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THEORETICAL STUDY OF THE INFLUENCE OF TECHNOLOGICAL FRICTION STIR WELDING PARAMETERS ON WELD STRUCTURE

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Abstract. Computer simulation by the movable cellular automaton method was performed to study the dynamics of friction stir welding of duralumin plates. It is shown that the ratio of the rotation rate to the translational velocity of the rotating tool has a great influence on the quality of the welded joint. A suitably chosen ratio of these parameters combined with additional ultrasonic impact reduces considerably the porosity and the amount of microcracks in the weld.

Introduction

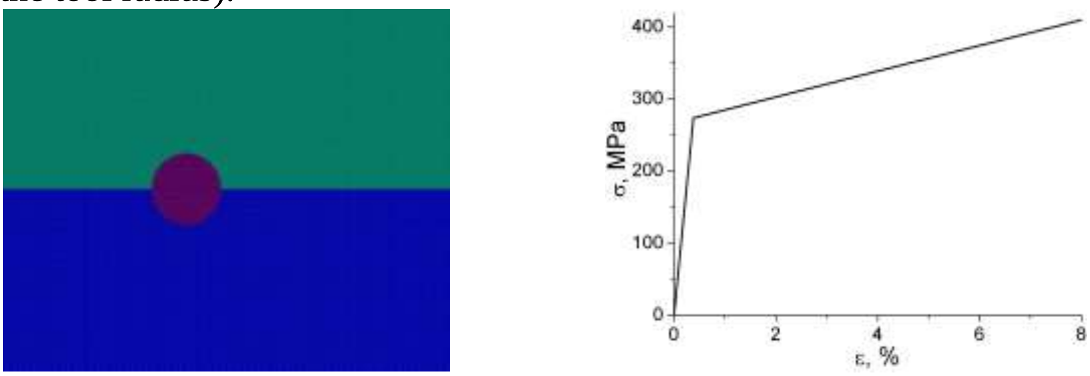
Progress in modern industry requires the development of new technologies for the production of non-detachable joints. A technological breakthrough in welding was the development and industrial implementation of the friction stir welding (FSW) technique [1], which was patented in the end of 1991 by The Welding Institute UK and found wide industrial application in the middle of the 1990s [1-4]. During FSW the welded components are joined by mixing the material of the welded edges with a special rotating tool plunged into the material and moving along the joint line [2-4]. The material mixed by the rotating tool stays within a zone limited by the tool shoulders where the weld is formed. In so doing, the welded materials are in the non-melted plastic state. The FSW technology has a number of important technological advantages. These are the absence of hot cracks, pores, possibility to join dissimilar alloys and materials (including those that were earlier considered unweldable by fusion welding) [2,3,5].

The practical application of FSW faces some serious difficulties associated with the choice of technological parameters such as the tool shape, penetration depth, rotation rate and tool speed, and so on [2,5,6]. A non-optimal choice of the FSW parameters often reduces the weld quality due to the formation of a large number of different-scale defects in the weld. As a result, the weld strength is reduced. The above FSW parameters are rather difficult to determine experimentally. Therefore it seems promising to use modern computer simulation methods to solve this problem. Since friction stir welding is accompanied by an intensive formation of damages and structural defects on different scales, by mass transfer, heating, and other processes, a discrete approach seems to be the most efficient to simulate this technology. This paper studies the dynamics of friction stir welding of duralumin plates based on computer simulation by the movable cellular automaton (MCA) method [7-8]. This method is a representative of the family of discrete element methods used to simulate the mechanical response of materials on different scales.

Problem statement

A two-dimensional structural model was developed to study the dynamics of FSW on the mesoscale within the MCA method framework (Fig. 1). The motion of a rotating absolutely rigid disc (hereinafter referred to as a working body or tool) along the interface of two metal plates (Fig. 1a) was considered. The plate dimensions were 10×25 mm. The diameter of working body was 3 mm. The working body was initially placed at a distance of 8 mm from the left lateral surface of the simulated system (Fig. 1a). This position of the tool was chosen so that to minimize the influence of the lateral faces (particularly, elastic wave reflection) on the dynamics of the FSW process.

A three-stage loading scheme was used. On the first stage the initial stress state of the system was simulated by its hydrostatic compression. This stage was necessary because we simulated a relatively small fragment of the joined materials. In this case, a large number of elastic waves can propagate in the plane of really joined plates as well as high elastic stresses can arise during the tool motion. These stresses within the considered model can be simulated by applying initial pressure. On the second stage the lateral, upper and lower faces of the simulated system were fixed, and the system was kept until the force equilibrium was reached. On the third stage the FSW process was simulated by the tool motion with translational velocity V_{trans} along the joint line between the two plates and its rotation about the disc axis with angular velocity ω (the instantaneous linear velocity of rotation on the disc surface was $V_{rot}=\omega R$, where R is the tool radius).



