NUMERICAL SIMULATION AND MICROSTRUCTURE ANALYSIS OF FRICTION STIR WELDED AL 6082

CHERNIKOV Evgenii[1,a], NAUMOV Anton[1], GOLUBEV Iurii[1], MICHAILOV Vesselin[1]

[1] *Peter the Great Saint Petersburg State Polytechnic University, St. Petersburg, Russian Federation*

[a] *evgnchernikov@gmail.com*

Abstract

Strain and temperature distribution field during FSW included plunging and welding stage was simulated using licensed software Deform 3D™ with the Lagrangian Incremental formulation settings. Non-uniform temperature and strain and distribution field was observed. Developed model has a good agreement with experiment. Microstructure of friction stir weld was analyzed. Significant grain size refining was observed.

Keywords: FSW, numerical simulation, grain size.

1. INTRODUCTION)

Friction Stir Welding (FSW) (Fig 1.) was invented at The Welding Institute (TWI) of UK in 1991 as a solid-state joining technique [1]. The first steps to this invention were done in USSR in 1967, invention certificate number is №195846 [2]. FSW has a number of advantages compare to conventional welding methods such as reduced heat affected zone; porosity, hot cracks, harmful evaporation and UV emission elimination. Friction Stir Processing (FSP) is a targeted sort of FSW. During FSW an equiaxed and homogeneous microstructure with fine grain size is usually observed in the nugget zone of the weld [3]. Such type of microstructure improves mechanical properties of the weld compared to fusion welding methods. This metallurgical aspect is the conception of FSP invention as a solid state, thermo-mechanical metal processing technique. The purpose of FSP is to achieve microstructure modification by homogenization and refinement by means of severe plastic deformation in metallic alloys without welding or joining.

FSP/FSW process has 4 stages (**Fig. 1**):

1. *Plunging*. Tool with a shoulder and a pin plunges into a metal. The heat generated by frictional rubbing of tool shoulder softens the metal.
2. *Dwelling*. Required elevated temperature (lower then melting point) is achieved for subsequent metal stirring.
3. *Stirring*. After dwelling tool translates along the surface of the work piece.
4. *Pulling*. In the end of the process the tool pulls in vertical direction, in the processed material the exit hole occurs (except run-on plate or Retractable Pin options are used).

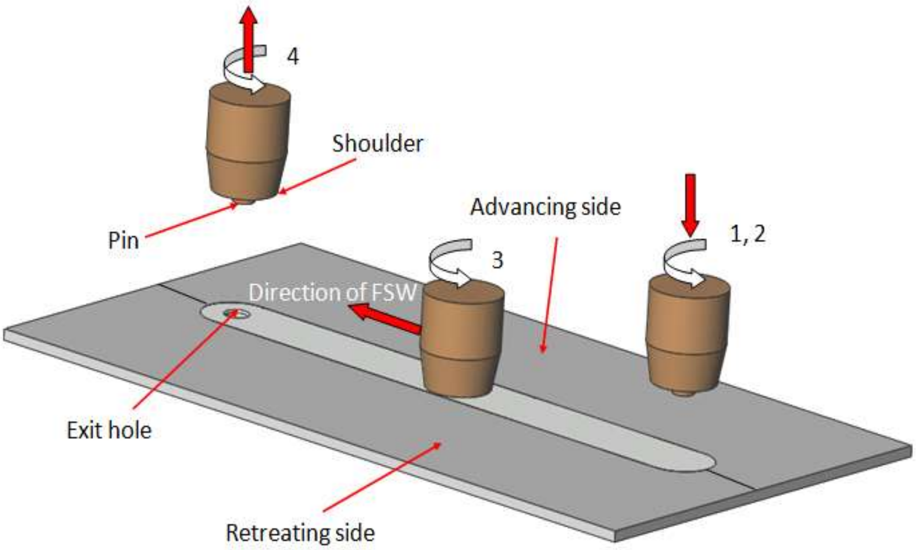


Fig.1 Principal scheme of FSW

2. FSW NUMERICAL SIMULATION

2.1 MODEL DICRIPTION

Licensed Deform 3D^{TM} software for numerical simulation of FSW/FSP plunging and welding stage with the Lagrangian Incremental formulation was used. Detailed description of numerical simulation formulation is given in [4]. Workpiece with 50x50x2 mm in dimensions was modeled as rigid-perfectly plastic material, the tool with shoulder diameter equaled 12.5 mm and pin diameter of 4.2 mm on a tip is rigid, backplate has the similar to processed plate dimensions (**Fig. 2**).

