EAN 2017
55th conference on experimental stress analysis

# Modeling of friction stir welding of ferritic steels by considering phase transformations

Daniel Kaločany[1,a], Pavel Élesztős[2,b], Ladislav Écsi[3,c], Roland Jančo[4,d]

[1] EDAG Engineering CZ, spol. s. r. o., Praha 5, CZ

[2,3,4]SjF STU in Bratislava, Bratislava, SK

[a]daniel.kalocany@gmail.com, [b]pavel.elesztos@stuba.sk, [c]ladislav.ecsi@stuba.sk, [d]roland.janco@stuba.sk

**Keywords:** FEM, friction stir welding, SYSWELD.

**Abstract.** The paper content deals with readers familiarisation with the numerical simulation of friction stir welding issues and computation verification according to the experimental measured data. In order to achieve results as close to the reality as possible, microstructure transformation of the weld joint and heat affected zone, and also temperature dependent material nonlinearities must be taken into account. Temperature field distribution in time depends on the type of heat source and parameters of the welding process. Also, microstructure and state transformations have influence on temperature field distribution. Temperature field distribution has significant influence on stress and strain development during and after welding.

## Introduction

Welding joints belongs to the most commonly used technologies of permanent joint manufacturing processes. The weld is created by local temperature increase of joined materials to the temperature that is usually higher than its melting temperature. Friction welding methods, including friction welding with mixing, do not reach a temperature higher than the melting point. Rapid local temperature changes cause high temperature gradient slopes, which causes temperature loads, phase and state transformations. Clamping condition loads during welding and the nonlinear material behaviour make welding simulations a very complex problem. Phase distribution in the weld and a heat affected zone develops during cooling after welding and has an influence on residual stresses distribution in the welded specimen. The combination of residual stresses and external loads have an influence on fatigue life of the welded constructions or on the development of discontinuities in the welds. In order to increase fatigue life of the welded structures it is necessary to keep the residual stresses on as low values as possible. A numerical simulation based on the finite element method can be a very useful tool for predicting residual stresses development during and after welding. The current state of the finite element method development leads to a tendency to simulate complex problems as technological processes. . With the use of the finite element method it is possible to transform a system of partial differential equations for finite amount of discrete points into a system of algebraic equations. These algebraic equation systems can be solved and evaluated effectively.

## Problem description

Friction stir welding is a method of joining materials permanently in a solid state. That means that temperature in the welding location will not be increased over the melting temperature of the welded materials. The material is heated by friction of the rotation tool with the shape of a pin, which is plunged by force into the specimen that will be welded. By sufficient heating the material becomes more easily plastic-formable. Material retreat and stir are then caused by the rotational movement of the tool. After the rotating tool is fully plunged into the material, the tool will start to move along the weld trajectory by translational movement. Blinding of the hole after welding is provided by the tool's shoulder that also has the function of protecting the weld. This welding process was primary developed for aluminium welding in the airospace industry with this welding method high-quality, high-strength, and low-distortion welds can be achieved. Another advantage of this method is the absence of additional materials and harmful fumes. These undisputed advantages lead to the acceptance and willingness of applying friction stir welding in the commercial sphere. Nowadays numerical simulations have become a common part of industry. In order to fully integrate friction stir welding into industry, numerical simulation of the whole process with cooling, taking in account phase transformation, need to be created. The current level of commercially available tools for friction stir welding simulations, FSW Toolbox for SYSWELD, have limited options. The use of this toolbox is primary intended for friction stir welding of aluminium alloys and only for quasi-unstable time step. The content of the presented paper deals with the simulation results after implementation of ferritic steel material models. These material models are taking into account phase transformations. That makes friction stir welding a very complex problem, which is coupled with the task of fluid flow, heat transfer, metallurgy and mechanics. In this case, metal is considered as an incompressible liquid that behaves according to the Norton-Hoff law.

## Computation of quasi-unstable time step for friction stir welding of ferritic steels

In the computation of quasi-unstable time step temperature depending material properties of steel S355J2G3 (STN 11 503) were used. The sequence scheme of algorithms for quasi-stable time step computation is shown in Fig. 1.