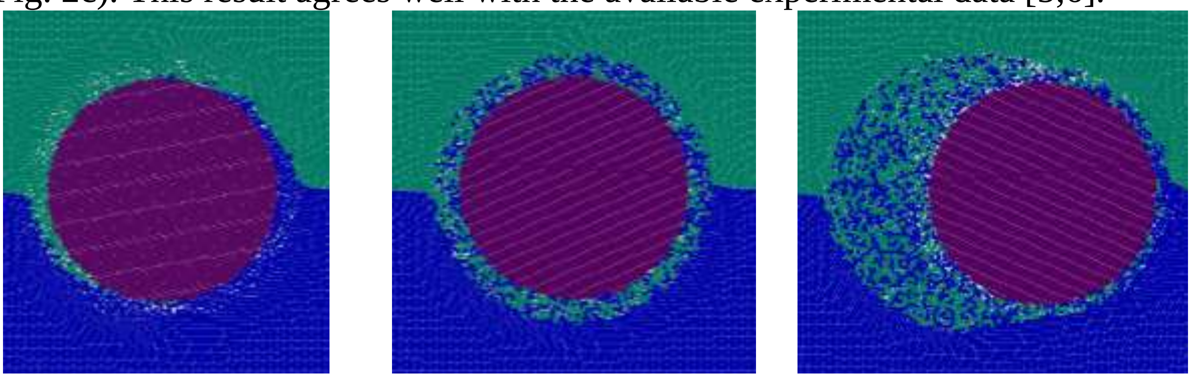
a b

Figure 1. Structure of the simulated system (a) and response function of duralumin plates (b).

The inelastic deformation of moveable cellular automata was described using the plastic flow theory with the von Mises yielding criterion [7-8]. The input parameters of moveable cellular automata within the used MCA method formalism are the elastic characteristics and uniaxial loading diagram of the simulated material which determine the response function of a moveable cellular automaton. The response function of the cellular automata that simulated the welded plates was described by the elastic-plastic loading curve with linear hardening (Fig. 1b) plotted by approximating the uniaxial tension curve of macroscopic duralumin samples. An essential advantage of the MCA method, like in all discrete element methods, is that a discrete element can change its neighborhood. This allows one to explicitly take into consideration the breaking and reformation of chemical bonds between material fragments simulated by individual elements. Bond breaking in the MCA method is simulated by switching the state of a pair of interacting discrete elements from chemically linked to unlinked state. Pairs of unlinked discrete elements can experience only contact interaction that includes the compression resistance force of a pair and dry/viscous friction force. The switching from linked to unlinked state is criterial. The MCA simulation of friction stir welding processes was conducted using a two-parameter Drucker–Prager fracture criterion. The chemical bond formation in pairs of unlinked (contacting) moveable cellular automata was also simulated using a special criterion. The criterion of new bond formation between elements was the value of work of plastic deformation.

Discussion of results

In this paper, the dynamics of friction stir welding was analyzed. The computer simulation results have shown that when the rotating tool starts to move materials of the plates adhere to the tool surface, during which fragments of matter in the contact region between the joined plates and the tool are torn off and intensively stirred (Fig. 2a). As the tool advances, materials of the plates continue to stir and the stirred material is transferred from front (region to the right from the rotating tool in Fig. 2) to back around the tool (Fig. 2b) to form the weld (Fig. 2c). It is seen from Fig. 2c that the region behind the tool includes at least two zones. Directly behind the tool is observed an area in which take place processes of mixing of the substance and which are characterized by relatively high porosity. At a distance of about 1/6 of the tool radius, starting the area in which the mixing processes are completed. This zone is characterized by a relatively uniform distribution of the welded materials. The produced weld is slightly asymmetric relative to the joint line between the plates. The width of the weld zone below the joint line is by about 7% larger than that of the upper zone (Fig. 2c). This result agrees well with the available experimental data [5,6].



