Michał Szczecina
Structure and Environment 2023, vol. 15, (4), pp. 196-207, Article number: el 017
https://doi.org/10.30540/sae-2023-017

Structure and Environment
ISSN 2081-1500
e-ISSN 2657-6902
https://content.sciendo.com/sae
https://sae.tu.kielce.pl

Kielce University of Technology

DOI: 10.30540/sae-2023-017

NUMERICAL ANALYSIS OF STRESS AND TEMPERATURE IN THE FRICTION STIR WELDING (FSW) PROCESS OF STEEL

NUMERYCZNA ANALIZA ROZKŁADU NAPRĘŻEŃ I TEMPERATURY W PROCESIE ZGRZEWANIA TARCIOWEGO Z PRZEMIESZANIEM DLA STALI

MICHAŁ SZCZECINA*
Kielce University of Technology, Poland

Abstract

Friction stir welding (FSW) is a modern technology for joining various metals, which has already undergone many laboratory tests, but still requires the development of numerical models. Author of the paper decided to summarize the current state of scientific knowledge regarding the modelling of the FSW process using the finite element method (FEM) and showed the main directions of development of numerical research on this process. Very advanced models are a combination of solid mechanics and fluid dynamics, but they often require expanding the computing environment with its own subroutines, as well as calibration and validation of some material parameter and constants occurring e.g. in the heat generation and heat flow laws. The Author of the paper proposed his own, simplified model, based on the computational solid mechanics and Lagrangian formulation. The model turned out to be an effective tool to reproduce stress and temperature fields during the FSW process.

Keywords: friction stir welding, numerical modelling, Abaqus, FEMs

Streszczenie

Zgrzewanie tarciowe z przemieszaniem (FSW) jest nowoczesną technologią łączenia różnych metali, posiadającą wiele zalet w porównaniu z tradycyjnym spawaniem. Zgrzewanie tarciowe zostało do tej pory poddane licznym badaniom laboratoryjnym, natomiast wymaga ciągłego rozwoju modeli numerycznych do symulacji tego procesu metodą elementów skończonych (MES). Autor artykułu postanowił dokonać podsumowania aktualnego stanu wiedzy dotyczącej modelowania zgrzewania tarciowego przy użyciu MES oraz wskazać główne kierunki rozwoju symulacji numerycznych tego procesu. Zaawansowane modele numeryczne zgrzewania tarciowego są kombinacją mechaniki ciała stałego z dynamiką płynów, a więc często wymagają rozbudowania środowiska obliczeniowego za pomocą własnych podprogramów, jak również kalibracji i walidacji wielu parametrów i stałych wymaganych do zdefiniowania np. prawa wytwarzania ciepła i prawa przepływu strumienia ciepła. Autor zaproponował swój własny uproszczony model bazujący na mechanice ciała stałego i opisie Lagrange'a. Model okazał się efektywnym narzędziem do odtworzenia naprężeń i pola temperatury w procesie zgrzewania tarciowego z przemieszaniem.

Słowa kluczowe: zgrzewanie tarciowe z przemieszaniem, modelowanie numeryczne, Abaqus, MES

*Corresponding Author: e-mail: michalsz@tu.kielce.pl

References

[1] Thomas W.M., Murch M.G., Nicholas E.D., Temple-Smith P., Needham J.Ch., Dawes Ch.J.: *Improvements relating to friction welding. European patent application*, EP0653265A2, European Patent Office, 27.11.1992.

[2] Thomas W.M., Nicholas E.D.: *Friction stir welding for the transportation industries*, Materials&Design, vol. 18, pp. 269-73, 1997, doi:10.1016/S0261-3069(97)00062-9.

[3] Neto D.M., Neto P.: *Numerical modeling of friction stir welding process: a literature review*. The International Journal of Advanced Manufacturing Technology, vol. 65, pp. 115-126, 2013, doi:10.1007/s00170-012-4154-8.

[4] Abaqus/CAE 2017. Simulia User Assistance. Johnston, RI, USA: Dassault Systemes Simulia Corp., 2017.

