contact region had a gap to imitate the influence of roughness on the faces of the joined crystallites. The initial crystallographic orientations were [100], [010], and [001] along the corresponding axes. Rigid boundary conditions were given along the X and Y axes, and the free surfaces were directed along the Z axis. The tool consisted of iron atoms; it had a cone shape with the base diameter 4.9 nm and rotation axis parallel to the Z axis. The angular and translational velocities of the tool were $V = 50$ m/s and $\omega = 0.31$ ps^{-1}, respectively. Additional vibration was applied to the rotating tool in a coordinate axis direction and was specified by changing a corresponding coordinate of the tool rotation axis by a sinusoidal law. The angular velocity of the vibrating tool was $\omega = 3.14$ ps^{-1}. The additional vibrational on the atomic scale qualitatively corresponds to the ultrasonic treatment applied in welding of macro workpieces. The tool motion led to failure of the crystal structure and subsequent mixing of atoms at the interface between the crystallites (Fig. 1b). Heat was rejected from the workpiece by introducing artificial viscosity for atoms of all its outer surfaces. The integration step for motion equations was 0.001 ps.

SIMULATION RESULT

The mechanical action exerted on the material loaded by the mode similar to friction stir welding was studied on the atomic scale by analyzing the time dependences of the resistance force F acting on the rotating tool from the joined crystallites. These dependences (Fig. 2a) were constructed for the directions of additional vibration applied to the tool which corresponded to the coordinate axes directions (see Fig. 1). The additional vibration amplitude was 2.025 Å. Calculation results showed that the applied additional vibration causes resistance force F to grow by 10–30% compared to welding without additional vibration. The applied additional vibration leads to a slower resistance force increase with time, which indicates the possibility to control the loading force applied to the material during welding.

The mass transfer process in the simulated workpiece during friction stir welding was studied by analyzing the dependences of the atomic concentration distribution for each crystallite along the workpiece length after the tool passage. The studied weld zone is indicated by the dashed line in Fig. 1b. It was found that owing to the additional vibration applied to the tool in any of the considered directions the penetration depth of atoms from one crystallite to the opposite increases by 11–13% compared to welding without additional vibration (Fig. 2b). Note also that atoms penetrate to a larger depth in the crystallite in which the atomic motion direction during welding coincides with the translational motion direction of the tool, which agrees with experimental results [1]. Thus, the additional vibration application on the considered scale affects the weld width and, consequently, the weld strength properties.

The thermal influence exerted on the material during friction stir welding was studied by constructing two time dependences of kinetic temperature: total T_t (for the entire simulated workpiece) and local T_l (for a cylindrical region whose rotation axis coincides with the tool rotation axis and which rotates together with the tool (indicated by the dashed line in Fig. 1a)). Calculation results showed that the additional vibration applied to the tool in any of the considered directions increases the kinetic temperature in a local zone around the tool T_l (by about 50% (Fig. 3a)) and increases significantly the kinetic temperature of the entire simulated system T_t (Fig. 3b).
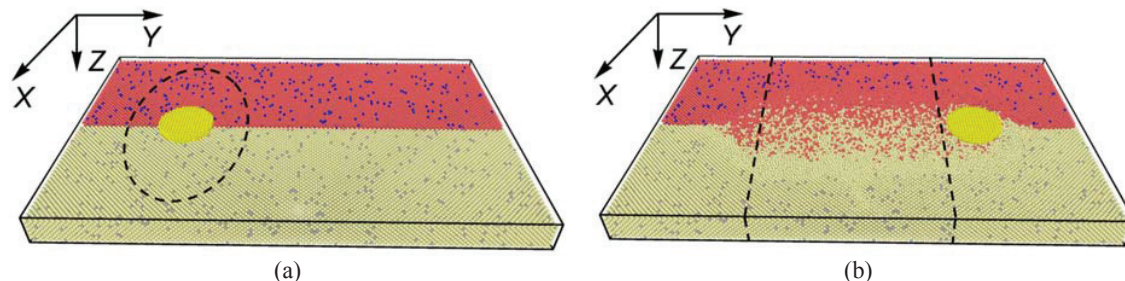

