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3D MODELLING OF MATERIAL FLOW IN FRICTION STIR WELDING USING MOVABLE CELLULAR AUTOMATON METHOD

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Abstract. The paper is devoted to the theoretical investigation of the peculiarities of material flow taking place in friction stir welding (FSW). The investigation was based on 3D computer simulation by the movable cellular automaton (MCA) method, which is a representative of the particle methods in mechanics of materials. Usually, material flow in FSW is simulated based on computational fluid mechanics, which assumes that the material is a continuum and does not take into account the material structure. MCA considers a material as an ensemble of bonded particles. Breaking of inter-particle bonds and formation of new bonds enables simulation of crack nucleation and healing, as well as mas mixing and microwelding. The simulation results showed that using pins of simple shape (cylinder, cone, pyramid) without shoulder results in small scattered displacements of the plasticised material in the workpiece thickness direction. Nevertheless, the optimal ratio of the longitudinal velocity to the rotational speed allows transporting of the welded material around the pin several times and producing the joint of good quality. Applying additional ultrasonic vibration to the pin may lead to better mixing of the plasticized material behind the pin.

1 INTRODUCTION

The structure of the modern materials may be very complex and have hierarchical nature starting from the nanoscale. The most of the modern materials are heterogeneous composites and may include so called soft components. One of the main properties of soft matter is its ability to change functional properties of the material which includes it. This primarily refers to heterogeneous contrast materials. The high mobility of soft matter and their low shear stiffness leads to intensive elastic energy dissipation in the system even at low applied stress.

The involvement of dissipation mechanisms induced by the redistribution of soft components results in a strong and nonlinear dependence of mechanical properties of the contrast material on the strain rate. The strain rate range where the change of the integral properties of the material occurs is determined by the time range of elastic energy dissipation and by the amplitudes of the contribution of dissipative constituents associated with the redistribution of soft components in the material volume.

The wide use of modern materials in technological and medical application causes new requirements for their joining. One of the hardest of them concerns keeping the material structure to be unchanged. A necessary requirement for the problem solving approach is the possibility to widely vary characteristic loading rates and time range of elastic energy dissipation in the material, mechanical properties of the components, and special features of the internal structure of contrast materials. These studies should be conducted in a wide range of spatial scales (from nanoscopic to macroscopic) and take into account the possibility of fracture of solid components accompanied by contact interaction of the crack surfaces and local stirring of fragments.

An important achievement of the last decades in the field of material joining is the development of friction stir welding (FSW) [1–4]. Recent studies have shown that FSW is an effective way to obtain high quality joints for structures of various dimensions and shapes. The main feature of the FSW is the ability to weld without melting of the joined materials, which allows avoiding changes in material properties due to hot temperatures and joining dissimilar alloys and materials including those that impossible to join by traditional welding technology [2, 3].

The main problem in the industrial application of FSW technology consists in finding the correct technological parameters of the process (such as the tool shape and size, rotation and travel speed, etc.) [2]. It is impossible to define the optimal technological parameters without full understanding the fundamental processes occurring in the material during FSW. The main fundamental problem here is to understand the mechanisms of severe plastic deformation that enable plastic flow, mass mixing and material coalescing behind the tool (i.e. plasticized material behaviour in FSW).

This paper is devoted to the theoretical investigation of the peculiarities of material flow taking place in FSW. The investigation was based on 3D computer simulation by the movable cellular automaton (MCA) method [5], which is a representative of the particle methods in mechanics of materials. Usually, material flow in FSW is simulated based on computational fluid mechanics, which assumes that the material is a continuum and does not take into account the material structure. MCA considers a material as an ensemble of bonded particles. Breaking of inter-particle bonds and formation of new bonds enables simulation of crack nucleation and healing, as well as mas mixing and microwelding.

