Michał Szczecina
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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

1. INTRODUCTION

Friction stir welding (FSW) was invented by Thomas et al. [1] in 1991, so one can say that it is a relatively young and innovative technology. For over 30 years FWS has been used in many high technology applications, e.g. aerospace [2], and has also been a subject of numerous scientific research. There are a few advantages of the FSW process, and namely: lower temperatures in comparison with traditional welding, no melting, a FSW tool is unconsumable [3]. A development of computational methods, especially finite element method (FEM), allowed for advanced numerical modelling of the stir welding process. The modelling covers not only mechanical, but also thermal and coupled thermal-mechanical behaviour of welded parts. Some important phenomena can also be taken into account, i.e. heat generation and dissipation, metal flow, sticking and sliding. Author of the paper summarized the current state of the research field, indicate some issues of the numerical modelling of the SFW and propose their own, simplified numerical approach of the process. Additionally, author demonstrate how the FSW can be modelled using Abaqus [4] software to reproduce stress and temperature fields during the process.

1.1. General description of the process

The FSW process can be divided into three phases: plunging, dwelling and welding. An operating tool consists of a conical shoulder and a pin, which is shaped in a few various ways, e.g. cylindrical, threaded, square or tapped (Fig. 1). In the first stage the rotating pin is lowered down into a joint line, which is determined by two surfaces (workpieces) prepared to be welded. Then the rotating tool is held steady to produce heat, which dissipates into the neighbouring material. In this stage temperature of the welded parts increases which causes material softening. Finally, the welding operation is performed by the relative displacement of the tool along the joint line (Fig. 2). The material transported form the front to the back of the welding tool forms a joint between two workpieces.

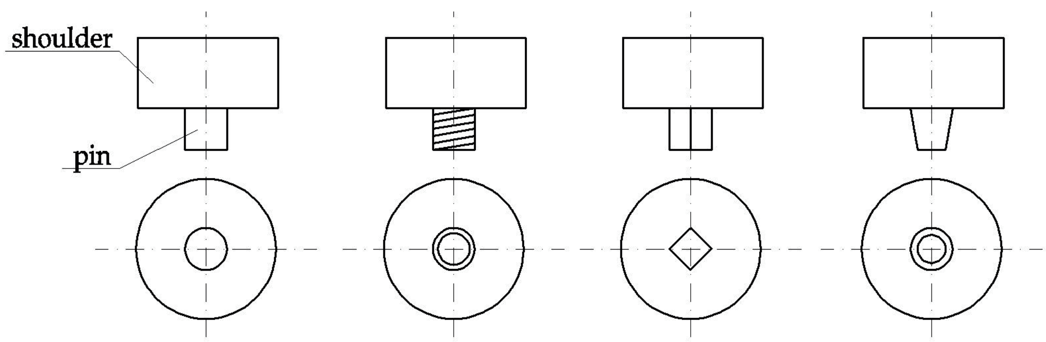

Fig. 1. Sample shapes of the operating tool used in the FSW process

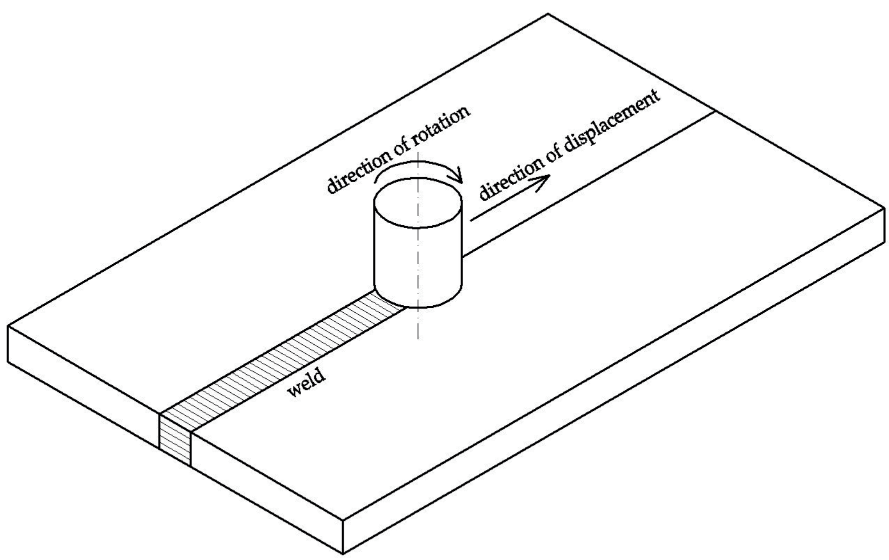

Fig. 2. General view of the FSW process

There are many important parameters that affect the whole welding process, first of all:

- geometry of the whole operating tool, discussed inter alia by Mishra&Ma [5], Sun et al. [6] and Nandan et al. [7];
- geometry of the operating tool shoulder [8];
- tilt of the operating tool and target depth [5];
- speed (transverse and rotational) of the operating tool [5, 6, 9];
- downward force;
- metallurgical and microstructural aspects, grain size and microhardness [6, 10];
- welding configuration of workpieces made of dissimilar metals [6];
- preheating or cooling of workpieces [5];
- joint design, especially when the joint is more complicated than a simple butt or lap joint [5].

