FE-simulation of rotary friction welding process considering thermo-mechanical-metallurgical coupling

B.-A. Behrens[1], A. Chugreev[1*], C. Kock[1], K. Brunotte[1], T. Matthias[1], H. Wester[1]

[1]Institute of Forming Technology and Machines (IFUM), Leibniz Universität Hannover, An der Universitaet 2, Garbsen, 30823, Germany
*Corresponding Author, (chugreev@ifum.uni-hannover.de)

Keywords: Friction welding, Simulation, FEA, Thermo-metallurgical coupling

Abstract

In the recent decades the finite element method has become an essential tool for the cost-efficient process design in the metal processing industry. In the automotive branch it is often employed in order to counter the constantly increasing quality standards and intensified international competition. In terms of multi-material component design, solid-state welding and particularly rotary friction welding (RFW) offers a cost-efficient joining process with an outstanding joint quality due to the intensive plastic flow within the heat-affected zone. However, since RFW involves phase transformations, local heating almost up to the melting point and high plastic strains, FE-based modelling of RFW comprising thermo-mechanical-metallurgical coupling becomes challenging and is the main objective of the current study.

1. Introduction and aspects of the developed numerical model

Almost all international governments are intensively working on the overall reduction of CO_2 emissions. The most ambitious aims were set by the European government in the transport sector with an objective of 95 g CO_2/km for new vehicles from 2020. According to a McKinsey study [1], major OEMs have to cut their fleet CO_2 emissions by approx. 30% in order to accomplish these goals. Moreover, due to constantly increasing international competition in the automotive industry, companies are strongly compelled to solve this challenging task under strong economical restrictions. Therefore, besides alternative energy sources and engine technologies, an efficient utilization of materials in car body or powertrain and thus material joining technologies will gain even more increasing importance in the next decades. In this context, rotary friction welding (RFW) represents a promising technology for production of multi-material high-performance lightweight components. Friction welding and its modifications has manifold application possibilities, e. g. solid state welding of even conventionally non-weldable materials [2], friction plug welding [3] or flow drill applications [4]. With the help of RFW, cost-intensive high-strength material can be utilized in the component area opposed to a high thermal or mechanical load. The rest of the joint part can be made of a lightweight (aluminum) or a less expensive (unalloyed carbon steel) material. The resulting friction weld exhibits excellent bonding strength and in some cases can even represent the strongest part of the component due to the deformation induced grain refinement [2].

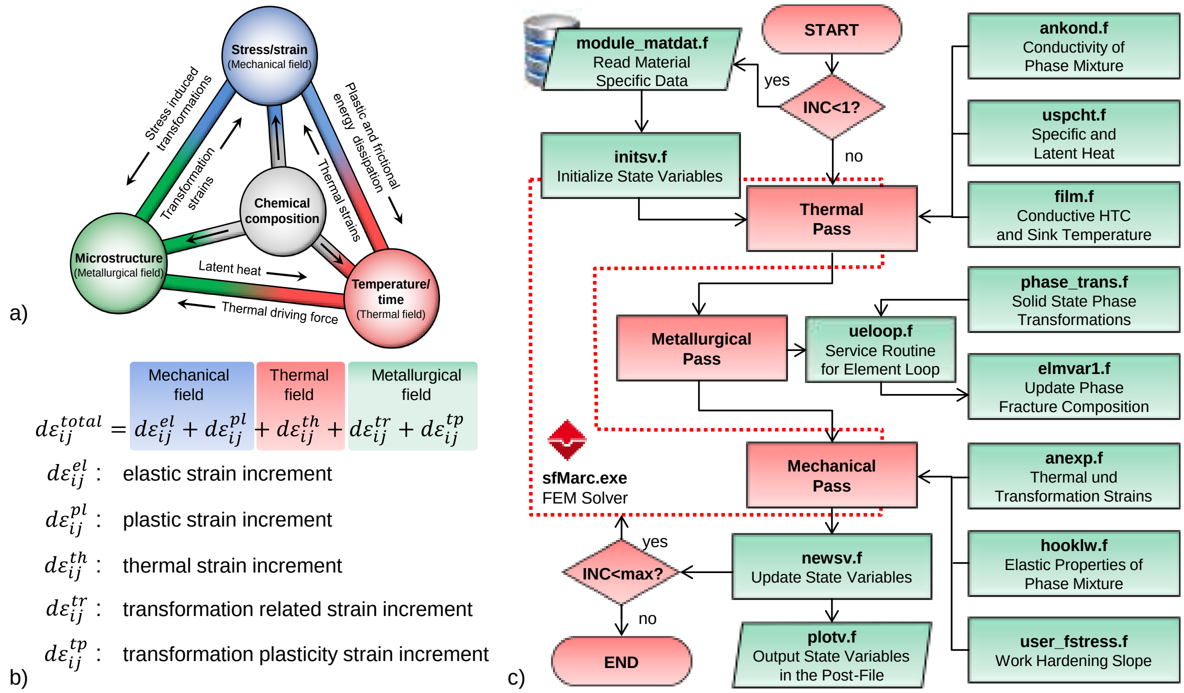

Figure 1. Interrelated thermo-mechanical-metallurgical material phenomena occurring during an RFW process (a), schematics of the involved additive strain decomposition method (b) and flowchart of the material model implementation in sfMarc-solver (c)