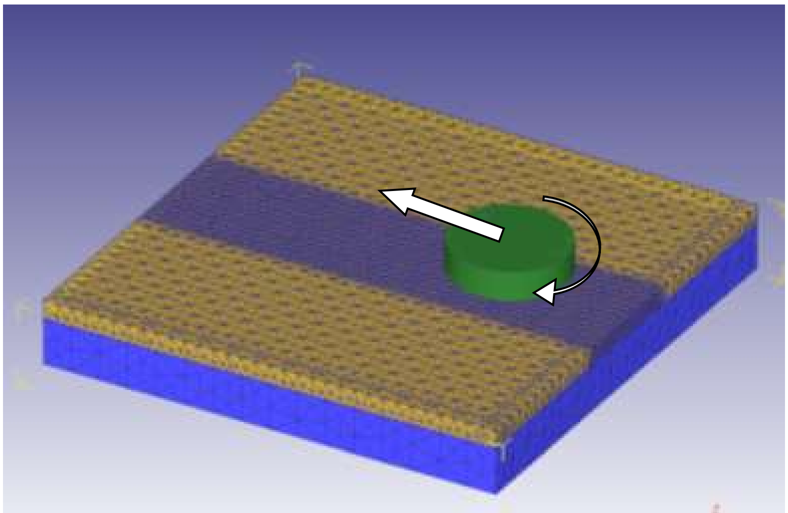
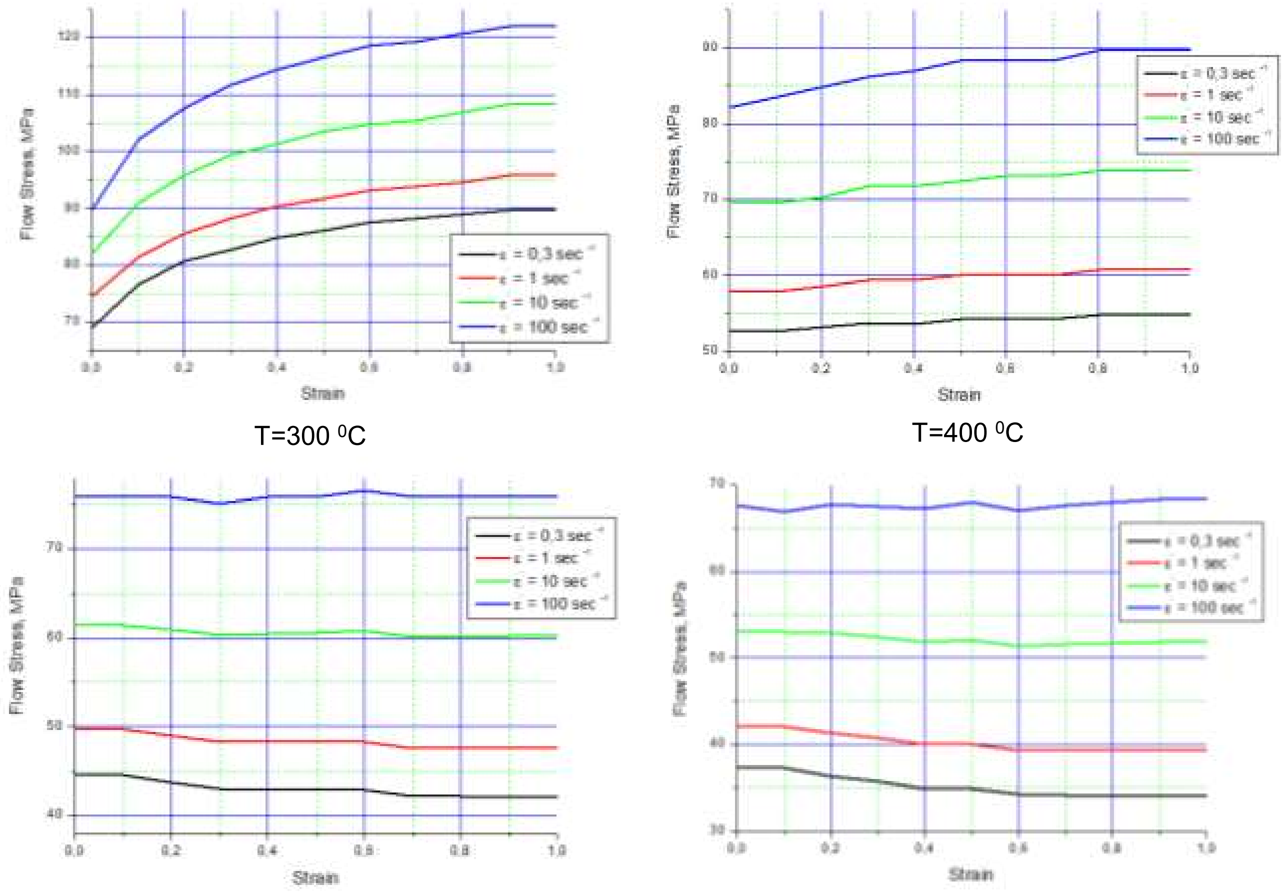