A few important phenomena which occur in the whole FSW process and a few properties of welded materials have also been described in the subject literature [5]:

- metal flow, visualized in laboratory tests with the use of tracer technique by marker, welding of dissimilar materials, microstructural observations or particle tracing [11];
- heat generation, heat transfer [12];
- microstructural evolution in a nugget zone [13], a thermo-mechanically affected zone and a heat-affected zone [14];
- change in hardness of alloys [15];
- residual stress [16];
- change in postweld mechanical properties, especially strength, ductility, fracture toughness and fatigue [5];
- corrosion behaviour [17];
- interfacial sticking and slipping [18].

Kossakowski et al. [19] performed a macrostructural analysis of FSW joints, taking into consideration weld structure, rotation speed, tool travel and showing joint defects as a result of process parameters. The same authors [20] analysed effect of tool rotation and travel speed on joint parameters. Static and dynamic performance of FSW butt joint, including fatigue crack growth, was presented by Richards [21].

According to Mishra [5], the FSW process has many benefits, some of them in comparison to a traditional welding. The benefits can be divided into metallurgical (no cracking of a weld, no loss of material, low distortion of workpieces etc.), environmental (no grinding waste, no use of shielding gas, surface cleaning or solvents for degreasing) and energy benefits.

1.2. Numerical modeling of the FSW process

A finite element method approach to the FSW process has already been applied in many scientific research. A literature review on the topic was presented by Neto&Neto [3] and a comparative study of different FEM approaches can be found in a work of Meyghani et al. [22]. A critical review of the FSW numerical modelling was given by Lorrain et al. [23]. Some important introduction to FEM simulation of the FSW was presented in a few PhD and master theses [24-26]. There are few current studies and literature reviews concerning current progress in numerical modelling; one can refer to works of Bhattacharjee&Biswas [27] and Sen&Murugesan [28]. Author of this paper decided to complete and summarize the current state of the research field.

The first issue of a proper numerical simulation of the FSW process is a choice of theory that describes the material flow and thermo-mechanical behaviour. There are two main theories chosen for this purpose: computational fluid dynamics (CFD) and computational solid mechanics (CSM). A detailed study of both approaches was given by Bhattacharjee&Biswas [27]. Pros and cons of the above mentioned theories were described by Meyghani et al. [29].

The CFD is based on the Eulerian description with a fixed mesh and material is assumed as a non-Newtonian fluid. This approach allows to avoid numerical problems in case of large strains and element distortions, but it does not allow the separation of the element. Thanks to the flow boundary conditions only a small region around the welding tool can be modelled, which leads to a significant reduction of finite elements number and calculation time. Colegrove&Shercliff [30, 31] demonstrated the use of the CFD package FLUENT and modelled the 3D metal flow. The modelled recreated the FSW process quite well, but over-predicted the weld temperature and poorly predicted the welding forces. A viscosity relationship, including material softening, was proposed to overcome those problems. Jacquin et al. [32] presented a simple 3D thermo-mechanical model with velocity fields in a steady-state, solved using Abaqus/CAE software with extra procedures written in Fortran.

The CSM approach is based on the Lagrangian formulation, where the finite element mesh is attached to the material and follows its deformation [29]. Using an explicit time integration one can avoid numerical problems with convergence, but still large distortions can lead to a significant reduction of a time step size. A detailed description and discussion on a global and local level modelling is described in a monograph written by Dialami et al. [33]. The same authors [34] demonstrated the finite volume method to model the FSW process. The technique of tracer particles in the FEM model based on CSM was presented by Gao and co-workers [35] in Abaqus environment.

The geometrical interpretation of the main difference between the Lagrangian and Eulerian formulation is presented in Figure 3. An excessive distortion of the FE mesh can appear in the Lagrangian description while in the Eulerian element boundaries do not have to coincide with the mesh.

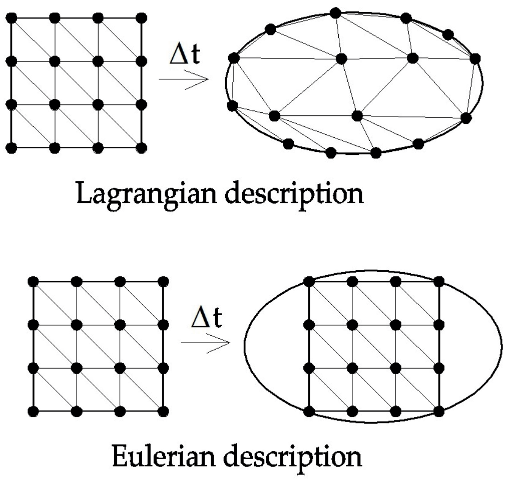

Fig. 3. Different mesh behavior in the Lagrangian and Eulerian formulation

In the research field there are also known and developed mixed methods, which are combinations of both Langrangian and Eulerian formulations, and namely the so-called Arbitrary Lagrangian-Eulerian (ALE) and Coupled Eulerian-Lagrangian (CEL). The first approach assumes splitting into subsequent Eulerian and Lagrangian steps, computing the mesh velocity and remapping [25, 36]. The CEL method allows to define the workpiece as an Eulerian body while the welding tool is modelled as a rigid Lagrangian body [37]. This approach can bring promising results, as shown in the works [38, 39].