However, due to the combination of high temperature gradients, high plastic deformation, contact problems with two simultaneously deformed contact partners and presence of diverse phase transformations (Fig. 1a), an appropriate numerical simulation of a friction welding process still stays an objective of a current research. In [3, 5-7] a detailed literature survey on the modelling of RFW processes is given. Besides an unprecise description of weld geometry due to e. g. lack of remeshing, one of the most challenging drawbacks remaining often unconsidered, is the coupling of thermo-metallurgical material phenomena especially of local phase transformations and its impact on the mechanical material behavior [8, 9]. Modelling of the frictional heat generated within an RFW process is mostly realized as a function of conducted frictional work (W_{FR}) and its dissipation coefficient (β_{FR}), which is conventionally set to 0.9 meaning that 90% of frictional work is dissipated into heat [10]. Due to the rotational movement within the RFW, incremental frictional work of a node i on the contacting surface ($\partial\Omega^{contact}$) can be described as a function of its axial distance from the rotation centre (r_i), current frictional shear stress ($\tau_{R(i)}$), rotational speed ($\omega = 2 \cdot \pi \cdot n$) and incremental time ($dt$) [3, 9]:

$$dq_{FR(i)} = \beta_{FR} \cdot dW_{FR(i)} = \beta_{FR} \cdot \tau_{R(i)} \cdot \omega \cdot r_i \cdot dt \quad \text{on} \quad \partial\Omega^{contact} \qquad (1)$$

Because of the high frictional heat input, local temperatures may exceed the austenitization point of steel leading to local phase transformations with a corresponding influence on the material flow behavior. Therefore, a thermo-mechanical-metallurgically coupled material model originally developed in [11, 12] and applied for simulation of hot forging process chain [13] has been modified and applied to an RFW process case study. The model is based on the additive strain decomposition method (Fig. 1b) and has been implemented in Simufact Forming by means of user-subroutines (Fig. 1c).

3. Application and conclusions

The proposed material model was applied to an RFW process of a steel-steel weld with an objective of experimental validation. Therefore, a low-alloyed Cr-Mo steel 42CrMo4 (DxL = 40x200 mm) and an unalloyed steel C22 (DxL = 40x135 mm) have been welded at a KUKA Genius RFW machine. Besides the integrated force-displacement measurement, additional equipment consisting of infrared (IR) cameras, thermocouples and control units have been installed in the RFW machine for a real-time process data acquisition (Fig. 2a). The workpieces have been welded with 75 kN friction force at 1500 rpm stroke-controlled till a 4 mm burn-off was reached and subsequently forged with a force of 188 kN applied for 4 seconds.

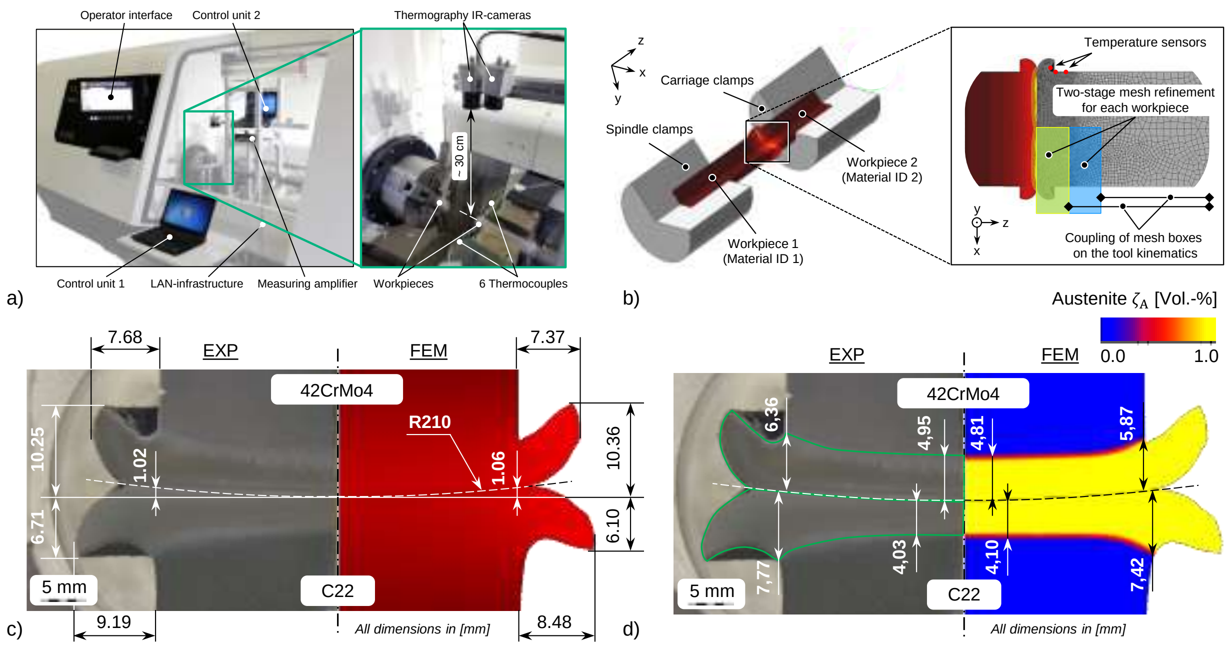

Figure 2. Experimental setup of RFW (a) and corresponding FE-model (b) as well as comparison of the final flash geometry (c) and heat-affected zone (d)