[5] Mishra R.S., Ma Z.Y.: *Friction stir welding and processing*, Material Science and Engineering, vol. 50, pp. 1-78, 2005, doi:10.1016/j.mser.2005.07.001.

[6] Sun Y., Gong W., Feng J., Lu G., Zhu R., Li Y.: *A Review of the Friction Stir Welding of Dissimilar Materials between Aluminum Alloys and Copper*. Metals, vol. 12, pp. 675, 2022, doi:10.3390/met12040675.

[7] Nandan R., DebRoy T., Bhadeshia H.K.D.H.: *Recent advances in friction-stir welding – Process, weldment structure and properties*, Progress in Material Science, vol. 53, pp. 980-1023, 2008, doi:10.1016/j.pmatsci.2008.05.001.

[8] Fabregas Villegas J., Martinez Guarin A., Unfried-Silgado J.: *A Coupled Rigid-viscoplastic Numerical Modeling for Evaluating Effects of Shoulder Geometry on Friction Stir-welded Aluminum Alloys*, International Journal of Engineering, vol. 32, pp. 313-321, 2019.

[9] Gao S., Zhou L., Sun G., Zhao H., Chu X., Li G., Zhao H.: *Influence of Welding Speed on Microstructure and Mechanical Properties of 5251 Aluminum Alloy Joints Fabricated by Self-Reacting Friction Stir Welding*, Materials, vol. 14, pp. 6178, 2021, doi:10.3390/ma14206178.

[10] Dialami N., Cervera M., Chiumenti M.: *Numerical Modelling of Microstructure Evolution in Friction Stir Welding (FSW),* Metals, vol. 8, pp. 183, 2018, doi:10.3390/met8030183.

[11] Dialami N., Chiumenti M., Cervera M.: *Material flow visualization in Friction Stir Welding via particle tracing*, International Journal of Material Forming, vol. 8, pp. 167-181, 2015, doi:10.1007/s12289-013-1157-4.

[12] Chao Y.J., Qi X., Tang W.: *Heat Transfer in Friction Stir Welding – Experimental and Numerical Studies*, Journal of Manufacturing Science and Engineering, vol. 125, pp. 138-145, 2003, doi:10.1115/1.1537741.

[13] Xie G.M., Ma Z.Y., Geng L.: *Partial recrystallization in the nugget zone of friction stir welded dual-phase Cu–Zn alloy*, Philosophical Magazine, vol. 89, pp. 1505-1516, 2009, doi:10.1080/14786430903019040.

[14] Fonda R.W., Bingert J.F.: *Microstructural Evolution in the Heat-Affected Zone of a Friction Stir Weld*, Metallurgical and Materials Transactions A, vol. 35, pp. 1487-1499, 2004, doi:10.1007/s11661-004-0257-7.

[15] Richmire S., Hall K., Haghsnehas M.: *Design of experiment study on hardness variations in friction stir welding of AM60 Mg alloy*, Journal of Magnesium and Alloys, vol. 6, pp. 215-228, 2018, doi:10.1016/j.jma.2018.07.002.

[16] Liu X., Xie P., Wimpory R., Li W., Lai R., Li M., Chen D., Liu Y., Zhao H.: *Residual Stress, Microstructure and Mechanical Properties in Thick 6005A-T6 Aluminium Alloy Friction Stir Welds*, Metals, vol. 9, pp. 803, 2019, doi:10.3390/met9070803.

[17] Shyamlal Ch., Shanmugavel R., Winowlin Jappes J.T., Nair A., Ravichandran M., Abuthakeer S.S., Prakash Ch., Dixit S., Vatin N.I.: *Corrosion Behavior of Friction Stir Welded AA8090-T87 Aluminum Alloy*, Materials, vol. 15, pp. 5165, 2022, doi:10.3390/ma15155165.

[18] Schenider J., Beshears R., Nunes Jr. A.C.: *Interfacial sticking and slipping in the friction stir welding process*, Materials Science and Engineering A, vol. 435-436, pp. 297-304, 2006, doi:10.1016/j.msea.2006.07.082.

