Deformation-induced surface roughening of an Al-Mg alloy

Paul Knysh¹, Kanta Sasaki², Tsuyoshi Furushima³, Marko Knezevic¹ and Yannis P. Korkolis¹*

¹Department of Mechanical Engineering, University of New Hampshire
²Department of Mechanical Engineering, Tokyo Metropolitan University
³Institute of Industrial Science, University of Tokyo

*yannis.korkolis@unh.edu

Abstract. We analyze the deformation-induced surface roughening of an Al-Mg alloy. One aspect of our work is an effort to model the exact roughening behavior of a mesoscale-size specimen that contains a small number of grains. Such a specimen is obtained using prestrain, recrystallization annealing and subsequent machining. It contains one layer of grains through the thickness and is tested under uniaxial tension. A laser confocal microscope is then used in order to measure the surface profile of a deformed specimen. We apply crystal plasticity finite element method to a voxel model of a given specimen. The exact arrangement of grains in the voxel model is reconstructed from a pair of electron backscatter diffraction (EBSD) scans using a custom-developed shape interpolation procedure. The material properties of the Al-Mg alloy are found using an efficient black-box optimizer. The exact shape of the deformed specimen wasn’t fully captured, however results on average surface roughness show good matching between model and experiment.

1. Introduction
During forming, the sheet metal undergoes plastic deformation. Assuming this deformation does not cause necking and fracture [1], it still often causes additional side effects that influence the look and performance of the resulting metal part. One of such effect is deformation-induced heating [2]. Another effect is the topic of the current study – deformation-induced surface roughening.

Research on surface roughening of metals was performed for many materials including pure aluminum and aluminum alloys ([3], [4]), titanium [5], iron [6], stainless steel [7], copper ([8], [9]) etc. The most common testing technique is the uniaxial tension test ([6], [10]); however, other techniques are also used, for example cup drawing ([8], [9]) or friction forming [3].

In order to model the proper physics of deformation, crystal plasticity models are most commonly used ([4], [5], [11]). Most of these studies are constructing the artificial texture using different procedures, only few studies were attempting to reconstruct the exact texture of the given specimen.

In the current paper we are studying the roughening behavior of an oligocrystal specimen that contains one layer of grains through the thickness. Because of a reconstruction procedure developed for this work, it is possible to take into account the real, instead of columnar, shapes of the grains, which increases the modeling accuracy.

2. Experiments
We performed a tension test on mesoscale-size A5052-O specimens. The relative size and absolute dimensions of such specimens are shown in Fig. 1. A special material preparation procedure that
includes prestrain, heat treatment and machining was developed in order to produce a desired range of grain sizes, starting from a polycrystal. The obtained specimen contains one layer of grains through the thickness, which allows reconstructing its volumetric texture using only top and bottom scans.

The tension test was performed using Zwick/Roell universal testing machine with a laserXtens extensometer. The specimen is tested under displacement control at a strain-rate of \(4.17 \times 10^{-4} \text{ s}^{-1}\).

![Image](image1.png)

Fig 1. a – size of the specimen in comparison to rice grains; b – specimen dimensions (in mm)

3. Modeling

3.1. Crystal plasticity finite element (CPFE) model overview

The majority of studies on surface roughening try to predict the overall roughness metrics (such as \(R_a\)). The major challenge of current study is an attempt to capture not only the average roughness parameters, but also the deformed geometry of the (oligocrystal) specimen. Solving this task even partially would provide useful insights on capabilities and limitations of used micromechanical model. Furthermore, as roughening can trigger localization of deformation and this failure, capturing the deformed geometry can be critical for predictions of failure in polycrystalline metals.

In order to capture the physics of crystal plasticity, we need to use the appropriate material model. We use the crystal plasticity based constitutive law coupled with dislocation density evolution \([12]\). Below we provide the overview of this model.