Due to the rotational symmetry a 2D axisymmetric FE-model depicted in Fig. 2b with the frictional heat generated on the contacting surfaces (Eq. 1) has been implemented in Simufact Forming, whereby a user-defined material model according to Fig. 1 and implicit solver procedure of MSC.Marc have been employed. Phase-dependent material data used in the current case study was mainly generated by means of the thermo-dynamical simulation software JMatPro [14] based on the chemical composition of the investigated alloys. Utilization of shear friction model enabled direct coupling of the tangential frictional stress to the local yield stress. Therefore, it was possible to describe the self-regulation effect preventing melting during RFW as discussed in [3]. The validation of the model parameters has been carried out based on the in-situ temperature-, force-, displacement- and ex-situ geometry and metallographic measurements. An exemplary comparison between experimentally produced and numerically computed flash resulting from the plastic material flow and the heat-affected zone (HAZ) geometries are presented in Fig. 2c-d. Compared to 42CrMo4, C22 workpiece shows a slightly larger flash formation which indicates an intensified plastic material flow due to its lower yield stress. Reliable prediction of the flash geometry and the material flow has been possible due to the tailored mesh design with adaptive element edge size from 2.5 to 0.3 mm (Fig. 2b) and stable remeshing algorithms involved. Furthermore, due to the consistent thermo-metallurgical material modelling, prediction of the HAZ geometry was possible. As depicted in Fig. 2d, the width of HAZ clearly correlates with the elements undergoing austenitization during the welding process. In general, the developed material model has led to a good prediction of the real material behavior within this preliminary case study. The future works will aim at the investigation of further material combinations and process parameters for purpose of a more comprehensive validation and prediction of the final component properties or resulting residual stress state.

9. Acknowledgments

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – Nr. 374871564, Nr. 252662854.

10. References

[1] Heuss R (2012) Lightweight, heavy impact. Advanced Industries, McKinsey & Company, 1-22
[2] Lienert TJ (Ed.) (2011) ASM Handbook Welding Fundamentals and Processes. ASM Int., Ohio
[3] Schmicker D (2015) A holistic approach on the simulation of rotary friction welding. PhD Thesis, Otto-von-Guericke University Magdeburg
[4] Kumar R, Rajesh Jesudoss Hynes N (2018) Finite-element simulation and validation of material flow in thermal drilling process. J. Br. Soc. Mech. Sc. Eng., 40:162-171. doi: 10.1007/s40430-018-1091-y
[5] Li W, Vairis A, Preuss M, Ma T (2016) Linear and rotary friction welding. Int. Mat. Reviews, 61-2: 71-100. doi: 10.1080/09506608.2015.1109214
[6] Furrer DU, Semiatin SL (2010) ASM Handbook Vol. 22B Metals Process Simulation. ASM Int., Ohio
[7] Maalekian M (2007) Friction welding – critical assessment of literature. Sc. and Tech. of Welding and Joining, 12-8:738-759. doi: 10.1179/174329307X249333
[8] Prokopczuk MP (2011) Neue Herstellungsverfahren für integral beschaufelte Rotoren. PhD Thesis, Technical University Munich
[9] Li W, Shi S, Wang F, Zhang Z, Ma T, Li J (2012) Numerical simulation of friction welding processes based on ABAQUS environment. J. Eng. Sc. Tech. Review, 5-3: 10-19
[10] ASM HandbookW Volume 22A Fundamentals of Modeling for Metals Processing
[11] Behrens BA, Schroedter J, Brands D, Scheunemann L, Niekamp R, Chugreev A, Sarhil M, Uebing S, Kock C (2018) Experimental and numerical investigations on the development of residual stresses in thermo-mechanically processed steels, Prod. Eng. (submitted)
[12] Behrens BA, Chugreev A, Kock C (2019) Experimental-numerical approach to efficient TTT-generation for simulation of phase transformations in thermomechanical forming processes, Mat. Sc. and Engineering, 461-1
[13] Behrens BA, Chugreeva A, Chugreev A (2018) FE-simulation of hot forging with an integrated heat treatment with the objective of residual stress prediction. AIP Conf. Proc., 1960-040003.
[14] Guo Z, Saunders N, Schille JP, Miodownik AP (2009) Material properties for process simulation. Mat. Sc. Eng.: A, 499-1-2:7-13. doi: 10.1016/j.msea.2007.09.097