Another problem related to the FEM simulation of the FSW is a proper definition of the thermal and thermo-mechanical model. An early work of Chen&Kovacevic [40] presents the use of the ANSYS software to reproduce the influence of thermal fluctuations on the stress tensor components. One year later, Schmidt&Hattel [41] proposed a fully coupled thermomechanical 3D model using Abaqus software and the ALE formulation. The same authors [42] described basics of the thermal modelling in the FSW process, including the heat conduction equation and the total heat generation equation and presented a new thermal-pseudomechanical model. Hamilton and co-workers [43] presented a thermal model introducing a slip factor, determined according to energy per unit length of weld. Mehta et al. [44] defined subroutines in Abaqus environment called DFLUX, FILM, USDFLD and UMASFL to capture the non-uniform heat flux, convective heat transfer, tool properties and mass velocity. Their work concerned the welding tools with polygonal pins.

Coupled thermo-mechanical models are nowadays widely used in the FSW simulations. Chiumenti et al. [45] presented a fully coupled model, where the local form of the FSW problem is stated in the form of coupled mechanical and transient heat transfer equations. It is also possible to apply a thermo-mechanically coupled viscoplatic flow model. A sample formulation is shown in a work of Santiago et al. [46], inspired with an early work of Ulysse [47].

Another important issue of the FSW simulation is a formulation of contact conditions, including sliding and sticking. Usually researchers define a classical Coulomb friction law, which can be expressed in the form:

$$\tau = \mu P \tag{1}$$

where: τ – indicates the friction stress (in [Pa]), μ – friction coefficient (unitless), P – contact force (in [N]).

Zhang [48] compared the classical and modified Coulomb laws and stated, that the classical law is limited to lower angular velocity of the welding tool. In case of higher velocity, the modified Coulomb law should be applied. More complex contact states were categorized and presented by Schmidt et al. [49] and contact conditions can be defined separately for sticking and sliding [3].

Finally, a constitutive material model for plastic or viscoplatic behaviour and behaviour for flow modelling of metal is also required as an input. Ulysse [47] and Santiago et al. [46] modelled the FSW process using 3D viscopastic modelling. The other approach was presented by Zhu&Chao [50], which applied the von Mises yield criterion and the associated flow rule. As regards materials behaviour for flow modelling, the Sellars-Tegart and John-Cook models are the most common approach [3].

The finite element method is the most common technique used in numerical modelling of the FSW process. Sen&Murugeshan [28] presented a comparative study of three FEM software packages, and namely ANSYS, ABAQUS and FLUENT. A very interesting approach to the FSW modelling is a use of artificial neural networks (ANN). Abdullah et al. [51] showed how to use ANN to model surface roughness of aluminium alloy. Okuyucu et al. [52] analysed a correlation between the FSW parameters and mechanical properties of aluminium using ANN.

One of the most important issues in welding is a phase transition in material. The phenomenon was not yet taken into consideration by the author of the paper because of its complexity. Nevertheless, a few publications [53-55] on the issue show that FEM simulation of the effect is possible, among other using SYSWELD software.

To sum up, all the above presented approaches are based on very robust, advanced numerical models. The models demand on a precise calibration and validation of input data and can take into account various physical phenomena, accompanying the FSW process. Numerical modelling of the FSW is developing still and reported results of FEM calculations are still closer to laboratory tests results. On the other hand, structural engineers need also simple numerical models which can give quick information about stress and temperature fields during the FSW process. Author of the paper made an attempt to create such a model, presented in the following sections.

2. INPUT DATA

The author of the paper would like to demonstrate a use of a simple numerical model of the FSW process, defined in the Abaqus environment [4]. The main goal of the research is a numerical reproduction of residual stress after the FSW process. Geometry and material properties of specimens were taken from the laboratory experiment of Hashemzadeh et al. [56]. All materials were defined as isotropic. Two steel plates, each 2000x150x12 mm of dimensions, were modelled. Mechanical and thermal properties of ASTM A36 carbon steel applied in the model are listed in the Table 1. Temperature dependency of the properties were taken from the paper of Chang&Teng [57]. Ultimate strength of steel was assumed as 450 MPa [58] and Poisson's ratio was temperature-independent and equal to 0.3. The author's choice fell on steel, because the author of the paper recognized that laboratory tests on steel [56] were documented in the most detailed way among all the results of laboratory tests that were collected for the purpose of performing numerical analyses in this paper.

The FSW tool was assumed as hybrid W-Re/pcBN [51]; geometry of the tool was defined according to [59] and shown in Figure 4. Main properties of the FSW process are as listed: rotation speed of the tool: 150 rpm, transverse speed of the tool: 0.1 ms^{-1}, vertical force acting on the shoulder of the tool: 90 kN [56]. Friction coefficient was assumed as equal to 0.3.