2 METHOD OF MOVABLE CELLULAR AUTOMATA

MCA is a new efficient numerical method in particle mechanics that is different from methods in the traditional continuum mechanics. Within the frame of MCA, it is assumed that any material is composed of a certain amount of elementary objects (automata) which interact among each other and can move from one place to another, thereby simulating a real deformation process. The automaton motion is governed by the Newton-Euler equations:

$$\begin{cases} m_i \dfrac{d^2\mathbf{R}_i}{dt^2} = \sum\limits_{j=1}^{N_i} \mathbf{F}_{ij}^{\text{pair}} + \mathbf{F}_i^{\Omega}, \\ \hat{J}_i \dfrac{d\boldsymbol{\omega}_i}{dt^2} = \sum\limits_{j=1}^{N_i} \mathbf{M}_{ij} \end{cases} \quad (1)$$

where $\mathbf{R}_i$, $\boldsymbol{\omega}_i$, m_i and $\hat{J}_i$ are the location vector, rotation velocity vector, mass and moment of inertia of ith automaton respectively, $\mathbf{F}_{ij}^{\text{pair}}$ is the interaction force of the pair of ith and jth automata, $\mathbf{F}_i^{\Omega}$ is the volume-dependent force acting on ith automaton and depending on the interaction of its neighbours with the remaining automata. In the latter equation, $\mathbf{M}_{ij} = q_{ij}(\mathbf{n}_{ij} \times \mathbf{F}_{ij}^{\text{pair}}) + \mathbf{K}_{ij}$, here q_{ij} is the distance from the centre of ith automaton to the point of its interaction ("contact") with jth automaton, $\mathbf{n}_{ij} = (\mathbf{R}_j - \mathbf{R}_i)/r_{ij}$ is the unit vector directed from the centre of ith automaton to the jth one and r_{ij} is the distance between automata centres, $\mathbf{K}_{ij}$ is the torque caused by relative rotation of automata in the pair.

The forces acting on automata are calculated using deformation parameters, i.e. relative overlap, tangential displacement and rotation, and conventional elastic constants, i.e. shear and bulk moduli. A distinguishing feature of the MCA method is calculating of forces acting on the automata within the framework of multi-particle interaction [5], which provides for an isotropic behaviour of the simulated medium regarded as a consolidated body rather than a granular medium. Moreover, stress tensor components could be calculated for the automaton taking into account all the forces acting on the automaton [5], which enables the realization of various models of the plastic behaviour of materials developed in the frame of continuum mechanics.

A pair of elements might be considered as a virtual bistable cellular automaton, which permits simulation of fracture and cracks healing and microwelding by the MCA. In this work, a fracture criterion based on the threshold value of von Mises stress was used. A criterion based on the threshold value of plastic work was used for making a new bond between contacting automata. Switching of a pair of automata from bonded to non-bonded state and vice versa would result in a changeover in the forces acting on the elements; in particular, non-bonded automata would not resist moving away from one another.

Thus, the MCA makes a feasible simulation of solid body behaviour at different scale levels, including viscoelastic and plastic deformation, fragmentation and further interaction of fragments as a loose (granular) material [6–8].

3 DESCRIPTION OF THE MODEL

3.1 Material characterization

Here we model the process of FSW of two plates of aluminium-based alloy D16. The mechanical properties of the material were characterized by the following parameters: the shear modulus G = 27.27 GPa, the bulk modulus K = 66.67 GPa, the yield stress σ_y = 274 MPa. Plastic behaviour was simulated by linear hardening up to the strength limit σ_t =

800 MPa at the ultimate strain $\varepsilon_t = 0.15$. The automata in unbounded state switch to bounded state at the plastic work in the pair to be equal to $W_b = 50$ MJ/m^3.

3.2 Geometry of the model and scheme of loading

The geometry of the model is shown in Fig. 1. There were two plates of the dimensions 6.5×18.0 mm and the thickness 2.5 mm. Joining of the plates was performed by moving of the hard pin along axis Y. The pin also rotates with the velocity ω around its axis, which is always parallel to coordinate axis Z. Initially, the pin was placed at the distance of 6 mm from the left face.