Fig.2 FSW simulation model

Process parameters such as tool rotation of 710 rpm, feed rate of 400 mm/sec, plunging rate equal 8 mm/min, tilt angle of 2^0 and sinking depth of 0.1 mm, were used. Workpiece was realized as a single plate to prevent contact instabilities during simulation [4]. Treated plate was meshed with tetrahedral elements with finer elements close to the tool (minimum edge element size was 0.4mm). Tool was also meshed with similar elements for thermal analysis. Tree sides of workpiece were fixed to prevent any displacement of the body caused by tool rotation. Materials flow stress curves (strain rate ε' = 1 – 100 sec $^{-1}$, temperature range 300-500 ^{0}C) and thermal characteristics of Aluminum 6082 from Deform 3D^{TM} database was utilized and shown on **Fig. 3**.



T=300 ^{0}C

T=400 ^{0}C

T=450 ^{0}C

T=500 ^{0}C

Fig.3 Used rheology properties of Al 6082.

No dependence in heat capacity and thermal conductivity from temperature was applied: thermal conductivity k=180 [W/m·^{0}C], heat capacity c= 2.4 [N/(mm^2·^{0}C]. For achieving welding temperature in thin plate convection coefficient of 20 [W/(m^2·°C)] was used during simulation. Contact heat transfer coefficient between tool, workpiece and backplate equal to 15 [kW/(m^2·°C] and constant shear frictional factor equal to 0.65 were used.

2.2 FSW simulation results

The maximum temperature of about 500 ^{0}C was achieved as a result of FSW numerical simulation and shown in **Fig** 4. The maximum temperature is located on the top of processed plate just behind the tool pin. It is about 0.83 from melting temperature. Non-uniform temperature distribution under the tool was obtained; it is related with the contact features: tool shoulder back part gets into contact with workpiece earlier because of tool tilt angle; FSW features as retreating and advancing sides (RS and AS respectively).

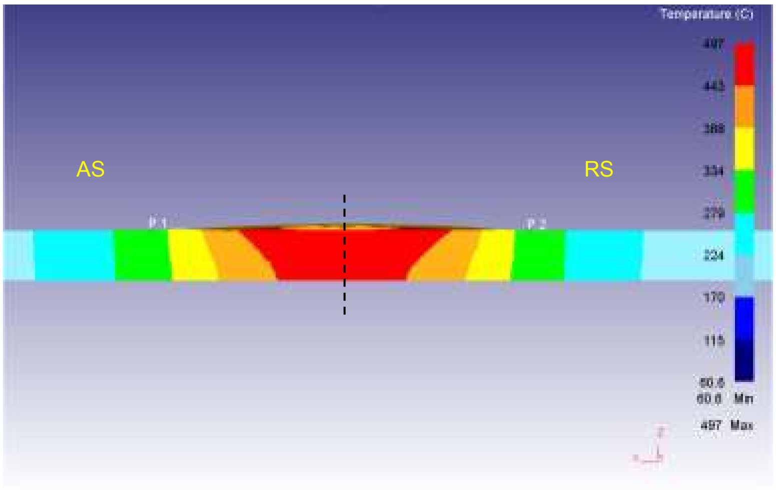


Fig.4 Temperature field (cross section view).

Non-uniform strain distribution in processed area was observed. Strain profile also has similar V-shape view and displaced to AS. Maximum strain intensity was reached on AS, it is equal to 40 and shown in **Fig.** 5. According FSW features strain field is displaced to AS.