Table 1. Mechanical and thermal properties of ASTM A36 carbon steel

Temperature [°C]	Young's modulus [GPa]	Yield stress [MPa]	Specific heat [$Jkg^{-1}K^{-1}$]	Conductivity [$Wm^{-1}K^{-1}$]	Expansion [$10^{-6}K^{-1}$]
20	210	380	450	51	11.2
100	195	340	475	50	11.8
210	195	320	530	49	12.4
330	185	262	560	46	13.1
420	168	190	630	41	13.6
540	118	145	720	38	14.1
660	52	75	830	34	14.6
780	12	40	910	28	14.6
985	11.8	38	1055	25	14.6
1320	10.4	28	2000	32	14.6
1420	10.2	25	2100	42	14.6
1500	10	20	2150	42	14.6

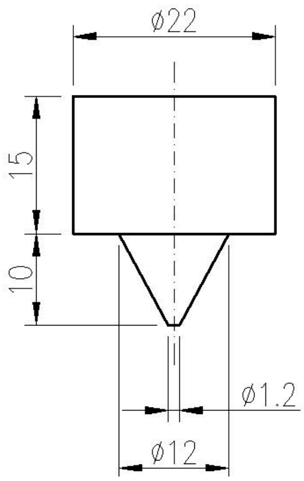

Fig. 4. Geometry of the welding tool (dimensions in [mm])

3. FEM MODEL

Numerical analysis was performed using the finite element method in Abaqus environment [4]. Author decided to apply the Lagrangian approach and the explicit dynamic step with the fully coupled thermal-stress analysis (the so-called temperature-displacement in the Abaqus code). The plates were meshed with C3D8T brick finite elements, 12x12x3 mm each and the welding tool was discretized with C3D4T tetrahedrons and the average mesh size was assumed as 3 mm. The meshed assembly is presented in Figure 5 while, for the sake of visibility, the magnified welding tool with the plates were shown in Figure 6.

All mechanical and thermal properties were defined as shown in the section 2. Moreover, the classical von Mises yield criterion (input variable PLASTICITY in Abaqus code) was taken into account. The stress-strain relationship was defined as bi-linear with the following values of the yield strain (Eq. 2) and ultimate strain (Eq. 3) in the initial temperature, equal to 20°C:

$$\varepsilon_y = \frac{\sigma_y}{E} = \frac{380\ \text{MPa}}{210\ \text{GPa}} = 0.00181 \tag{2}$$

$$\varepsilon_u = \frac{\sigma_u}{E} = \frac{450\ \text{MPa}}{210\ \text{GPa}} = 0.00214 \tag{3}$$

and the relationship of a uniaxial behaviour is presented in Figure 7.

