# Finite element simulation of microstructure evolution during friction stir welding of automotive aluminum parts

**A.Khalkhali[1,*], M. J. Saranjam[2]**

1. Assistant Professor, 2.MSc Student Automotive Simulation and Optimal Design Research Laboratory, School of Automotive Engineering, Iran University of Science and Technology, Tehran, Iran

* Corresponding Author

**Abstract**

7000 series Aluminum alloys are widely used in the automotive industries for structural lightweight components due to their exceptional high strength to weight ratio. However, this class of aluminum alloy is difficult to join by conventional fusion welding techniques so Friction stir welding (FSW) widely is used for welding this alloys. The process has been demonstrated to be effective and is currently industrially utilized for materials difficult to be welded or "un weldable", especially aluminum and magnesium alloys. In this paper in order to predict the average grain size occurring in FSW of AA7050 plates due to the dynamic recrystallization (DRX) phenomena due to the welding process, a microstructure evolution model have been implemented in 3D fully coupled thermo-mechanical FEM in which the tool – work piece interaction in FSW of butt joint was investigated.

***Keywords**: Friction Stir Welding (FSW), Microstructure evolution, Dynamic recrystallization, Finite Element Method (FEM), Average grain size*

## 1. Introduction

7000 series Aluminum alloys based on the Al-Zn-Mg-Cu system are widely used in the automotive industries for structural lightweight components due to their exceptional high strength to weight ratio, better corrosion resistance, excellent toughness, low cost as well as good machinability [1]. However, this class of aluminum alloy is difficult to join by conventional fusion welding techniques because the dendritic structure formed in the fusion zone can seriously compromise the mechanical properties of the joint [2]. Therefore, Friction stir welding (FSW) widely is used for welding 7000 series aluminum alloy to similar or dissimilar materials.

Friction stir welding is a solid state welding process, patented in 1991 by The Welding Institute (TWI), in which rotating tool is inserted into the adjoining edges of the sheets to be welded with a proper tilt angle and moved all along the joint. The composition of the tool rotation and advancing velocity vectors induces a characteristic metal flow all around the tool contact surface. The tool movement determines heat generation due to friction forces and material deformation work. The process has been demonstrated to be effective and is currently industrially utilized for materials difficult to be welded or "unweldable", especially aluminum and magnesium alloys [3].

Because material subjected to FSW does not melt and recast, the resultant weldment offers advantages over conventional arc weldments such as better retention of baseline mechanical properties, less distortion, lower residual stresses, and fewer weld defects. Friction stir welding achieves solid phase joining by locally introducing frictional heat and plastic flow by rotation of the welding tool with resulting local microstructure changes in aluminum alloys. The local microstructure determines the weld mechanical properties. Therefore, it is important that details of microstructural evolution during the severe thermo-mechanical conditions imposed by FSW be well-defined [2]. The FSW joint contains four different zones, namely the stir zone, thermo-mechanical affected zone (TMAZ), heat affected zone (HAZ) and the unaffected base metal, respectively.

In materials with high-stacking fault energy such as aluminum and its alloys, dynamic recovery and recrystallization are the main restoration processes during and after thermo-mechanical treatment. At specific boundary conditions, such as chemical composition, initial grain size, accumulated strain, strain rate and temperature, dynamic recrystallization (DRX) can occur during hot deformation of aluminum alloy. DRX is a process in which a fine and nearly equiaxed grain structure is formed [4].

Recently, research activities have been developed on the numerical simulation of FSW processes. In order to reveal the thermal and mechanical behavior near the tool of FSW, many numerical studies have been conducted, where, for examples, finite element method (FEM), finite different method (FDM), computational fluid dynamics (CFD) and arbitrary Lagrangian – Eulerian (ALE) formulation were employed. However, FEM is one of the most powerful tools for predicting the welding process and microstructure evolution. Since the welding process is transient behavior thermally and mechanically, both the thermal and mechanical analyses should be conducted alternately with increasing the time step. Generally, the transient thermal distributions are computed at first and then the elastic-plastic analyses are conducted using the temperature distributions obtained [5].