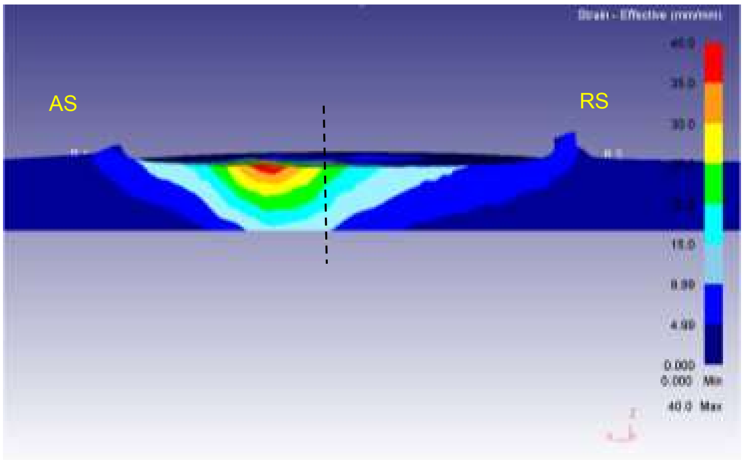


Fig.5 Strain effective distribution (cross section view behind the pin).

For validation of the simulation comparison between calculated and measured values was made based on experiment. K-type thermocuples were placed on the top surface of the welded plates in 8 mm distance from the center line. Point P1 is located at AS, P2 – at RS respectivly. Experiment shows that the temperature field also displaced to AS (**Fig.** 6). The maximum relative deviation (MRD) in the maximum calculated and measured temperatures at points P1 and P2 is 4 %.
Accordingly [5] the maximum measured temperature on the bottom surface in the center line is 450 ^{0}C for the similar FSW parameters and material thickness. The actual maximum calculated temperature for bottom surface of workpiece is 461 ^{0}C (MRD = 2.4%).

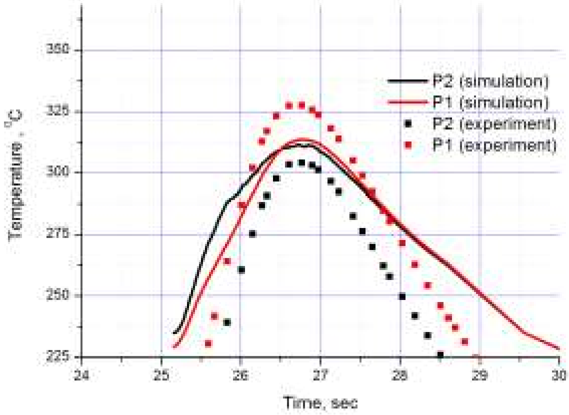
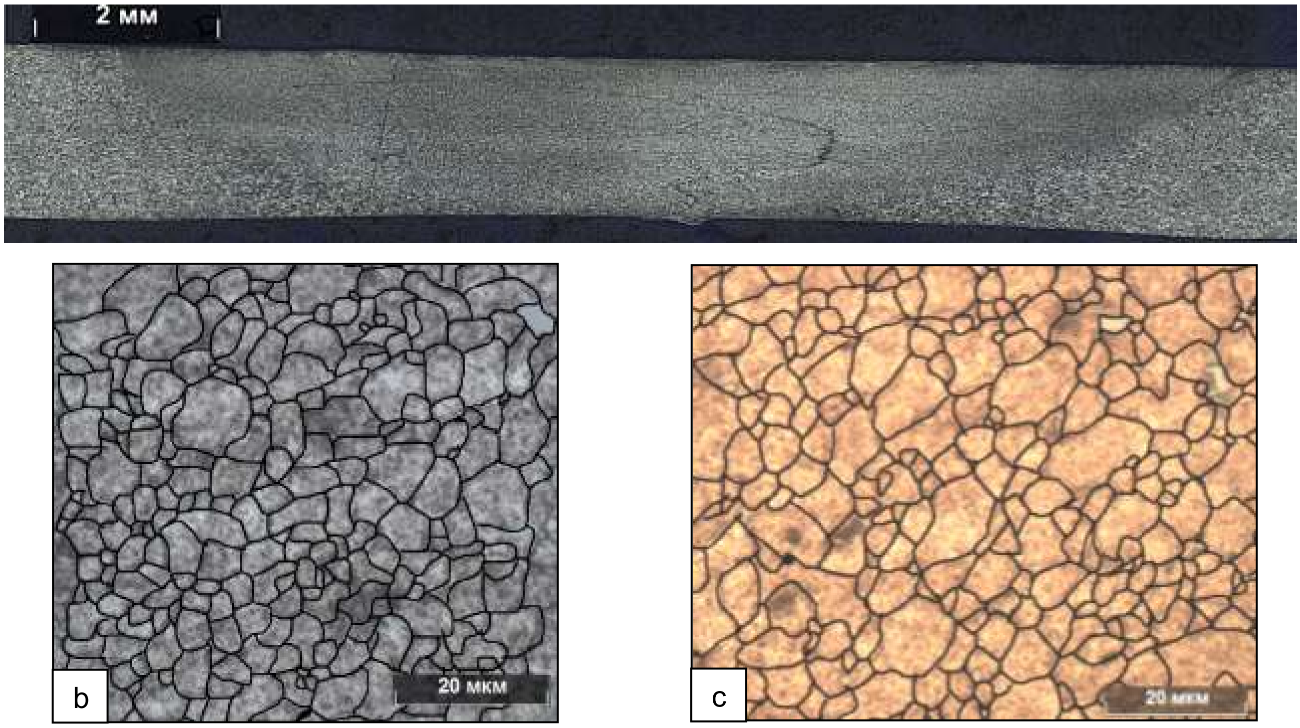


