Two dimensional Coupled Eulerian Lagrangian (CEL) model for banded structure prediction in friction stir welding with trigonal tool

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Two Dimensional Coupled Eulerian Lagrangian (CEL) Model For Banded Structure Prediction In Friction Stir Welding With Trigonal Tool.

A. Tongne[1,a)], H. Robe[1,2], C. Desrayaud[3], M. Jahazi[4], E. Feulvarch[1,b)]

[1] *Univ Lyon, ENISE, LTDS, UMR 5513 CNRS, 58 rue Jean Parot, 42023 Saint-Etienne cedex 02, France*
[2] *TRA-C industrie, ZAC des Olmes, 69490 Les Olmes, France*
[3] *École des Mines de Saint-Etienne, LGF UMR 5307 CNRS, 158 Cours Fauriel, 42023 Saint-Etienne, France*
[4] *École de Technologie Supérieure, 1100 Rue Notre-Dame Ouest, Montréal, QC H3C 1K3, Canada*

[a)] Corresponding author: a.tongne@gmail.com
[b)] eric.feulvarch@enise.fr

Abstract. A finite element model has been developed by means of a coupled Eulerian-Lagrangian approach. The banded structure which is related to the periodical material deposition is predicted in two dimensions as the experimental investigation shows that, during FSW with trigonal tool, the material flow operates mainly in the welded plates plan.

INTRODUCTION

A banded structure observed in FSW welds which is called onion rings in transversal section is related to the periodical material layer deposition as reported by [1]. For cylindrical tools as well as threaded ones, the periodicity is equal to the tool rotation periodicity whereas for polygonal tool as trigonal one, it is equal to the tool rotation periodicity divided by the number of the tool edges (see [2] and [3]). Therefore, the bands observed in the banded structure are very thin so that it is not exhibited in most of simulated FSW welds observed in the literature. Actually, in FSW, thermomechanical coupling, high deformation and non-linearity increase heavily the computation time. Using fine mesh in order to exhibit banded structure will blowup computation time. An alternative approach is to use analytical material flow model as proposed by Tongne et al. [2]. However, this kind of model requires a strong material flow study. Moreover for the trigonal tool, the material flow is mainly in the plan of the welded plate. The process can be therefore simulated numerically in 2D.

EXPERIMENTAL STUDY

The experimental section is based on the works of Tongne et al. [2] in which FSW process is carried out using a trigonal carbide tool. The welded material is aluminum alloy 6082-T6. Tool rotational and feed speeds are equal to 2000 rpm and 600 mm/min, respectively. The optical microscopy of the weld exhibits alternating dark and clear bands, which is referred to as banded structure, in the weld sections including the horizontal one as shown in Fig. 1. The banded structure is related to the periodical deposited material layer. The material flow is mainly two dimensional and it has been observed that banded structure did not cover the entire weld width. There is No Banded Structure Zone (NBSZ) located to the Retreating Side (RS) and Banded Structure Zone (BSZ) located to the Advancing Side (AS). Base on the numerical investigation, an answer will be given to the banded structure origin (contrast difference and position of bands) in the weld horizontal section.

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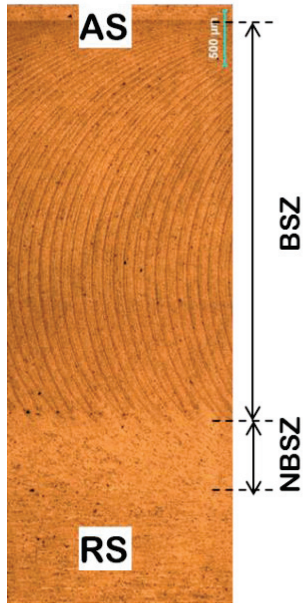


FIGURE 1. No banded structure and banded structure zones identification in the weld width