In this paper in order to predict the average grain size occurring in FSW of AA7050 aluminum alloy plates due to the dynamic recrystallization (DRX) phenomena due to the welding process, a 3D fully coupled thermo-mechanical FEM model have been presented in which the tool – workpiece interaction in FSW of butt joint was investigated. In particular, the material microstructure evolution was taken into account through a proper model of grain size evolution due to recrystallization phenomena. It should be observed that in FSW processes DRX occurs due to the tool pin action. The tool stirring action generates fine, equiaxed, recrystallized grains; such new microstructure determines the local material mechanical properties and the overall joint resistance.

## 2. The theoretical equations

### 2.1. Constitutive equation

The Arrhenius equation is widely used to describe the relationship among the strain rate, flow stress and temperature at high temperatures. In order to adapt all stress conditions, a hyperbolic sine in Arrhenius type equation containing activation energy Q and temperature T can be expressed as:

$$\dot{\varepsilon} = A[\sinh(\alpha\sigma^p)^n]\exp(\frac{\mathrm{Q}}{\mathrm{RT}})$$

where A, α and n are the constants independent of temperature, σp is the peak stress, $\dot{\varepsilon}$ is the strain rate, Q is the activation energy for hot deformation, R is the universal gas constant (8.314472 [J/K.mol]) and T is the absolute temperature. However, in this paper the value for A is 5.83e18 and α, n, Q are 0.01239, 7.598 and 2.6406e5 [J/mol] respectively [6].

### 2.2. The Avrami model

It is known that only when dislocation density or strain reaches a critical value can dynamic recrystallization occur during hot deformation. Dislocation density or strain is related with temperature and strain rate. Microstructure evolution is strongly associated with nucleation rate and grain growth kinetics. There are several dynamic recrystallization models for microstructure evolution. For the goal of simulation in this study, the models offered by DEFORM-3D™ are adopted, in which the constants can be evaluated by experimental data.

Generally, the onset of dynamic recrystallization occurs at a critical strain εc (εc = 0.8εp), and εp can be expressed as

$$\varepsilon_p = a_1 d_0^{n_1} \dot{\varepsilon}^{m_1} \exp\left(\frac{Q_1}{RT}\right) + c_1$$

Where Q1 indicates activation energy and the value in this paper is 1.318e4. a1, experimental coefficient, and m1, grain – strain – strain rate experimental exponent, are 4.107e-3 and 0.06 respectively [6].

The Avrami equation used to describe the relationship between the dynamically recrystallized fraction X and the effective strain can be written as

$$X_{DRX} = 1 - \exp[-\beta_d \left(\frac{\varepsilon - a_{10}\varepsilon_p}{\varepsilon_{0.5}}\right)^{k_d}]$$

**Table 1 –** Dynamic recrystallization coefficient

| | $\beta_d$ | $k_d$ | $Q_5$ | $Q_8$ | $a_5$ | $a_8$ | $a_{10}$ | $h_5$ | $m_5$ | $m_8$ |
|---|---|---|---|---|---|---|---|---|---|---|
| **Material data** | 0.693 | 2 | 5.335e4 | -19002.72 | 1.214e-5 | 78.6022 | 0.8 | 0.13 | 0.04 | -0.03722 |

Where βd is material data experimental coefficient; kd is material data experimental exponent and ε0.5 denotes the strain for 50% recrystallization volume fraction given as

$$\varepsilon_{0.5} = a_5 d_0^{h_5} \varepsilon^{n_5} \dot{\varepsilon}^{m_5} \exp\left(\frac{Q_5}{RT}\right) + c_5$$

The recrystallized grain size is expressed as a function of initial grain size, strain, strain rate and temperature, written as

$$d_{DRX} = a_8 d_0^{h_8} \varepsilon^{n_8} \dot{\varepsilon}^{m_8} \exp\left(\frac{Q_8}{RT}\right) + c_8$$

The average grain size can be calculated by the equation as

$$d = d_0(1 - X_{DRX}) + d_{DRX} X_{DRX}$$

All dynamic recrystallization coefficients for AA7050 have been demonstrated in table 1 [6].

## 3. The numerical model

The commercial FEM software DEFORM-3D™, Lagrangian implicit code designed for metal forming processes, has been utilized to model the FSW process. The assembly of the FEM model consists of three parts: tool, workpiece and back plate. The workpiece of AA7050 plates with nominal composition in table 2 was modelled as a rigid viscoplastic material. The utilized tool and back plate were made of hot-work steel H13 and considered as rigid bodies. The default values for both thermal and mechanical properties in DEFORM-3D™ were used for H13 in this work. The pin rotation speed was 630 rpm and the pin travel speed was 38 mm/min. The FSW numerical simulation modeled to investigate the thermo-mechanical phenomena in the formation of the weld nugget.