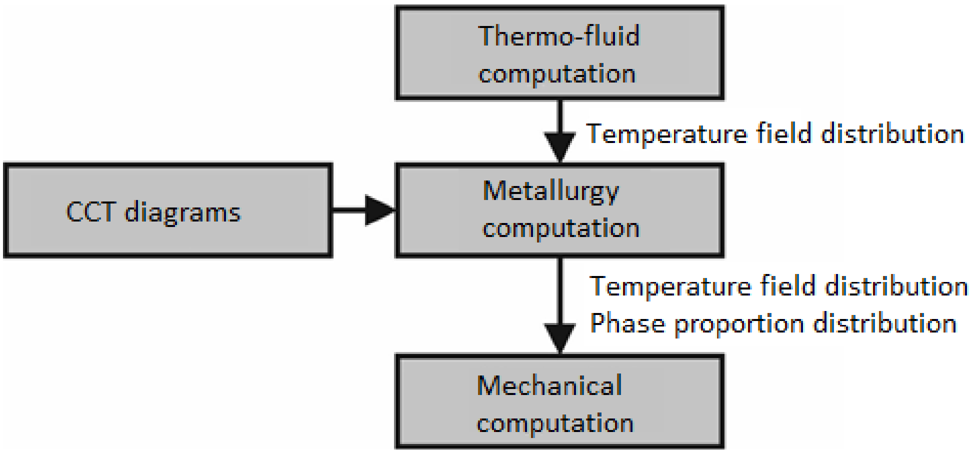



Fig.1. - Sequence scheme of friction stir welding computation

The first step is thermo-fluid computation for simulation of temperature field distribution, which is generated by the friction of the rotating tool. The weld metal is considered as an incompressible liquid that behaves according to the Norton-Hoff law and it depend only on the deformation speed rate. Heat transfer is considered according to the Fourier's law of heat conduction. As boundary conditions are considered convective temperature losses to the surroundings and technological parameters of the welding process, which have influence on the shape and efficiency of the heat source. The results of thermos-fluid computation are distributions of temperature field and velocity vectors for nodes. The temperature field distribution does not take into account temperature losses due to a phase or state transformation.

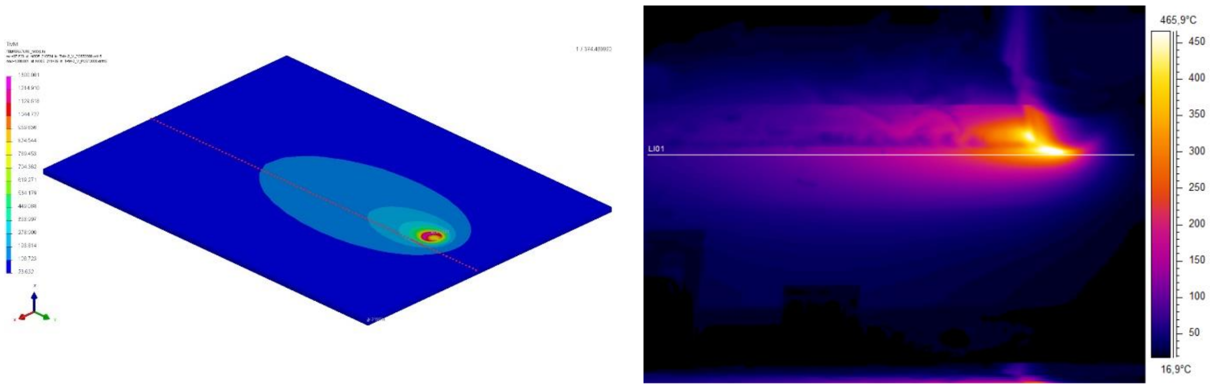
Metallurgy computation is used to determine the phase proportion distribution and takes into account temperature losses caused by phase and state transformation. For metallurgy computation the Johnson-Mehl-Avrami transformational kinetic law modified by Leblond is used, which takes into account CCT diagrams. Martensitic bi-difusional transformation is computed according to the Marburger's equation. These are semi-empirical equations. The results of metallurgy computation are phase proportion distributions and temperature field distributions with additional temperature losses caused by phase and state transformation.
Temperature field and phase proportion distributions are input loads for mechanical computation. Boundary conditions for this step of computation are clamping conditions and their stiffness. In general, for total strain rate computation Leblond's model is used in welding and heat treatment simulations.