NUMERICAL STUDY

The model is developed in Abaqus/Explicit using Coupled Eulerian Lagrangian (CEL) where the rigid tool is Lagrangian body plunged into an Eulerian domain where the welded material flows. Because of the fine mesh required for describing banded structure as well as the fact that trigonal tool material flow is mainly in (x,y) plan, the model is developed in two dimensions in order to reduce computation time. However, as CEL method cannot be used in 2D, we have used 3D elements with one element in thickness and fixed the vertical velocity to zero ($V_z = 0$). The mesh refinement depends on the distance between the bands to be predicted. Ten mesh elements along this distance will give better resolution for banded structure exhibition. As the distance between bands is $600/2000/3/10 = 0.1\,mm$, the mesh size should be $0.1/10 = 0.01\,mm$. To increase this size, we have decided to use $2000\,mm/min$ as feed speed which requires $0.033\,mm$ as element size. Whoever, in the angular direction, the element size was significantly increased as bands shape is circular. The Eulerian mesh domain is initially filled by aluminum and void in which the tool is located as shown in Fig. 2.

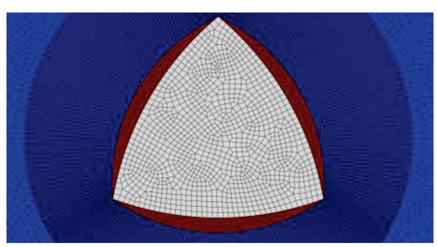


FIGURE 2. Parts configuration at the beginning of the process. Aluminum parts (blue); void zone (red) rigid tool (white).

The material behavior is the Johnson-Cook one used in [4] for AA6061-T6 where de yield stress is given by:

$$\sigma_y = \left(A + B\cdot\left(\varepsilon_{eq}^{p}\right)^{n}\right)\cdot\left(1 + C\cdot\ln\left(\frac{\dot{\varepsilon}_{eq}^{p}}{\dot{\varepsilon}_0}\right)\right)\cdot\left(1 - \left(\frac{T - T_{ref}}{T_{melt} - T_{ref}}\right)^{m}\right)$$

Where $A, B, n, m, C, T_{ref}, T_{melt}$ are material parameters given in TABLE 1. ε_{eq}^{p} and $\dot{\varepsilon}_{eq}^{p}$ are the equivalent plastic strain and strain rate, respectively. T is the temperature which is fixed to $300^{o}C$.

TABLE 1. Johnson-Cook parameters

A [MPa]	B [MPa]	n	m	C	T_{melt} [°C]	T_{ref} [°C]
324	114	0.42	134	0.002	583	24

The number of elements and nodes are 82696 and 124189, respectively. The equivalent plastic strain (ε_{eq}^{p}) and the maximal equivalent plastic strain rate ($\dot{\varepsilon}_{eqMax}^{p}$) reach by any material point are requested. To get $\dot{\varepsilon}_{eqMax}^{p}$, the evolution of $\dot{\varepsilon}_{eq}^{p}$ at material points is followed through state variable in VUSDFLD subroutine. For 0.3 s physical time, the computation time is 990 hours without parallelization. Figure 3 and Fig. 4 show the equivalent plastic strain (ε_{eq}^{p}) and the maximal equivalent plastic strain rate ($\dot{\varepsilon}_{eqMax}^{p}$), respectively. Both ε_{eq}^{p} and $\dot{\varepsilon}_{eqMax}^{p}$ clearly exhibit banded structure. Herein, the information reported in [2] that the experimental banded structure is related to $\dot{\varepsilon}_{eqMax}^{p}$ cannot be confirmed. Therefore, ratios of equivalent plastic strain and maximal equivalent plastic strain rate by their minimal value, across the bands, have been plotted in the same graph as shown in Fig. 5.

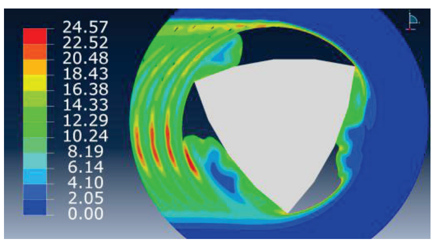


FIGURE 3. Equivalent plastic strain (ε_{eq}^{p})