Therefore, The size of workpiece is $150 \times 100 \times 4.3\ mm$. In order to optimise the resolution close to the tool and minimise the computational expenses, non-uniform mesh density with automatic remeshing was applied in the work piece. four mesh windows have been used for this purpose. Window number 1 with the finest mesh size under the tool was set to 0.5 mm and the outer mesh window was set to 3 mm. Figure 1 shows the numerical model of FSW. The sheet blank, 4.3 mm in thickness and the utilized tool were meshed with about 88,000 and 20,000 tetrahedral elements, respectively. For the auto remeshing during numerical simulation, tetrahedron element was used in DEFORM-3D™. During the deformation process, the relative interference depth 0.7 is used for the remesh criteria.

The friction coefficient between tool and work piece is an input parameter in the FE model and is used in heat generation formulations. The constant shear friction model was selected in this study. If the friction factor is too small, heat generation will be too low to plastify the materials and to weld them, while in the simulation, too large friction factors may result in an unreasonable thermal field. In this research, shear friction factor 0.45 was used.

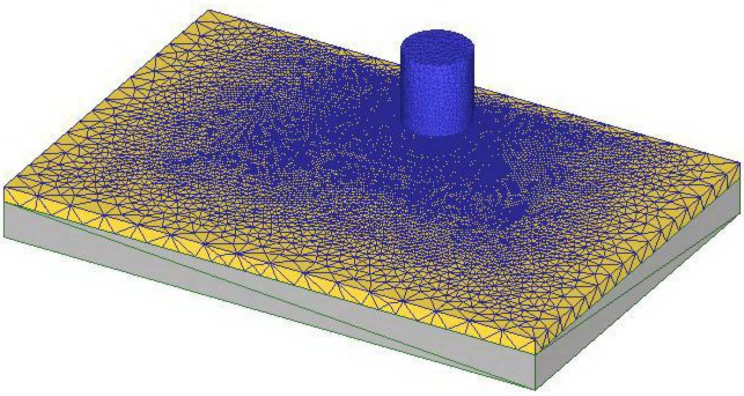

**Fig1.** The FEM model and Schematic illustration of tool, work piece and back plate

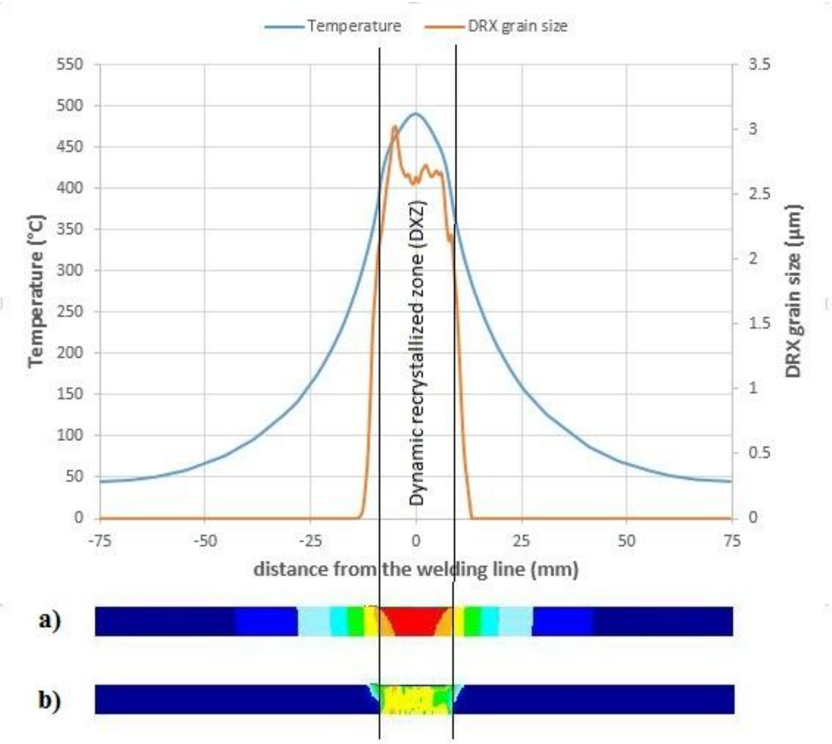


**Fig2.** temperature (a) and dynamically recrystallized grain size (b) profile and distribution in a transverse section of welded plates