[19] Kossakowski P.G., Wciślik W., Bakalarz M.: *Macrostructural Analysis Of Friction Stir Welding (FSW) Joints*, Journal of Mechanical Engineering Research, vol. 1, pp. 28-33, 2018, doi:10.30564/jmer.v1i1.486.

[20] Kossakowski P.G., Wciślik W., Bakalarz M.: *Effect of selected friction stir welding parameters on mechanical properties of joints*, Archives of Civil Engineering, vol. 65, pp. 51-62, 2019, doi:10.2478/ace-2019-0046.

[21] Richards B.: *Microstructure-Property Correlations in Friction Stir Welded Al6061-T6 Alloys*. BSc thesis, Worcester Polytechnic Institute, Worcester, Massachusetts, USA, 2010.

[22] Meyghani B., Awang M.B., Emamian S.S., Nor M.K.B.M., Pedapati S.R.: *A Comparison of Different Finite Element Methods in the Thermal Analysis of Friction Stir Welding (FSW).* Metals, vol. 7(10), pp. 450, 2017, doi:10.3390/met7100450.

[23] Lorrain O., Serri J., Favier V., Zahrouni H., El Hadrouz M.: *A contribution to a critical review of friction stir welding numerical simulation*, Journal of Mechanics of Materials and Structures, vol. 4(2), pp. 351-369, 2009, doi:10.2140/jomms.2009.4.351.

[24] Oliphant A.H.: *Numerical Modeling of Friction Stir Welding: A Comparison of Alegra and Forge3*, MSc thesis, Brigham Young University, Provo, Utah, USA, 2004.

[25] Guerdoux S.: *Numerical simulation of the friction stir welding process*, PhD thesis, l'Ecole des Mines de Paris, Paris, France, 2007.

[26] Arakere A.P.: *Computational modeling of the friction stir welding (FSW) process and of the performance of FSW joints*, MSc thesis, Clemson University, Clemson, South Carolina, USA, 2013.