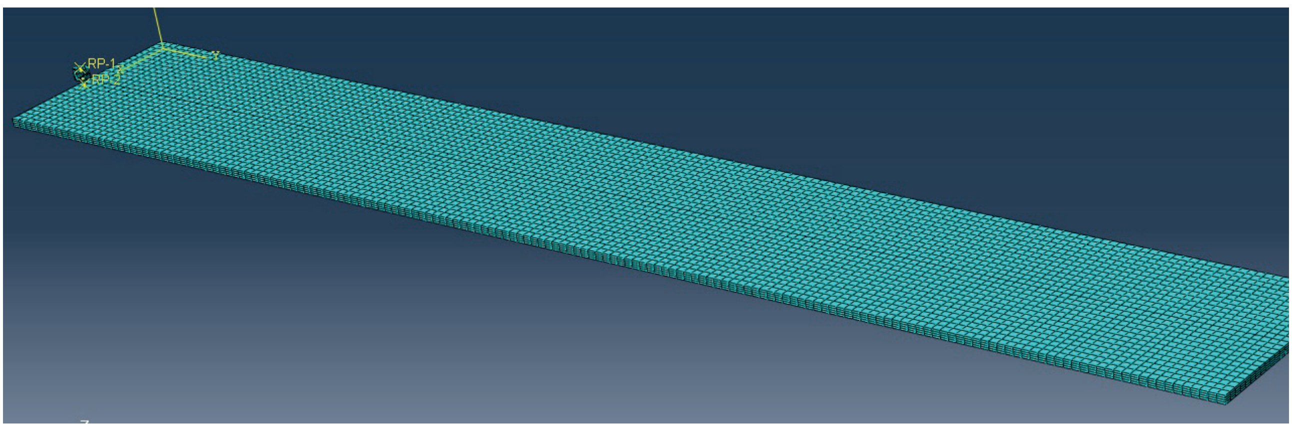

Fig. 5. Meshing of the plates and the welding tool

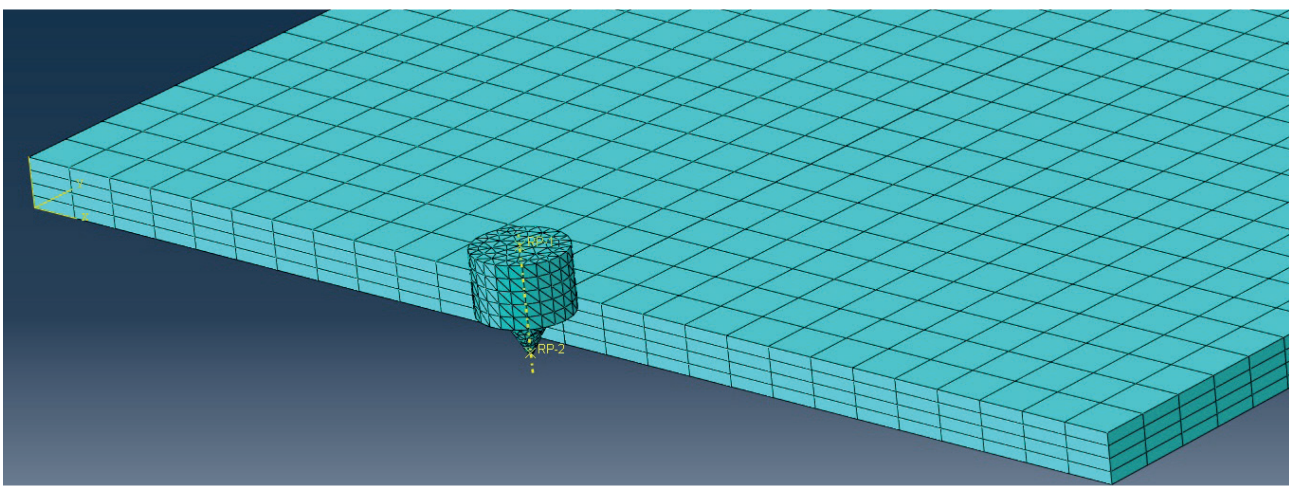

Fig. 6. The magnified welding tool with the edges of the plates

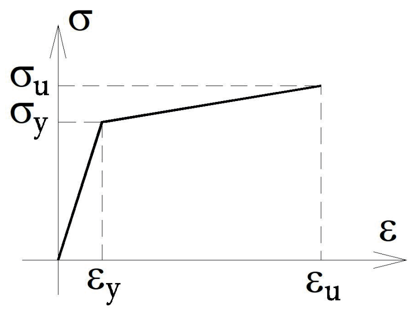

Fig. 7. Stress-strain curve defined in the numerical model

The welding tool was defined as a rigid body rotating with a constant angular velocity and the plates – as deformable elements moving with a constant transverse velocity. Boundary conditions were defined as follows:

- transverse velocity of the plates, shown in Figure 8;
- angular velocity of the welding tool and force acting on the shoulder, shown in Figure 9.

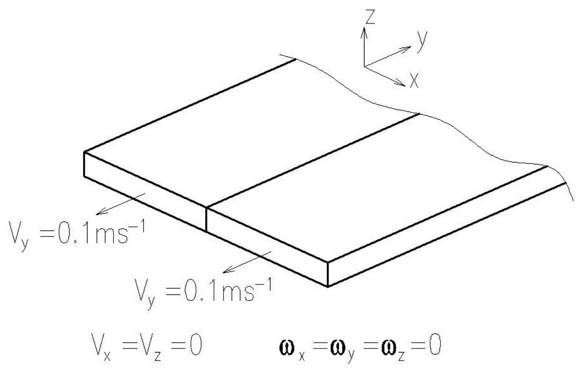

Fig. 8. Boundary conditions – transverse velocity of the welded plate

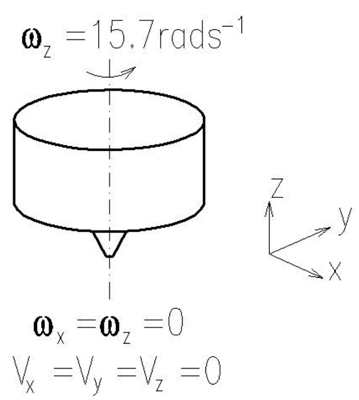

Fig. 9. Boundary conditions – angular velocity of the welding tool

Ambient temperature was set as 20°C, using the "predefined fields" option in the initial step in all nodes of the meshed model. A surface-to-surface contact between the welding tool and the plates was defined as follows:

- tangential behaviour – friction coefficient 0.3 (called "penalty" in Abaqus code);
- normal behaviour – "hard contact";
- heat generation with default 0.5 fraction of converted heat distributed to slave surface.

A time period was set as 22 s, which is enough for the welding tool to make a full weld joining the plates and to come out of them. A type of incrementation was assumed as fixed with the user-defined time increment equal to 0.001.