## 4. Results and discussion

The present investigation has confirmed that during FSW the original base metal grain structure is completely eliminated and replaced by a very fine equiaxed grain structure in the dynamically recrystallized zone (DXZ). Dynamic recrystallization during FSW has been considered to be created by locally introducing heat by both friction heating and severe plastic strain. The frictional heating and plastic strain increase from the TMAZ to the DXZ. Figure 2 shows temperature and dynamically recrystallized grain size profile and distribution in a transverse section of welded plates. Therefore, analysis of the microstructure changes from the TMAZ to the DXZ may give some understanding of dynamic recrystallization in the DXZ

The basic input data for the microstructure model, temperature, effective strain and strain rate are very important. Figure 3 shows temperature, effective strain and strain rate at 10 mm in advance from the beginning of the process. From the calculation, the peak temperature in the work piece can be estimated to be 494 °C, which is about 0.78 times the melting temperature of the base metal. The temperature distribution is symmetric and maximum temperatures appear at the interface between tool and work piece. The effective strain at the pin surface and below the shoulder is about 110 mm/mm, which is judged to be very high. The effective strain rate at the periphery of the pin is also quite large with values up to 140 (mm/mm)/s.

The Avrami model described earlier was implemented into DEFORM-3D to calculate the microstructure evolution during FSW. Dynamic recrystallization may take place if strain and deformation temperature reach some critical values synchronously, because the occurrence of dynamic recrystallization needs a process to build up the stored energy. The volume fraction of dynamic recrystallization increases with the increasing of strain and deformation temperature [9]. The fraction of dynamic recrystallization can be seen in Figure 4.

It can be seen in Figure 5 that the predicted grain size in stir zone at the end of process is around 2-5 µm which is in good agreement with previous articles [7]. In the other area out of the shoulder, the grain size remains unchanged due to the low heat input, about 90 µm, which is indicated in Figure 6.

To evaluate the effect of tool rotation speed on dynamic recrystallized grain size, four finite element simulations are performed for 300, 630, 960 and 1290 rpm. Figure 7 shows DRX grain size for different simulations. As can be observed, as the tool rotation speed is reduced, the final grain size is reduced