$$\dot{\varepsilon} = \dot{\varepsilon}_e + \dot{\varepsilon}_p + \dot{\varepsilon}_{th} + \dot{\varepsilon}_{tp} \quad (1)$$

| | | |
|---|---|---|
| $\dot{\varepsilon}$ | - | total strain rate [-] |
| $\dot{\varepsilon}_e$ | - | elastic strain rate [-] |
| $\dot{\varepsilon}_p$ | - | plastic strain rate [-] |
| $\dot{\varepsilon}_{th}$ | - | temperature and metallurgical strain rate [-] |
| $\dot{\varepsilon}_{tp}$ | - | transformation plasticity [-] |

**Tuning of temperature field distribution**

For the experimental measurement of temperature field distribution a non-contact thermal-vision measurement method with FLIR® sc660 thermal imaging camera was chosen. In order to avoid rough mistakes during measurement, it is necessary to keep the emissivity of measured specimens on the same value during the measurement. For this reason, special paint, ThermaSpray 800, with known emissivity $\varepsilon$ = 0,96 guaranteed to the value of 600 °C was spread on the specimens. Temperature profiles on a line from a simulation were compared to those of an actual measurement. Both lines were located 20 mm parallel to the weld trajectory to avoid rough mistakes caused by emissivity changes during the measurement.




Obr. 2 – Comparison of temperature distribution of a simulation and measurement in time t = 374 s

Tuned parameters for determining the temperature field distribution were heat source efficiency $H$, friction coefficient $\mu$ and exponent $R$. Values of these coefficients are shown in table Tab.1. Heat exchange coefficients to the environment were tuned for each specimen's areas, because of different cooling conditions. Fig.3. is shows the comparison of the temperature profiles obtained by simulation and measurement.

Tab. 1

| | $H$ | $\mu$ | $R$ |
|---|---|---|---|
| Default value | 0,5 | 1 | 1 |
| Tuned value | 0,210 | 0,315 | 1 |

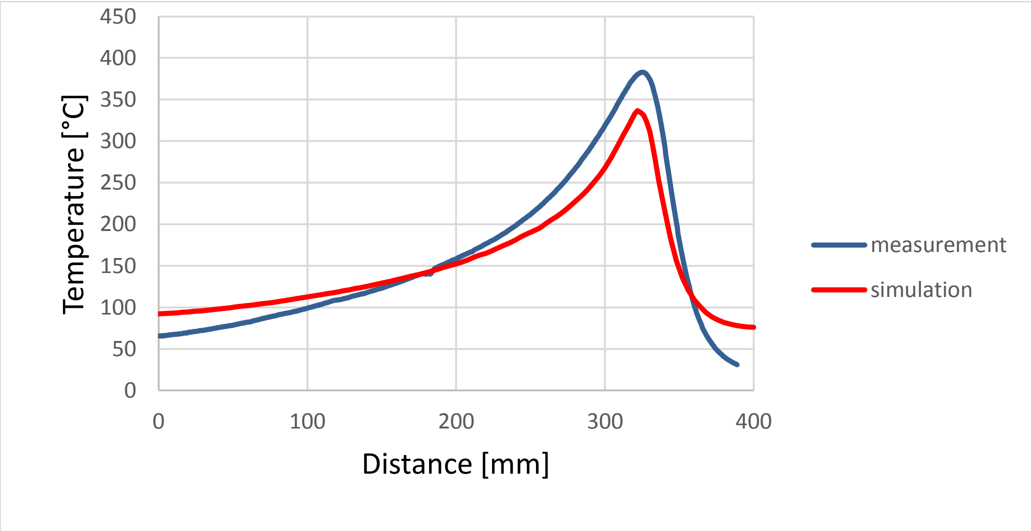
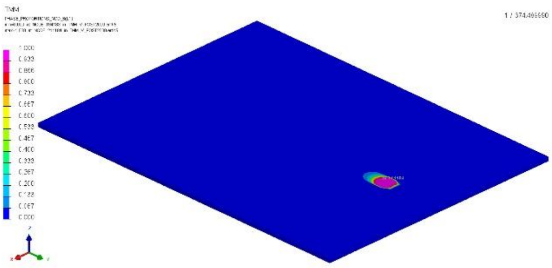
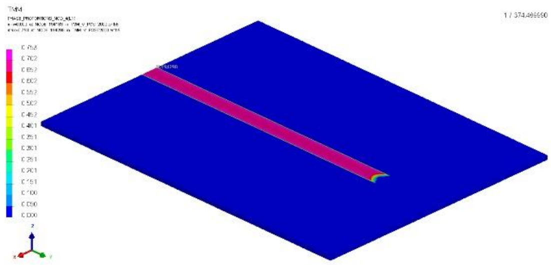