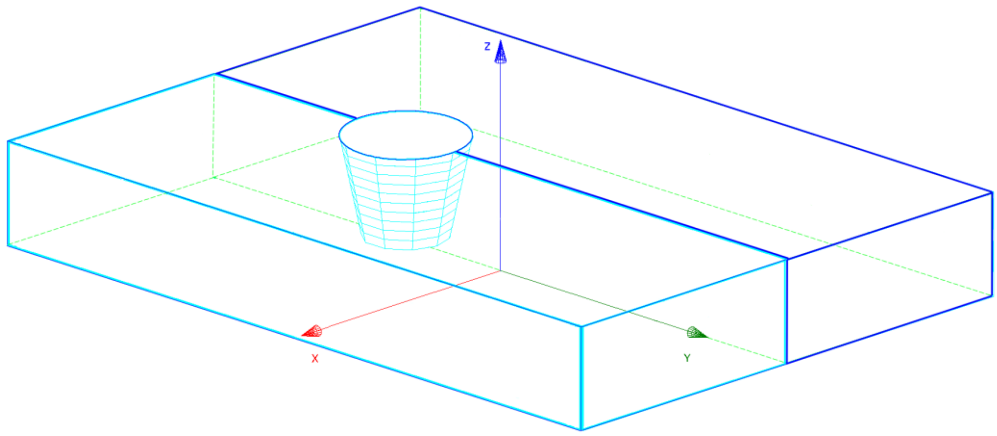

Figure 1: Initial geometry of the model

At the beginning of the joining process, the pin only rotates with the velocity $\omega = 800$ 1/s at the initial place, and its axis does not move. This preliminary stage is required for preparing plasticized zone around the pin and takes up to 5 full rotations. After that stage, the axis of the pin starts to move along axis Y with constant velocity V_t.

To simplify computations the following boundary conditions were set. To simulate the action from backing plate and pin shoulder the automata were not allowed to cross the lower and upper surface of the geometry. Unfortunately, this simplification did not account for the rotation of the pin shoulder and resulted in the size of plasticized zone smaller than one in the real process. At the other free surfaces of the plates, the automata were fixed.

3.3 A criterion for the weld quality

Behind the moving pin, the structure of the automata in the model weld region is not a periodic close packing as in the green material. The number of the bonded neighbours is not equal to the initial coordination number (12). It may be greater or less than 12. But the average number of the bonded neighbours is less than 12. The less is this number the weaker is the model weld material. To characterize the quality of the model weld we use the plot of the number of bonded automata N_l in the simulated system versus length of the pin path S. A typical picture for this plot is shown in Figure 2. A strong decrease of the bonded automata In the beginning of the pin path corresponds to the initial stage of the loading when the pin rotates and does not move. The main linear part of the plot corresponds to stable weld formation and indicates a good quality of the weld.

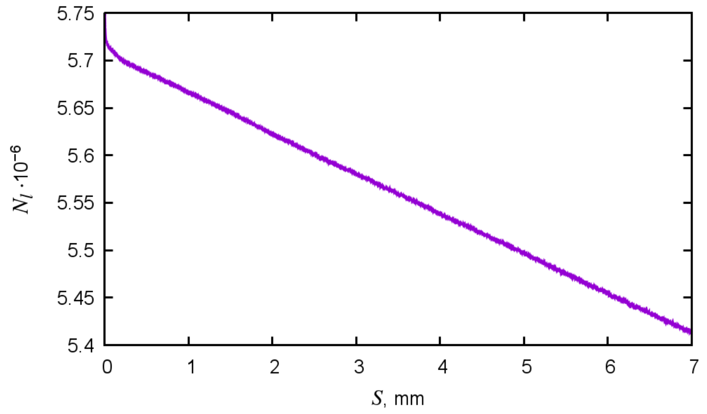

Figure 2: A plot for the number of bonded automata versus length of the pin path

4 SIMULATION RESULTS

First, let us consider the influence of the translation velocity V_t on the plot $N_l(S)$. For this purpose, the rotational velocity ω = 800 1/s was unchanged for all cases and the translation velocity was varied from 0.05 up to 0.50 m/s. The resulting plots $N_l(S)$ are shown in Figure 3. According to these results, the optimal value of V_t is equal to 0.10 m/s. The corresponding weld has the minimal number of unbounded automata and homogeneous distribution of them along the weld. The worst case corresponds to the velocity of 0.50 m/s. This simulation was aborted by the critical inhomogeneity of the weld. The results in Figure 3 also show that using of very slow translation of the pin results in the weld with the larger number of defects. These results are in very good agreements with the experimental evidence and the results of 2D simulations [2, 9].