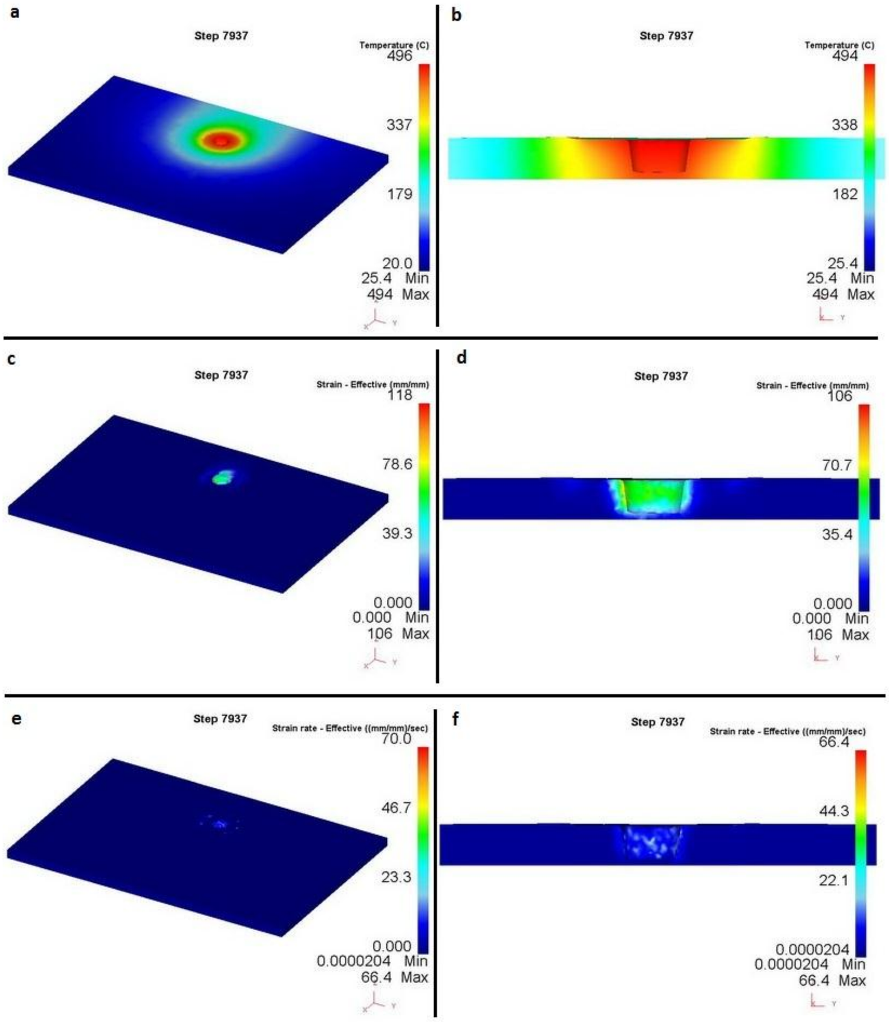


**Fig3.** Temperature (a, b), strain (c, d) and strain rate (e, f) distribution at 10 mm in advance from the beginning of FSW in full and cut – open view, respectively