FIGURE 1. Simulated workpiece at different time points of tool motion between crystallites. Randomly distributed Cu atoms are darker colored in the both crystallites (a, b). The dashed lines indicate: dynamic zone around the tool for which local temperature T_l was calculated (a); zone in which mass transfer was studied (b)
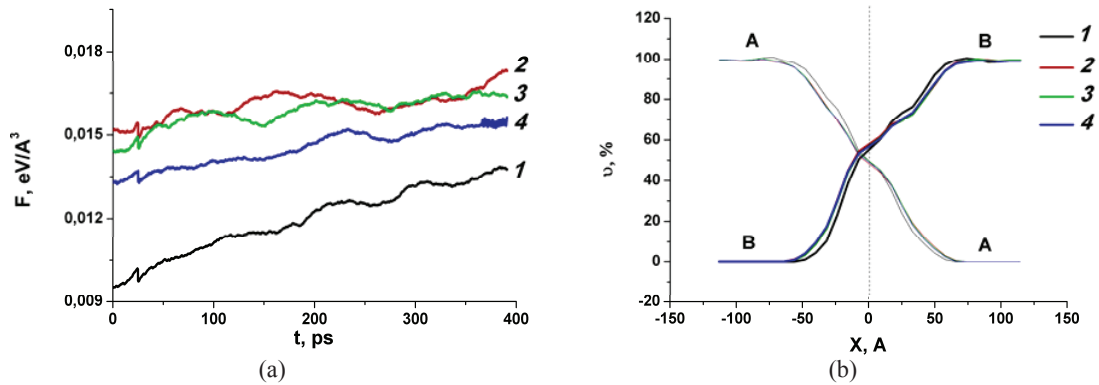
FIGURE 2. Time dependence of resistance force F acting on the rotating tool from the joined crystallites (a). Atomic distribution ν along the X axis of the simulated crystallites after tool passage. The letters A—first and B—second correspond to the joined crystallites. The dashed line indicates the initial interface between the two crystallites (b). The dependences are given for different directions of additional vibration application to the tool: *1*—without additional vibration; *2*—along the OX axis; *3*—along the OY axis; *4*—along the OZ axis

The curves in each family of the time dependences of the total and local kinetic temperature of the workpiece coincide almost completely for all the considered additional vibration application directions (Fig. 3). This suggests that the dynamics of structural defect generation and mass transfer during the simulated friction stir welding is qualitatively similar. This can be explained for the atomic scale by the similar properties of the crystal lattice in certain directions that coincide with the additional vibration application direction.

We also studied the influence of additional vibration intensity (amplitude) applied to the rotating tool on the mechanical action exerted on the material during friction stir welding. Calculations showed that an increase in the additional vibration amplitude leads to an increase in the resistance force F acting on the tool from the material (Fig. 4a). With the amplitude growth, the resistance force increase with time slows down. Analysis of the time dependences of kinetic temperature for the entire workpiece (T_t) and its local region around the tool which rotates together with the tool (T_l) showed that with the growing additional vibration amplitude the temperature growth rate first increases and then reduces to zero, reaching constant values. The higher is the additional vibration amplitude, the higher are these constant values (Fig. 4b). The additional vibration amplitude growth causes a 22% increase in the penetration depth of atoms from one crystallite to the opposite.
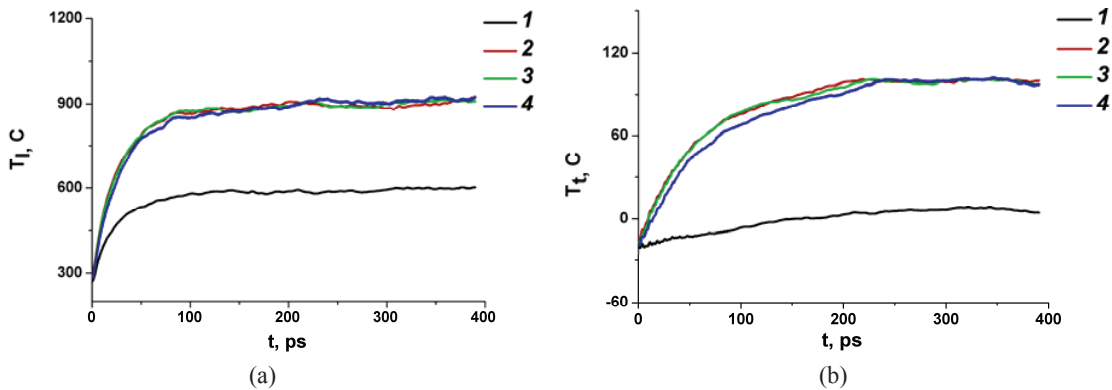