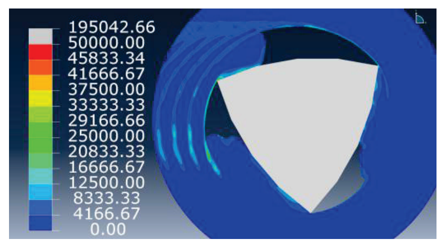


FIGURE 4. Maximal equivalent plastic strain rate ($\dot{\varepsilon}_{eqMax}^{p}$) [s^{-1}]

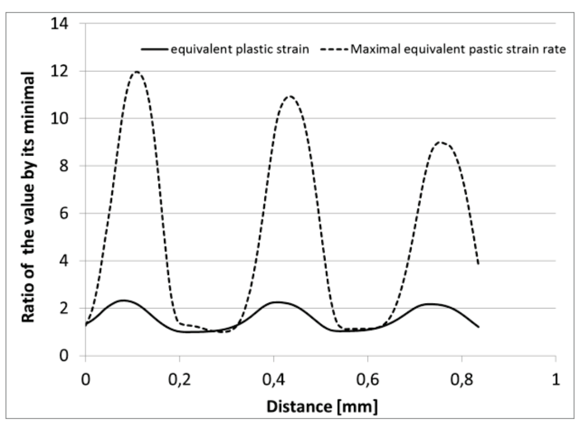
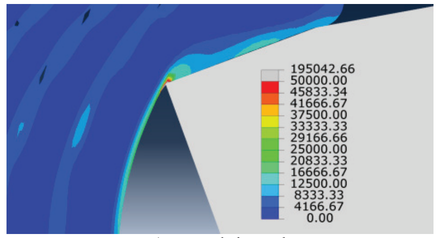


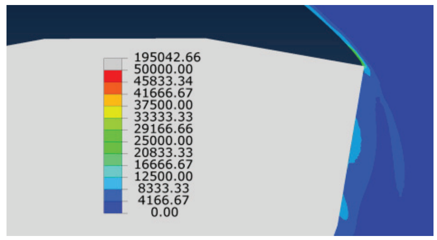
FIGURE 5. Ratio of equivalent plastic strain and maximal equivalent plastic strain rate by their minimal value, across the bands.

The maximal equivalent plastic strain rate ($\dot{\varepsilon}_{eqMax}^{p}$) ratio is very high compare to equivalent plastic strain (ε_{eq}^{p}) one. The experimental banded structure is therefore related to $\dot{\varepsilon}_{eqMax}^{p}$ as reported by [2].

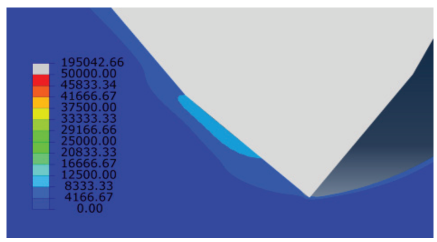
Moreover, the ratio of $\dot{\varepsilon}_{eqMax}^{p}$ reaches 12 close to the tool and decrease to 9 far from it. i.e. the gradients decrease during their convective flow. Actually, the maximal value of $\dot{\varepsilon}_{eqMax}^{p}$ shown in Fig. 4 is close to tool tip at the rear as shown in Fig. 6.a. If the strain rate at the tool tip was kept during the convective flow, the ratio should be much greater than 12 (it will be about 44). Therefore, banded structure accuracy prediction is strongly related to the mesh refinement. However, the maximal equivalent plastic strain rate at the front close to the tool tips is not as high as at the rear (see Fig. 6.b-c). This confirmed that shearing at the rear of the tool is higher than the one at the front as reported by [5].



a) tool tip at the rear



b) first tool tip at the front



c) second tool tip at the front

FIGURE 6. Zoom on the maximal equivalent plastic strain rate at the tool tips

Moreover, the banded structure in maximal equivalent plastic strain rate field (see Fig. 4) is located to the Advancing Side (AS) as on the weld optical microstructure.

CONCLUSIONS

Banded structure in the horizontal section of FSW welds are clearly related to the maximal equivalent plastic strain rate reach by material points using Coupled Eulerian Lagrangian (CEL) approach. The model shows that highest strain rates are reached at the rear close to the tool tip.

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