4. ANALYSIS OF TEMPERATURE AND STRESS IN PLATES

In order to visualize the whole welding process and stress during the welding process, the author decided to present maximal principal stress and nodal temperatures. Maximal principal stress on the upper surface of the welded plates after time $t = 22$ s is presented in Figure 10 (please note, that the results are presented in [Pa] using a native notation in Abaqus code, e.g. e+08 means 10 to the power of 8). We can see how the stress field is propagating on the surface of the plates while the welding tool is moving along the Y axis. Moreover, the stress field expands also in the *X* axis, transverse to the welding direction. Figures 11 and 12 present the maximal principal stress in a transverse cross section and nodal temperature in a longitudinal cross section of the weld. Temperatures obtained under the welding tool are above the steel melting point and stress exceeds the yield stress in three columns (in each plate) of finite elements, which proves a limited range of material deformation caused by the process. Moreover, one can see that the stress and temperature distribution in the left-hand side and right-hand side plates (looking from viewport adopted in Fig. 11) are different. This fact can be explained by rotational motion of the welding tool. Because of the motion, in one of the plates metal particles are displaced in front of the leading edge of the tool shoulder while in the other plate they are moved to the trailing edge, so the whole model is not symmetrical.

Variation of temperature and principal stress depending on the distance *z* from the top of the right-hand side (see Fig. 11) plate in the section under the welding tool are presented in Figures 13 and 14. High values of temperature (in some nodes above the melting point) and stress indicate large yielding of steel in the weld zone during the process, which is necessary to stir metal particles of both welded plates.

Total strains and plastic strains (maximal principal) are shown in Figures 15 and 16. The values of the strains are lower than ultimate strains presented in the previous chapter.

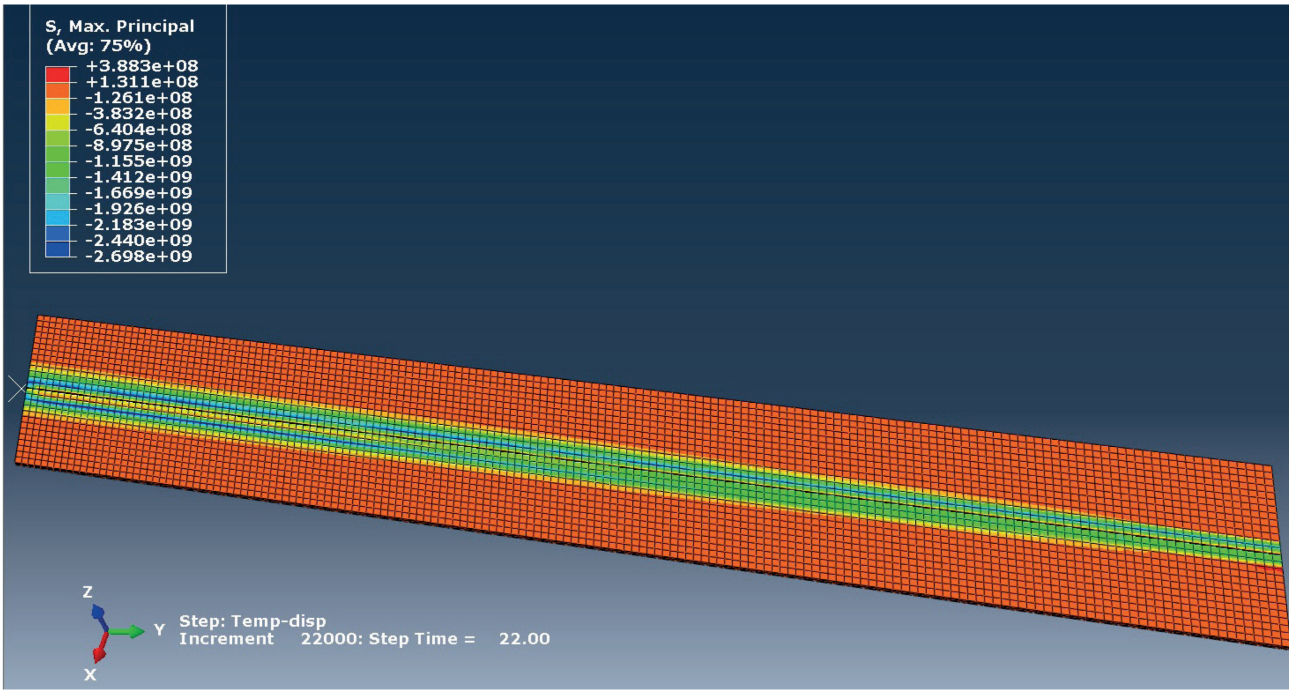

Fig. 10. Maximal principal stress after time t = 22.0 s; all results expressed in Pa