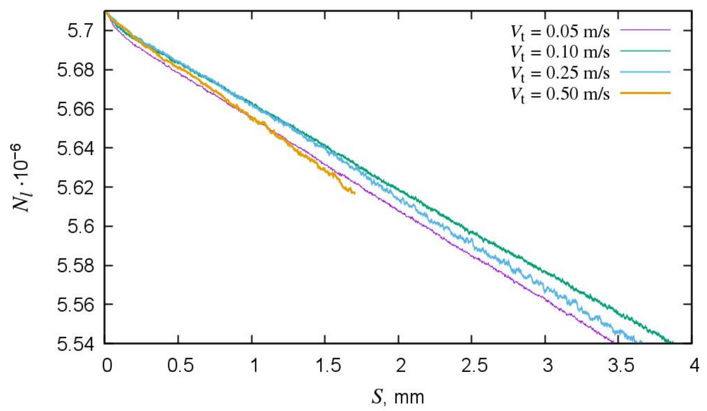

Figure 3: The plots $N_l(S)$ for different translation velocities V_t

For analysis of the influence of the pin shape on the FSW process within our model, several different pins were generated. Seven of them are shown in Figure 4. As one can see, these pins may be grouped by three basic geometrical bodies: cone, cylinder, and pyramid.

Cone and cylinder may have additional "wings" aimed to enforce material flow in the direction of the plate width (along axis *Z*).

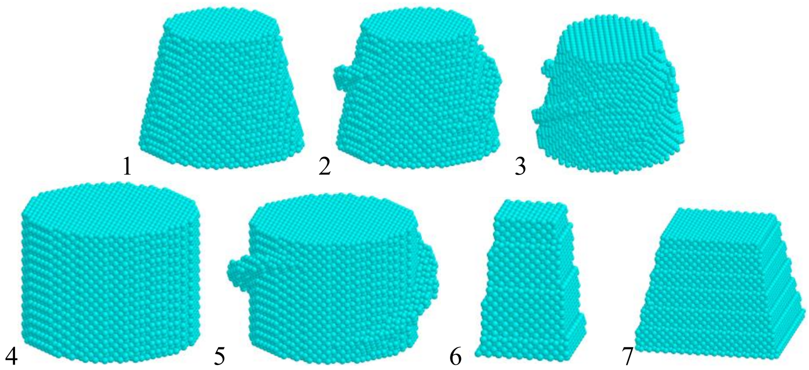

Figure 4: Seven different pin shapes used in simulations

The resulting plots $N_l(S)$ for different pin shapes are shown in Figure 5. First of all, one can see that maximal decay in the number of bonded automata occurring in the initial stage is proportional to the surface aria of the pin. However, the quality of the weld is determined by the inclination of the linear part of the curve $N_l(S)$. Therefore, the conclusion that may be drawn from the obtained results is that the best shapes for FSW pin are 2, 3, and 6 in Figure 4. From the other side, only shapes 1, 6, and 7 produce the homogeneous weld.

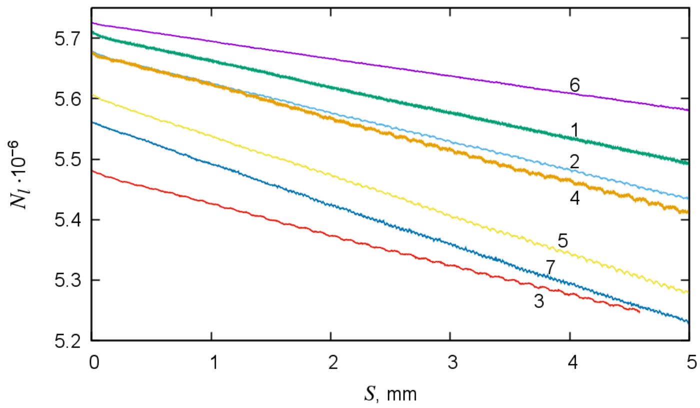

Figure 5: The plots $N_l(S)$ for different pins shown in Figure 4

The top view of the weld for the pin number 6 is shown in Figure 6. It has to be noted that the width of the weld for the pyramid is relatively wide comparing to the cone or cylinder because the width is determined by the diagonal of the square, which is the base of the pyramid, not by its side. The second important point is that this shape of the pin is not a body of revolution and hence provides better mixing of the plasticized material in the joint. But if compared with the wider pyramid (pin number 7) one may conclude that there an optimal ratio of the pyramid width and height should exist to produce the best weld.