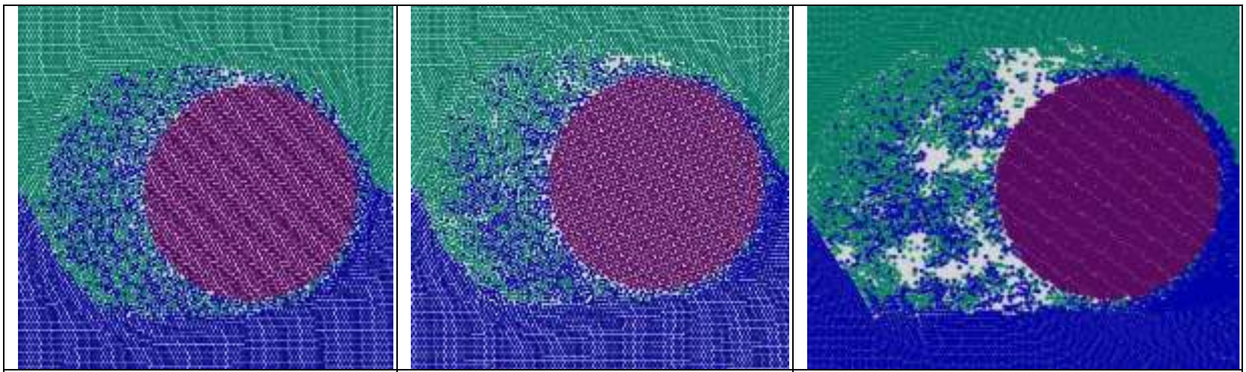
a b c

Figure 2. Structure of the material in the vicinity of the rotating tool at different points of time, V_{trans} = 0.2 m/s and V_{rot} = 7.6 m/s: t=0.0004 s (a), t=0.015 s (b), t=0.07 s (c).

Analysis of the computer simulation results showed that the weld quality, which is determined by its porosity, uniform volume distribution of welded materials, and other factors, greatly depends on the tool motion regime (on the ratio of instantaneous linear velocity of rotation on the tool surface V_{rot} to translational velocity V_{trans}). Figure 3 illustrates the structure of the produced weld for three different tool motion modes. It is seen from the figure that with the decreasing value of V_{rot}/V_{trans} (due to increasing velocity V_{trans}) the weld quality decreases. For example, at V_{rot}/V_{trans}=38 (V_{rot}=7.6 m/s, V_{trans}=0.2 m/s, Fig. 3a) the weld joint has rather low porosity (4.2 vol %, Table 1) and a small number of planar defects (microcracks). A two-fold decrease in V_{rot}/V_{trans} (V_{rot}=7.6 m/s, V_{trans}=0.4 m/s, Fig. 3b) leads to weld porosity increase (more than 1.5-fold, Table 1). In this case, the weld has a large number of long microcracks. With the further decrease in the ratio V_{rot}/V_{trans} (V_{rot}=7.6 m/s, V_{trans}=0.8 m/s, Fig. 3c) the weld loses its continuity. As one can see from Fig. 3c, the weld contains macropores and macrocracks even at a large distance from the rotating tool. The porosity value in the back region amounts to 23.4 vol % (Table 1). Consequently, the synchronization of the rotating and translational velocities of the tool is a necessary condition for producing welds with low amount of pores, microcracks, and uniform volume distribution of welded materials in the weld.

Table 1. Weld porosity versus tool motion mode.

V_{rot}/V_{trans}	Porosity, vol %
38 (V_{rot}=7.6 m/s, V_{trans}=0.2 m/s)	4.2
19 (V_{rot}=7.6 m/s, V_{trans}=0.4 m/s)	6.5
9.5 (V_{rot}=7.6 m/s, V_{trans}=0.84 m/s)	23.4



a b c

Figure 2. Structure of the produced weld: V_{trans}=0.2 m/s, V_{rot}=7.6 m/s (a); V_{trans}=0.4 m/s, V_{rot}=7.6 m/s (b); V_{trans}=0.8 m/s, V_{rot}=7.6 m/s (c).

A possible way of weld quality improvement during friction stir welding is application of additional ultrasonic impact to the rotating tool. Analysis of literature [9,10] shows that such additional treatment can increase the fatigue strength of the welded joint, provides microcrack and pore healing, and increases the weld microhardness. In this paper, we theoretically studied the influence of vibrational treatment on the welded joint properties. Ultrasonic vibration was simulated by applying, along with the translational and rotational velocities, additional sign-alternating velocity V_{us}, which is characterized by amplitude (A_{us}) and frequency (ν_{us}) of oscillation. Different values of amplitude and frequency of this ultrasonic impact were considered. Analysis of the obtained results revealed that the application of additional ultrasonic vibration to the rotating tool increases the quality (reduces porosity) of the produced weld. For all the considered vibration amplitudes and frequencies, the weld porosity is lower than in the case of welding without ultrasonic treatment (comparison data are given in Table 2). The lowest weld porosity value (1.2 vol %) was obtained at A_{us} = 6.28 m/s and ν_{us} = 33 kHz. This welding mode provided the most uniform distribution of the welded materials over the weld volume.

Table 2. Weld porosity versus ultrasonic vibration amplitude and frequency (V_{rot}=7.6 m/s and V_{trans}=0.2 m/s).

A_{us}, m/s	**ν_{us}, kHz**	**Porosity, vol %**
0	0	4.2
6.28	33	1.2
12.56	33	1.6
6.28	66	1.9
12.56	66	2.2

Conclusion

MCA computer simulation was performed to theoretically study the dynamics of friction stir welding of duralumin plates. It is shown that synchronizing the rotational and translational velocities of the tool is one of the necessary conditions for the production of welded joints with a small number of pores, microcracks, and uniform volume distribution of welded materials in the weld. The application of additional ultrasonic impact to the rotating tool reduces the weld porosity without significant increase in the weld width.

Acknowledgments

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