Fig. 3 Comparison of the temperature profiles obtained from simulation and measurement

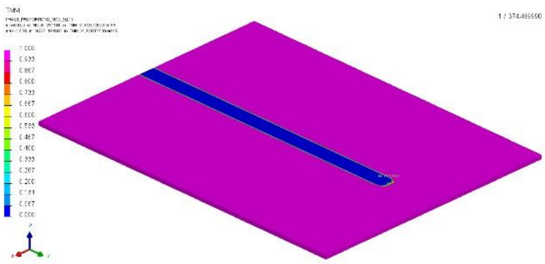
From the temperature field distribution phase proportions can be determined. In this case for the quasi-unstable time step in time t = 374 s. This time value is derived from the translational speed of the tool and from the weld line length. Phase proportion distributions are shown in Fig. 4.



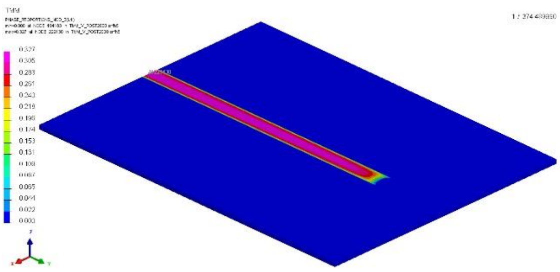
Austenit max. 100 %



Bainit max. 75 %



Ferit max. 100 %



Martenzit max. 32 %

Fig.4. - Phase proportion distribution in time t = 374 s

## Validation of Mechanical computation results

As boundary conditions for the mechanical computation clamped areas for nodes at certain localities were considered, where the specimen were clamped during the measurement. At a certain location, on the top surface of the measured specimen, a strain rosette was placed. Obtained data were processes in order to obtain results of the stress state according to Von Mises theorem. This Results were compared with the simulation results of stress state at a certain locality in time t = 374 s. Measurement locality is shown on the left in the red rectangle in Fig. 5 together with the stress distribution obtained by simulation at the same locality.

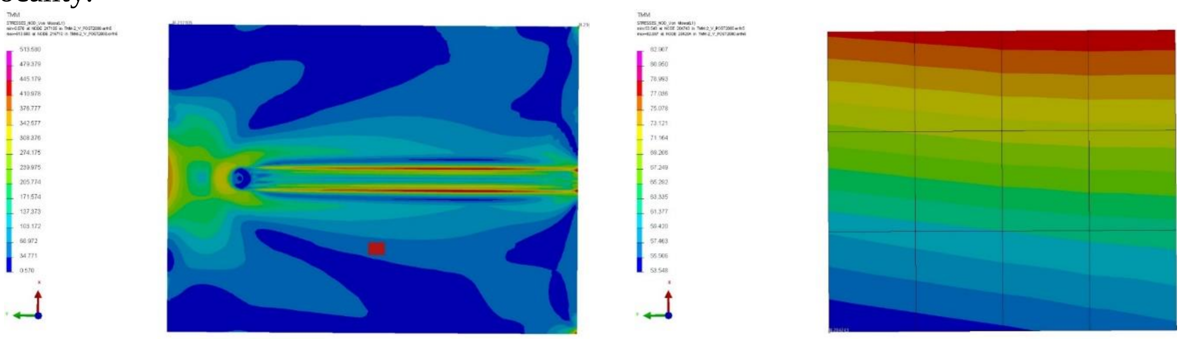


Fig.5. - Von Mises stress distribution in time t = 374 s, right – detail of measured locality $\sigma_{min}$ = 53,55 MPa, $\sigma_{max}$ = 82,91 MPa

Stress state results in time according to the Von Mises theorem obtained from the measurement in locality highlighted in Fig.5. are shown in Fig.6. Values of Von Mises stress in time t = 374 s are approximately around 60 MPa.