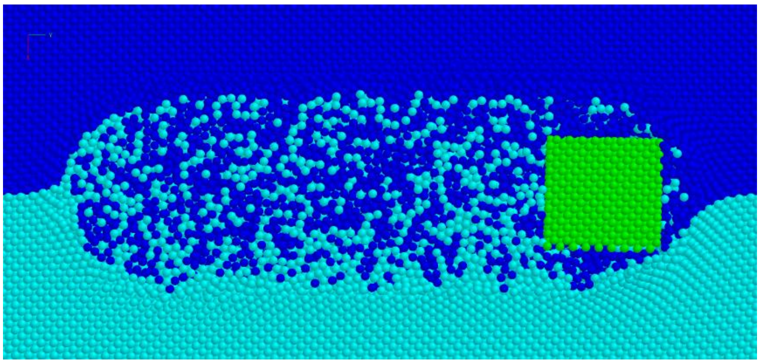

Figure 6: The top view of the weld produced by pin 4 in Figure 4

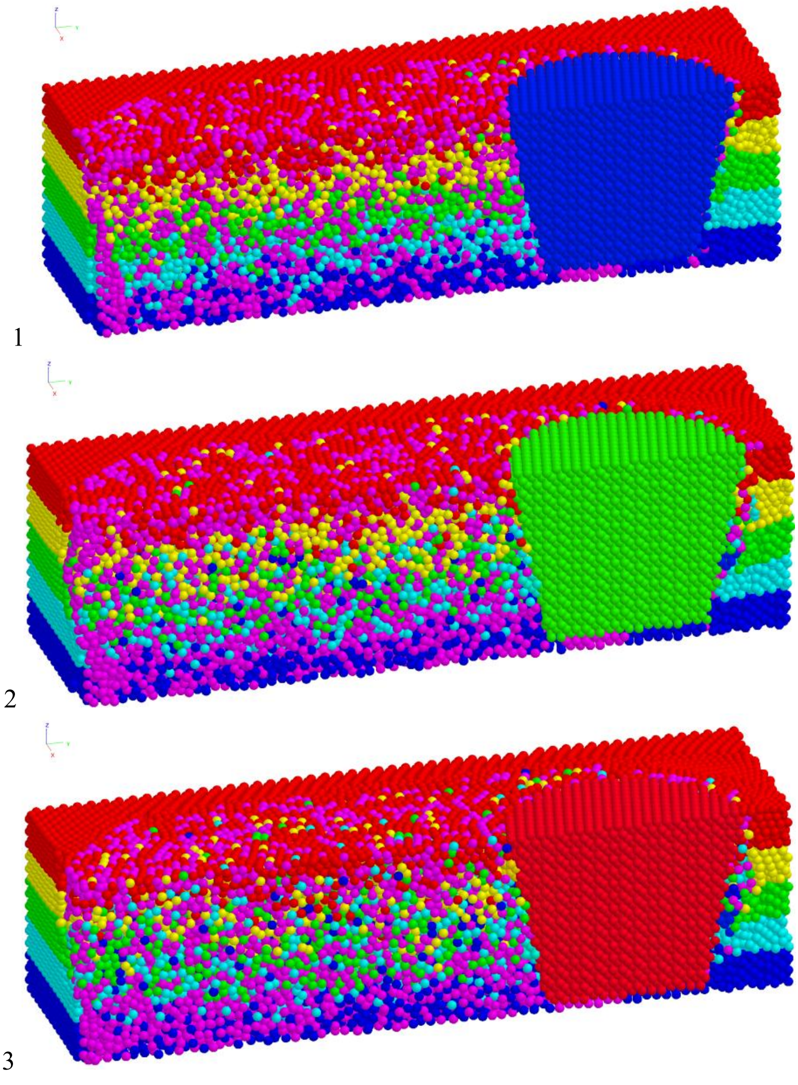

Figure 7: The top view of the weld produced by the pins 1–3 in Figure 4

To analyse the peculiarities of the material flow during friction stir welding executed by pins 2, 3 with additional “wings” the initial automata in the plates were coloured by horizontal layers (along axis Z). The final distributions of the mixed automata in the welds produced by three conical pins are shown in Figure 7. The results demonstrate no significant role of the additional “wings” on the material flow in the direction of plate width. However, it is well known from the experimental evidence that there is a marked flow in this direction in the vicinity of the pin. To explain this difference in the experiments and our modelling results we assume that the main role in the flow in the plate width direction belongs to the pin shoulder that provides a wide area of rotating material in the top of the plate and substantial gradient of rotating mass along the plate width direction.

The next interesting point in the improvement of FSW is applying additional vibrations to the pin during the joining process. In our calculations, such an action was modelled by adding to the longitudinal velocity of the pin axis motion the following value

$$V_{us}=A_{us}\sin(2\pi\nu_{us}t), \tag{2}$$

where A_{us} is the amplitude and ν_{us} is the frequency of this vibrating action in ultrasound range. We varied the direction of the vibration (along axis X or Y), the values of its amplitude and frequency. Below we will characterize the power of this action by maximal displacement of the pin per one period of vibration D_{us}, not by the amplitude of the corresponding velocity A_{us}.

The simulation results showed that additional vibration applied perpendicularly to the direction of welding produces much less effect comparing to the longitudinal direction. That is why further we will discuss the results obtained with the vibration applied along axis Y.