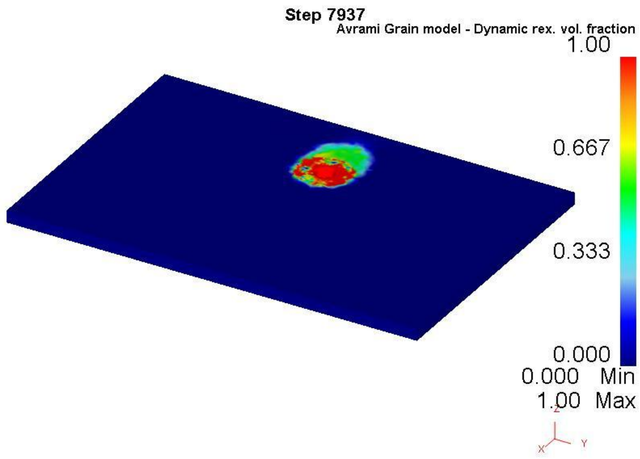


**Fig4.** The volume fraction of dynamic recrystallization at the end of simulation

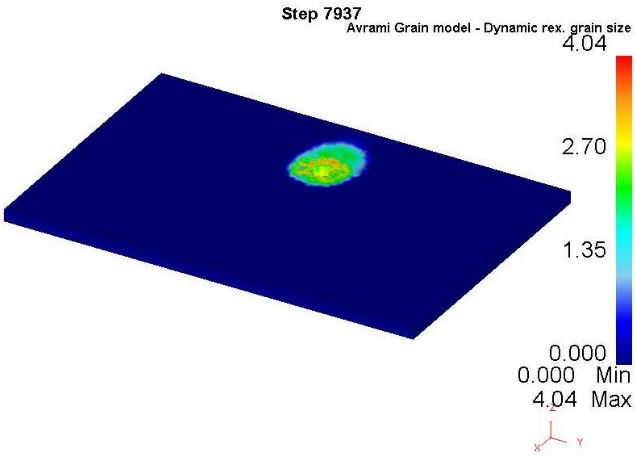


**Fig5.** The dynamically recrystallized grain size (µm) at the end of simulation

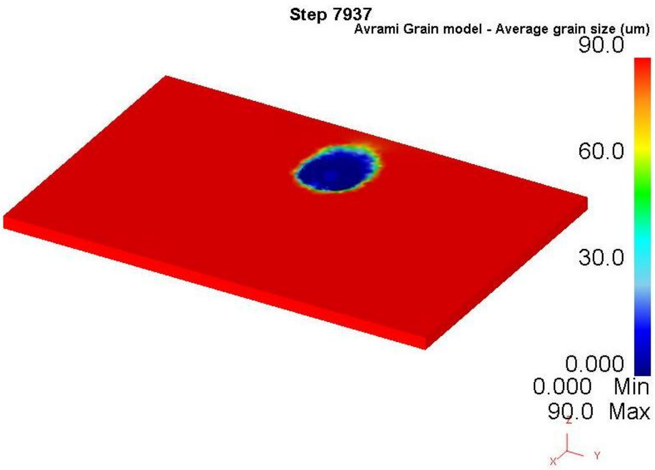


**Fig6.** The average grain size (µm) of welded plate at the end of simulation

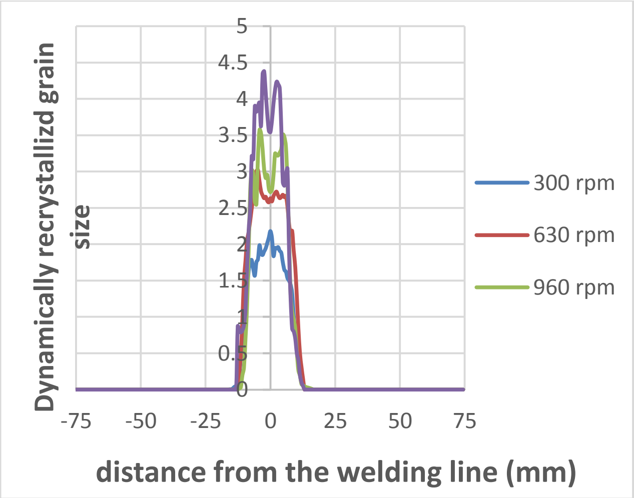


**Fig7.** Dynamically recrystallized grain size for 300, 630, 960 and 1290 rpm case study

## 5. Conclusions

In the paper, to understand the microstructural evolution during FSW in AA 7050 aluminum alloy, the Avrami model is implemented in the commercial FEM software DEFORM-3D™ and a FE model is used in order to calculate the final average grain size due to the DRX phenomena in FSW. The model returned calculated both the fraction of dynamic recrystallization and average grain size values in the nugget area close to the experimental efforts.

After FSW, the microstructure in the stir zone consists of a fine and equiaxed grain structure. The predicted grain size in the stir zone is around 2.5 µm, which agrees well with the experimental results. During FSW, the effective strain and strain rate is extremely high due to the high-rotational speed of the tool. The effective strain under the tool is high enough to exceed the critical strain which is necessary for DRX.

It can be easily predicted that further improvements in the FEM model and in the specific grain size evolution model would lead to an even more accurate grain size prediction.

## References

[1]. Wangtu Huo, Longgang Hou, Hua Cui, Linzhong Zhuang, Jishan Zhang, "Fine-grained AA 7075 processed by different thermo-mechanical processing", http://dx.doi.org/10.1016/j.msea.2014.09.026

[2]. J.-Q. Su, T.W. Nelson, R. Mishra, M. Mahoney, "Microstructural investigation of friction stir welded 7050-T651 aluminum", Acta Materialia 51 (2003) 713–729

[3]. Gianluca Buffa, Livan Fratini, Fabrizio Micari, "Mechanical and microstructural properties prediction by artificial neural networks in FSW processes of dual phase titanium alloys", Journal of Manufacturing Processes 14 (2012) 289–296

[4]. Z. Gao, J.T. Niu, F. Krumphals, N. Enzinger, S. Mitsche, C. Sommitsch, "FE modelling of microstructure evolution during friction stir spot welding in AA6082-T6", DOI 10.1007/s40194-013-0083-x

[5]. H Serizawa, J Shimazaki, F Miyasaka, G Yoshikawa, H Murakawa, "Basic numerical analysis of friction stir welding with a combination of MPS and FEM"

[6]. YI You-ping, FU Xin, CUI Jin-dong, CHEN Hua, "Prediction of grain size for large-sized aluminium alloy 7050 forging during hot forming", 10.1007/s11771−008−0001−3

[7]. T.R. McNelley, S. Swaminathan and J.Q. Su, "Recrystallization mechanisms during friction stir welding processing of aluminum alloys", Scripta Materialia 58 (2008) 349–354

[8]. B. Wu, M.Q. Li, D.W. Ma "The flow behavior and constitutive equations in isothermal compression of 7050 aluminum alloy", Materials Science and Engineering A 542 (2012) 79-87

[9]. G. Buffa, L. Fratini, R. Shivpuri, "CDRX modelling in friction stir welding of AA7075-T6 aluminum alloy Analytical approaches" Journal of Materials Processing Technology 191 (2007) 356–359

[10]. DEFORM-3D™ V10.2 User's manual, SFC, Columbus, Ohio, USA