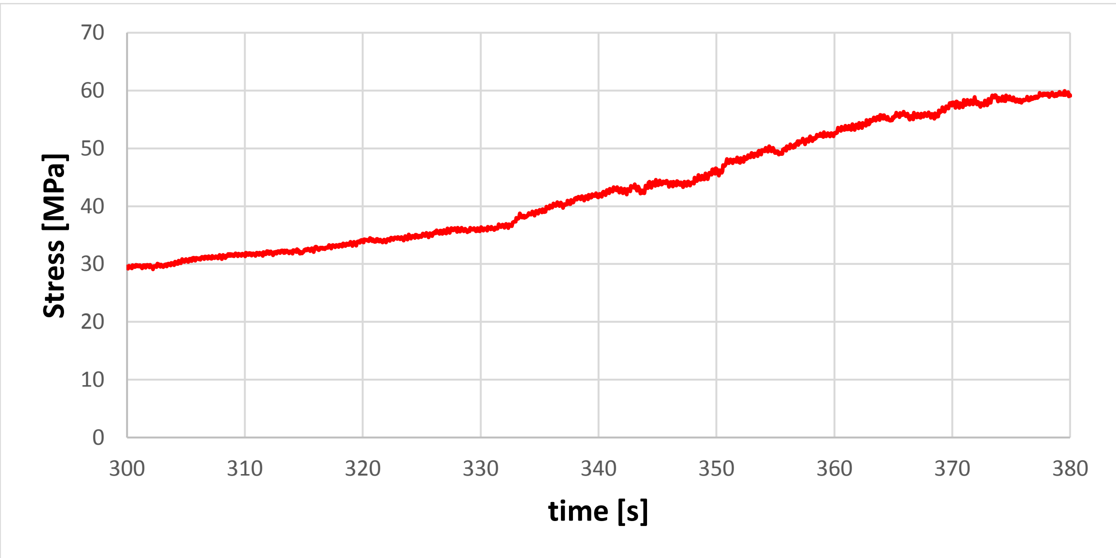



Fig. 6. – Stress state according to the Von Mises theorem obtained from measurement

## Summary

This paper deals with friction stir welding simulations of ferritic steels undergoing phase transformations. The use of temperature dependent material models for austenite, bainite, ferrite, perlite, and martenzite were verified by experiment. The tuning of boundary conditions, the heat source shape and parameters have shown that this simulation can be successfully used for ferritic steels as well.

## Conclusions

Further research has to be carried out to determine the final phases and the residual stress distribution over the body when the cooling process takes place.

## Acknowledgements

This publication is the result of the project implementation: Research of friction stir welding (FSW) application as an alternative to melting welding methods no. 26240220031 supported by the Research & Development Operational Programme funded by the ERDF. Funding from the VEGA grant 1/0740/16 is also greatly appreciated.

## References

[1] Feulvarch, E., Robin, V., Boitout, F., Bergheau, J. M.: 3D Modelling of thermofluid flow in friction stir welding including metallurgical and mechanical censequences. ESI Group, (2008)

[2] SYSWELD Reference Manual. ESI Group, (2013)

[3] Friction Stir Welding Modeling using SYSWELD V2008. ESI Group, (2008)

[4] Mishra, R. S., Mahoney, M. W.: Friction Stir Welding and Processing. 1. Vyd. AMS International, (2007)

[5] Slováček, M.: Numerické simulace zvařování. Výpočet a hodnocení dostorzí a zbytkových napětí. Dissertation thesis. Brno: Fakulta vojenskych technologii univerzity obrany v Brne, (2005) in Slovak

[6] Shercliff, H. R., Colegrove, P.A.: Modeling of Friction Stir Welding. Mathematical Modelling of Weld Phenomena 6, 927-974, (2002)

[7] Goldak, J., Akhlaghi, M.: Computational welding mechanics. Springer, (2005)

[8] Jančo, R., Écsi, L., Élesztös, P.: FSW Simulation of Aluminium plates by SYSWeld – Part I. The International Conference on Numerical and Experimental Solution of Welding, 15 – 19, (2014)

[9] Trebuňa, F., Šimčák, F., Bocko, J.: Using of numerical and experimental methods of mechanics to safety assessment of sluice equipments. In: Technológ. Roč. 5, č. 4 (2013), s. 19-22. in Slovak

[10] Jančo, R., Écsi, L., Élesztös, P.: FSW Simulation of Aluminium plates by SYSWeld – Part II. The International Conference on Numerical and Experimental Solution of Welding, 21 – 28, (2014)

[11] Kaločány, D.: Numerická a experimentálna analýza deformačného a napäťového stavu pri trecom zváraní s premiešavaním. PhD thesis. Bratislava: SjF STU, (2016) in Slovak