The plots $N_l(S)$ for different vibration frequencies are shown in Figure 8. For comparison, this figure also contains the plot for the case of no vibration. The power of the vibrations was the same D_{us} = 15 µm.

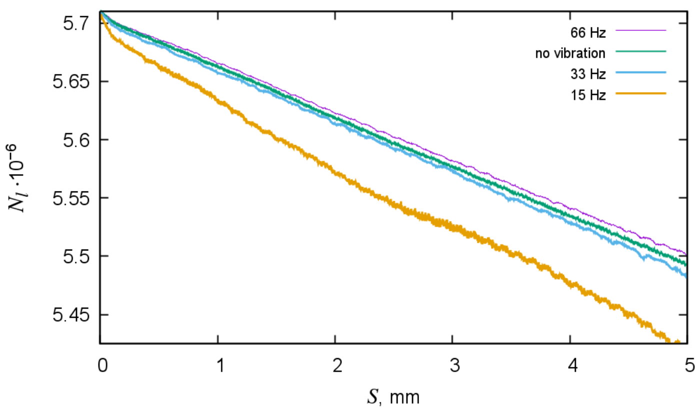

Figure 8: The plots $N_l(S)$ for different vibration frequencies ν_{us}

From the presented data one can conclude that the positive effect on the weld quality has vibrations of higher frequencies. For example, the vibration with ν_{us}= 15 Hz resulted in more defects in the weld and made the joining process to be unstable. From the other side, vibration with ν_{us}= 66 Hz allowed to enhance the weld quality. Varying of the vibration amplitude D_{us} in the range from 5 up to 100 µm showed that there was the optimal value of about 30 µm that allowed us to get the best weld characterized by the minimal inclination of the plot $N_l(S)$. The conclusion that there are the optimal parameters of ultrasound vibration which allow producing the better weld quality is also in good qualitative agreement with the results of 2D simulations [9].

5 CONCLUSIONS

A 3D model of friction stir welding based on movable cellular automaton method is presented. The obtained simulation results allow us to draw the following conclusions.

- The optimal ratio of the longitudinal velocity to the rotational speed allows transporting of the welded material around the pin several times and producing the joint of good quality.
- Using the pins of simple shape (cylinder, cone, pyramid) without a shoulder results in small scattered displacements of the plasticised material in the workpiece thickness direction.
- Applying additional ultrasonic vibration to the pin may lead to better mixing of the plasticized material behind the pin.

6 ACKNOWLEDGMENTS

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