Fig.6 Measured and calculated temperature during FSW (710 rpm, 400 mm/min of WS).

3. MICROSTRUCTURE ANALISYS

Processed samples with one welding speed (WS) of 400 mm/sec and rotation speed of 710, 900, 1120 rpm were cut for microstructure analysis. Polished and etched microsections of weld were viewed by optical microscope Carl Zeiss and analyzed using Thixomet® Pro software. Parent metal, thermo-mechanical affective zone, stir zone received microstructures are shown on **Fig.** 7.



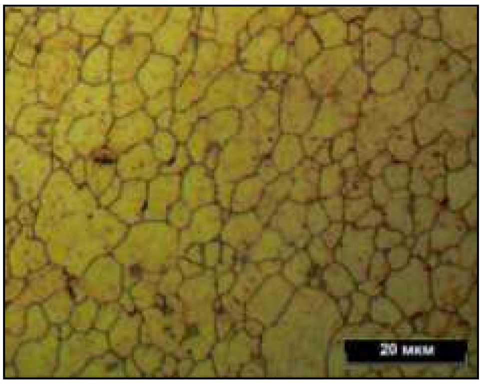


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Fig. 7 FSW samples: a) Macrosample of FSWed sample with 710 rpm, WS of 400 mm/sec; b) Microstructure of FSW nugget (710 rpm); c) Microstructure of FSW nugget (900 rpm); d) Microstructure of FSW nugget (1120 rpm); e) Parent metal.

Grain refinement is observed compared with pattern metal caused by the severe plastic deformation. Grain size (GS) of base metal was 25 μm. The most grain size refining was noticed in FSW nugget and reached 7.8 μm treated by schedule with 710 rpm and 400 mm/min of WS. In the rest FSW specimens GS in the nugget was about 11 μm.
Hardness test results for the minimum nugget GS sample was made and presented in **Fig.** 8. Hardness decreasing in HAZ was observed.

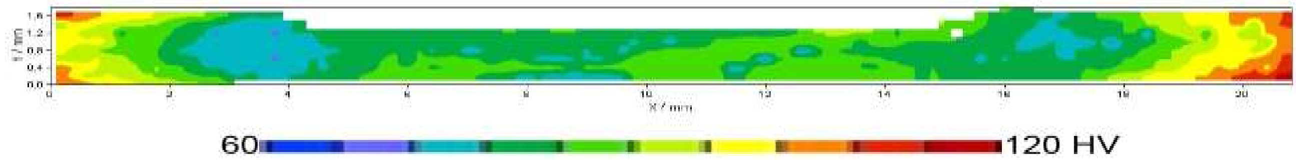

Fig.8 Hardness test result (710 rpm, WS of 400 mm/min).

CONCLUSION

Thermo-mechanical numerical simulation of FSW was made. The maximum temperature located just behind the tool pin was observed. Strain field is displaced to advancing side and reached a value of 40. Numerical model has a good agreement with the experiment in temperature measuring. Accordingly to microstructure analysis the minimum achieving grain size in the nugget is 7.8 microns. The maximum relative deviation of temperature calculation is 4%.

ACKNOWLEDGEMENTS

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