[27] Bhattacharjee R., Biswas P.: *Review on thermo-mechanical and material flow analysis of dissimilar friction stir welding*, Welding International, vol. 35, pp. 295-332, 2021, doi:10.1080/09507116.2021.1992256.
[28] Sen S., Murugesan J.: *Experimental and numerical analysis of friction stir welding: a review*. Eng Res Express 2022, 4, 032004. https://doi.org/10.1088/2631-8695/ac7f1e.
[29] Meyghani B., Awang M.B., Momeni M., Rynkovskaya M.: *Development of a Finite Element Model for Thermal Analysis of Friction Stir Welding (FSW),* IOP Conference Series: Materials Science and Engineering, vol. 495, pp. 012101, 2019, doi:10.1088/1757-899X/495/1/012101.
[30] Colegrove P.A., Shercliff H.R.: *Experimental and numerical analysis of aluminium alloy 7075-T7351 friction stir weld*, Science and Technology of Welding and Joining, vol. 8:5, pp. 360-368, 2003, doi:10.1179/136217103225005534.
[31] Colegrove P.A., Shercliff H.R.: *3-Dimensional CFD modelling of flow round a threaded friction stir welding tool profile*, Journal of Materials Processing Technology, vol. 169, pp. 320-327, 2005, doi:10.1016/j.jmatprotec.2005.03.015.
[32] Jacquin D., de Meester B., Simar A., Deloison D., Montheillet F., Desrayaud C.: *A simple Eulerian thermomechanical modeling of friction stir welding*, Journal of Materials Processing Technology, vol. 211, pp. 57-65, 2011, doi:10.1016/j.jmatprotec.2010.08.016.
[33] Dialami N., Chiumenti M., Cervera M., de Saracibar C.A.: *Local and global approaches to Friction Stir Welding*. Barcelona, Spain: International Center for Numerical Methods in Engineering, 2016.
[34] Dialami N., Chiumenti M., Cervera M., de Saracibar C.A.: *Challenges in Thermo-mechanical Analysis of Friction Stir Welding Processes*, Archives of Computational Methods in Engineering, vol. 24, pp. 189-225, 2017, doi:10.1007/s11831-015-9163-y.
[35] Gao E., Zhang X., Liu C., Ma Z.: *Numerical simulations on material flow behaviors in whole process of friction stir welding*, Transactions of Nonferrous Metals Society of China, vol. 28, pp. 2324-2334, 2018, doi:10.1016/S1003-6326(18)64877-0.
[36] Zhao H.: *Friction stir welding (FSW) simulation using an arbitrary Lagrangian – Eulerian (ALE) moving mesh approach*, PhD thesis, West Virginia University, Morgantown, West Virginia, USA, 2005.
[37] Chauhan P., Jain R., Pal S.K., Singh S.B.: *Modeling of defects in friction stir welding using coupled Eulerian and Lagrangian method*, Journal of Manufacturing Processes, vol. 34, pp. 158-166, 2018, doi:10.1016/j.jmapro.2018.05.022.
[38] Kishta E.E., Abed F.H., Darras B.M.: *Nonlinear Finite Element Simulation of Friction Stir Processing of Marine Grade 5083 Aluminum Alloy*, Engineering Transactions, vol. 62, pp. 313-328, 2014.
[39] Li K., Jarrar F., Sheikh-Ahmad J., Ozturk F.: *Using coupled Eulerian Lagrangian formulation for accurate modeling of the friction stir welding process*, Procedia Engineering, 207, 574-579, 2017, doi:10.1016/j.proeng.2017.10.1023.
[40] Chen C.M., Kovacevic R.: *Finite element modeling of friction stir welding – thermal and thermomechanical analysis*, International Journal of Machine Tools and Manufacture, vol. 43, pp. 1319-1326, 2003, doi: 10.1016/S0890-6955(03)00158-5.
[41] Schmidt H., Hattel J.: *A local model for the thermomechanical conditions in friction stir welding*, Modelling and Simulation in Materials Science and Engineering, vol. 13, pp. 77-93, 2004, doi:10.1088/0965-0393/13/1/006.
[42] Schmidt H., Hattel J.: *Thermal modelling of friction stir welding*, Scriptia Materialia, vol. 58, pp. 332-337, 2008, doi:10.1016/j.scriptamat.2007.10.008.
[43] Hamilton C., Dymek S., Sommers A.: *A thermal model of friction stir welding in aluminum alloys*, International Journal of Machine Tools and Manufacture, vol. 48, pp. 1120-1130, 2008, doi:10.1016/j.ijmachtools.2008.02.001.
[44] Mehta M., Reddy G.M., Rao A.V., De A.: *Numerical modeling of friction stir welding using the tools with polygonal pins*, Defence Technology, vol. 11, pp. 229-236, 2015, doi:10.1016/j.dt.2015.05.001.
[45] Chiumenti M., Cervera M., de Saracibar C.A., Dialami N.: *Numerical modeling of friction stir welding processes*, Computer Methods in Applied Mechanics and Engineering, vol. 254, pp. 353-369, 2013, doi:10.1016/j.cma.2012.09.013.
[46] Santiago D.H., Lombera G., Urquiza S., Cassanelli A., de Vedia L.A.: *Numerical Modeling of Welded Joints by the "Fric-tion Stir Welding" Process*, Materials Research, vol. 7, pp. 569-574, 2004, doi:10.1590/S1516-14392004000400010.
[47] Ulysse P.: *Three-dimensional modeling of the friction stir-welding process*, International Journal of Machine Tools and Manufacture, vol. 42, pp. 1549-1557, 2002, doi:10.1016/S0890-6955(02)00114-1.
[48] Zhang Z.: *Comparison of two contact models in the simulation of friction stir welding process*, Journal of Material Science, vol. 43, pp. 5867-5877, 2008, doi:10.1007/s10853-008-2865-x.
[49] Schmidt H., Hattel J., Wert J.: *An analytical model for the heat generation in friction stir welding*, Modelling and Simulation in Material Science and Engineering, vol. 12, pp. 143-157, 2003, doi:10.1088/0965-0393/12/1/013.
[50] Zhu X.K., Chao Y.J.: *Numerical simulation of transient temperature and residual stresses in friction stir welding of 304L stainless steel*, Journal of Materials Processing Technology, vol. 146, pp. 263-272, 2004, doi:10.1016/j.jmatprotec.2003.10.025.