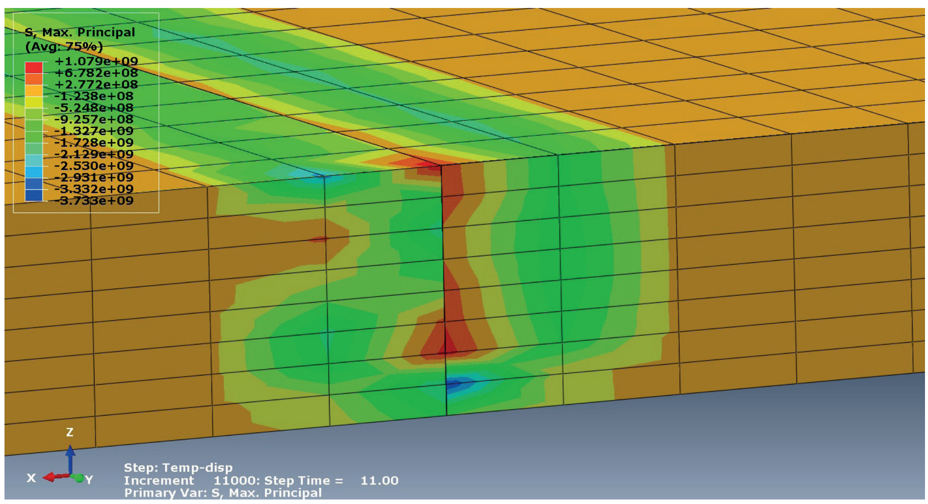

Fig. 11. Maximal principal stress in a transverse cross section of the plates, t = 11.0 s

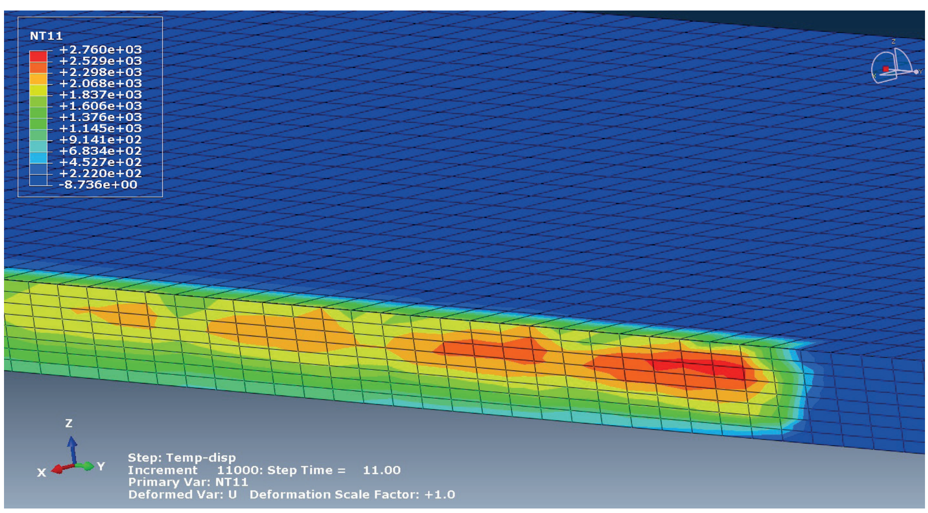

Fig. 12. Nodal temperatures (in °C) in a longitudinal cross section of the weld, t = 11.0 s

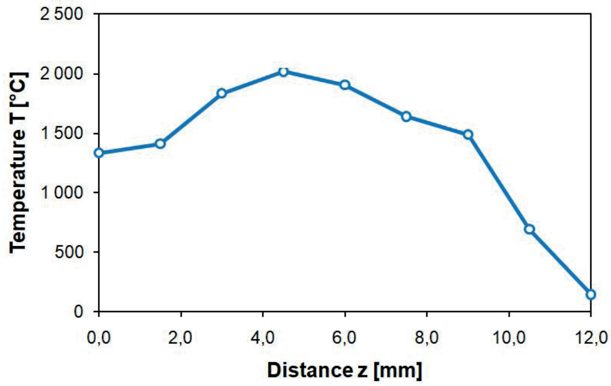

Fig. 13. Nodal temperature in a transverse section of the right-hand side plate vs distance z form the top of the plate, t = 11.0 s

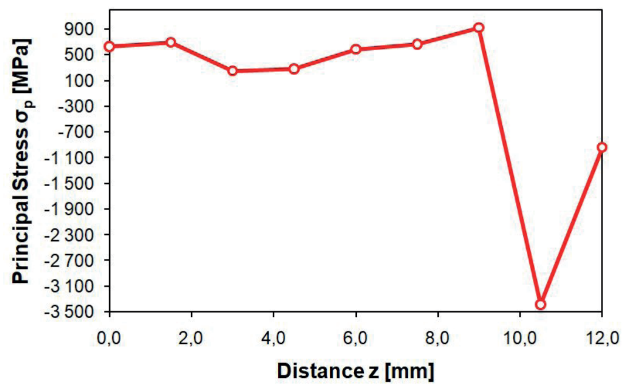

Fig. 14. Principal stress in a transverse section of the right-hand side plate vs distance z form the top of the plate, t = 11.0 s