FIGURE 3. Time dependences of kinetic temperature: T_l of a local cylindrical region around the tool whose rotation axis coincides with the tool rotation axis and which rotates together with the tool (indicated by the dashed line in Fig. 1a) (a); T_t of the total simulated system (b). The dependences are represented for different directions of additional vibration application to the tool: *1*—without additional vibration; *2*—along the OX axis; *3*—along the OY axis; *4*—along the OZ axis
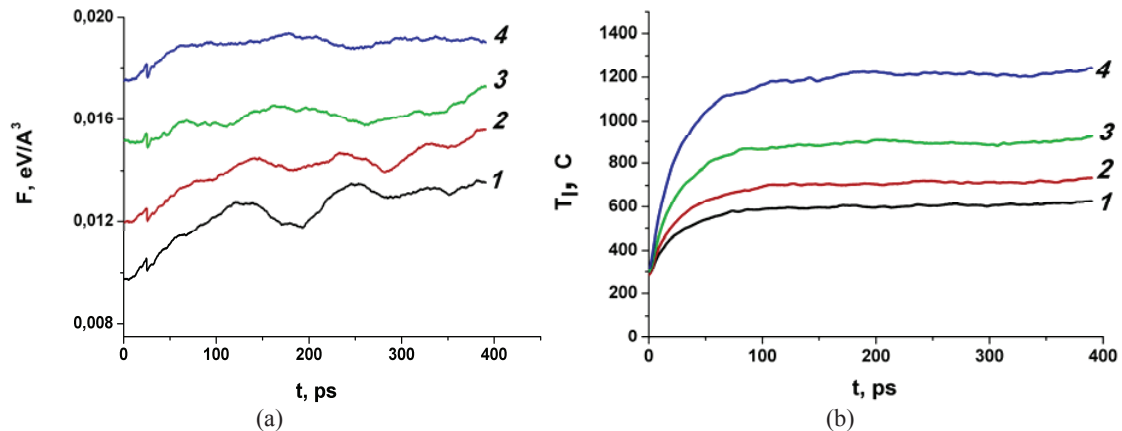
FIGURE 4. Time dependences of resistance force F acting on the rotating tool from the joined crystallites with the additional vibration applied to it (a) and kinetic temperature T_1 of a local cylindrical region around the tool whose rotation axis coincides with the tool rotation axis and which rotates together with the tool (indicated by the dashed line in Fig. 1a). The dependences are given for different additional vibration amplitude values (Am): $Am = 0.405$ (*1*), 1.215 (*2*), 2.025 (*3*), 2.835 Å (*4*)

CONCLUSION

It was shown that additional vibration of a workpiece loaded by the mode identical to friction stir welding can change the degree of thermomechanical influence on the material on the atomic scale. The intensity and continuity of this influence during the entire welding process qualitatively correspond to plastic deformation of material without melting and can be achieved by choosing different additional vibration parameters. The developed model can be used as a test system to estimate the influence of technological friction stir welding parameters on the weld geometry and its properties as well as to choose such welding conditions that would reduce the tool wear.

ACKNOWLEDGMENTS

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