[51] Abdullah I., Mohammed S.S., Abdallah S.A.: *Artificial neural network modelling of the surface roughness of friction stir welded AA7020-T6 aluminum alloy*, Engineering Research Journal, vol. 1, pp. 1-5, 2020, doi:10.21608/erjsh.2020.228168.

[52] Okuyucu H., Kurt A., Arcaklioglu E.: *Artificial neural network application to the friction stir welding of aluminum plates*, Materials&Design, vol. 28, pp. 78-84, 2007, doi:10.1016/j.matdes.2005.06.003.

[53] Jemioło S., Gajewski M.: *Symulacja MES obróbki cieplnej wyrobów stalowych z uwzględnieniem zjawisk termo-metalurgicznych. Część 1. Nieustalony przepływ ciepła z uwzględnieniem przejść fazowych* (Thermo-metallurgical phenomena in FE simulation of heat treatment for steel. Part 1: Unsteady heat transfer and phase change phenomena). Zeszyty Naukowe, Budownictwo, vol. 143, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2005.

[54] Jemioło S., Gajewski M.: *Symulacja MES obróbki cieplnej wyrobów stalowych z uwzględnieniem zjawisk termo-metalurgicznych. Część 2. Przykłady numeryczne z zastosowaniem programu SYSWELD* (Thermo-metallurgical phenomena in FE simulation of heat treatment for steel. Part 2: Numerical examples using SYSWELD program). Zeszyty Naukowe, Budownictwo, vol. 143, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2005.

[55] Jemioło S., Gajewski M.: *Zastosowanie programu SYSWELD w modelowaniu resztkowych naprężeń pospawalniczych* (SYSWELD program application in modelling of residual postwelding stresses). Zeszyty Naukowe, Budownictwo, z.143, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2005.

[56] Hashemzadeh M., Garbatov Y., Guedes Soares C., O'Connor A.: *Friction stir welding induced residual stresses in thick steel plates from experimental and numerical analysis*, Ships and Offshore Structures, vol. 17, pp. 1053-1061, 2021, doi:10.1080/17445302.2021.1893531.

[57] Chang P.H., Teng T.L.: *Numerical and experimental investigations on the residual stresses of the butt-welded joints*, Computational Materials Science, vol. 29, pp. 511-522, 2004, doi:10.1016/j.commatsci.2003.12.005.

[58] Jeyakumar M., Christopher T., *Influence of residual stresses on failure pressure of cylindrical pressure vessels*, Chinese Journal of Aeronautics, vol. 26, pp. 1415-1421, 2013, doi:10.1016/j.cja.2013.07.025.

[59] Giorjão R.A.R., Avila J.A., Escobar J.D., Ferrinho Pereira V., Marinho R.R., Torres Piza Paes M., Fonseca E.B., Costa A.M.S., Terada M.: *The study of volumetric wearing of PCBN/W-Re composite tool during friction stir processing of pipeline steels (X70) plates*, The International Journal of Advanced Manufacturing Technology, vol. 114, pp. 1555-1564, 2021, doi:10.1007/s00170-021-06932-8.

[60] Kossakowski P., Wciślik W., Bakalarz M.: *Selected aspects of application of aluminium alloys in building structures*, Structure and Environment, vol. 9(4), pp. 256-263, 2017, https://sae.tu.kielce.pl/33/S&E_nr_33_Art_4.pdf.

[61] Wciślik W., Kossakowski P., Sokołowski P.: *Stainless steel in building structures - advantages and examples of application*, Structure and Environment, vol. 9(3), pp. 191-198, 2017, https://sae.tu.kielce.pl/32/S&E_NR_32_Art_4.pdf.