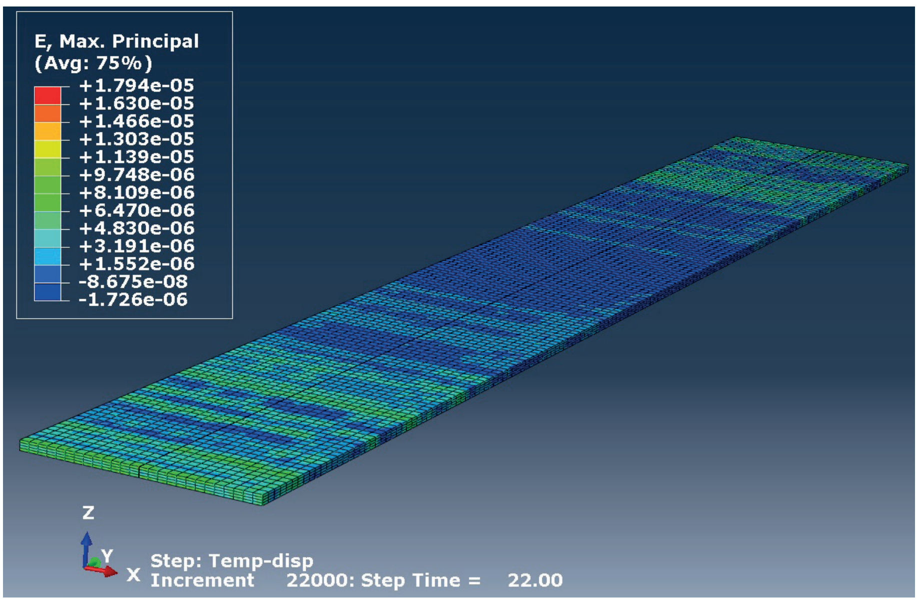

Fig. 15. Maximal principal total strains after time t = 22.0 s

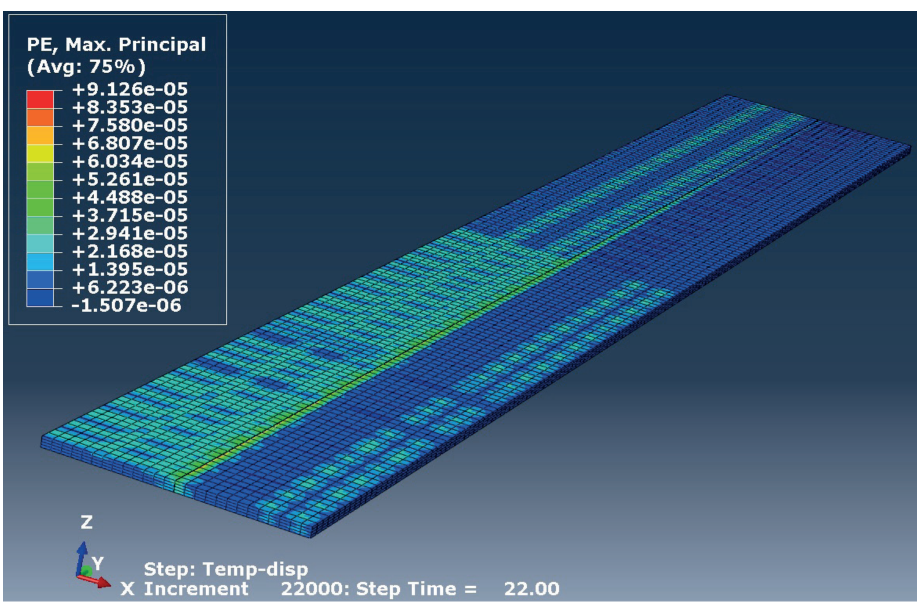

Fig. 16. Maximal principal plastic strains after time t = 22.0 s

5. DISCUSSION AND CONCLUSIONS

According to Neto&Neto [3], experimental investigations of the FSW process focused mainly on adjusting parameters such as angular and transverse speed of the welding tool, geometry of the tool, depth of penetration in welded parts. On the other hand, numerical simulation can be use to visualize some phenomena and results easier than in experimental investigations, e.g. material flow, heat generation and transfer, residual stress field and so on. Ten years after Neto&Neto [3] publication, the need for a new review and summary of progress in the numerical simulation of the FSW arose. This paper is an attempt to fill the gap. Author of this paper presented also a simple FEM simulation based on the Lagrangian approach and showed how to estimate stress in welded parts. The simple model can be useful in a practical use, e.g. for a structural engineer when designing a welded joint to make sure how large temperature and stress can be during welding.

The numerical model can be an effective tool in optimization and controlling of the FSW process. For a thorough scientific analysis, especially when laboratory tests are compared with FEM simulations, more robust and complex numerical models are necessary. The most promising approach are the Coupled Eulerian-Lagrangian (CEL) and Arbitrary Lagrangian-Eulerian (ALE) approach. Both methods are still being developed and while using them it is also possible to take into account the thermo-mechanical model of the FSW process. Researchers have already recognized the capabilities of advanced FEM codes and also try to incorporate their own subroutines. Some new opportunities are created by the use of artificial neural networks (ANN). At the moment ANN are rather applied to model some particular parameters of the FSW process or to find correlation between the parameters. The next step can be the so-called hybrid FEM and ANN modelling.

In this paper only one particular type of carbon steel was examined. As it was shown in works of Kossakowski et al. [60, 61], aluminium alloys and stainless steel are also in the scope of interest of contemporary construction industry. The author of this paper plans also to investigate the FSW process of these materials.

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.