The total deformation gradient \(F\) is decomposed into elastic (\(F^e\)) and plastic (\(F^p\)) components:

\[
F = F^e F^p.
\]  

The evolution of plastic component due to slip is given by:

\[
\dot{F}^p = L^p F^p,
\]

where \(L^p\) is the plastic velocity gradient that can be represented as:

\[
L^p = \sum_\alpha \dot{\gamma}^\alpha b^\alpha_0 \otimes n^\alpha_0.
\]

Vectors \(b^\alpha_0\) and \(n^\alpha_0\) indicate the slip direction and slip plane normal of a given slip system \(\alpha\). \(\dot{\gamma}^\alpha\) is the slip rate along \(\alpha\) that can be expressed with the following power law relationship:

\[
\dot{\gamma}^\alpha = \dot{\gamma}^\alpha_0 \left(\frac{|\tau^\alpha|}{\tau^\alpha_c}\right)^{1/m} \text{sign}(\tau^\alpha),
\]

where \(\dot{\gamma}^\alpha_0\) is a reference slip rate, \(m\) is the strain-rate sensitivity parameter, \(\tau^\alpha\) is the resolved shear stress and \(\tau^\alpha_c\) is the characteristic resistance shear stress, which can be decomposed into 4 different contributions:

\[
\tau^\alpha_c = \tau^\alpha_f + \tau^\alpha_{HP} + \tau^\alpha_{for} + \tau^\alpha_{sub}.
\]

All 4 terms in (5) represent different physical aspects – \(\tau^\alpha_f\) is a friction term, \(\tau^\alpha_{HP}\) is a Hall-Petch, or barrier effect term, and \(\tau^\alpha_{for}\) and \(\tau^\alpha_{sub}\) are the contributions from interaction of dislocations. While the first two terms account for the initial value of slip resistance and in turn yield stress, the latter two terms govern strain hardening and evolve with plastic strain. A more detailed description of each term is given in [12].
3.2. Identification of material properties

We approach the material identification problem in a systematic way and consider it as an optimization task. The corresponding objective function is a Python function assembled from several blocks and shown in Fig. 2a. It takes a vector $x$ of 4 unknown parameters as an input, runs the FEA model of the tension test, compares how well the corresponding engineering stress-strain curve matches the experiment (Fig. 2b) and returns the integral error $E$ between these two curves.

We use “blackbox” – an optimization method [13] designed specifically for expensive black-box functions (ones that have input-output nature). The method was successfully used previously for identification of post-necking hardening curves [14]. Since the method is also implemented as a Python module, it can be easily integrated into our environment.

Fig 2. a – optimization procedure; b – matching between FEA (optimized parameters) and experimental stress-strain data

Fig 3. a – processed EBSD scans of top and bottom; b – a 3D model of corresponding tensile specimen and boundary conditions
3.3. Mesh construction
A 3D voxel model of the given specimen that is reconstructed from top and bottom scans (Fig. 3a) is shown in Fig. 3b. A corresponding 3D shape interpolation method based on morphing technique was developed and used. The overall resolution of the obtained voxel mesh is 316×50×6, which results in about 100k elements. The model was created in Abaqus/Standard using C3D8 elements (linear, full-integration).

Boundary conditions are shown in Fig 3b. Prescribed displacements are applied at both ends of the specimen. In addition, a vertical edge and its adjacent vertex are fixed (zero displacements) in order to prevent the rigid body motion.

4. Comparison between experiment and model
We compare the surface profiles of the deformed specimen based on FEA results with the experimental measurements using laser confocal microscope (Fig. 4a). As can be seen, our predictions are not matching the experiment perfectly. Additional physical features such as geometrically necessary dislocations and local back stress might be included into the crystal plasticity model for accuracy improvements.

Another result that can be extracted from the FEA simulation is the evolution of the average surface roughness $S_A$ with the axial strain, see Fig. 4b. The dependence is very close to linear, which is in accordance with the previous studies ([10], [11], [15], [16]).

5. Conclusions
We analyzed the deformation-induced surface roughening of an Al-Mg alloy by looking at the roughening behavior of a mesoscale-size specimen that contains a small number of grains during the uniaxial tension test. The exact arrangement of grains in the voxel model is reconstructed from a pair of EBSD scans using a custom-developed shape interpolation procedure. We then applied crystal plasticity finite element method. The corresponding material properties of the Al-Mg alloy were calibrated using an efficient black-box optimizer. The exact deformed shape of the specimen wasn’t fully predicted, however the results are showing a good matching between the model and the experiment in an average sense.

References
[1] Suresh, S. and Ritchie, R.O., 1982. A geometric model for fatigue crack closure induced by fracture surface roughness. Metallurgical Transactions A, 13(9), pp.1627-1631.
[2] Knysh, P. and Korkolis, Y.P., 2015. Determination of the fraction of plastic work converted into heat in metals. Mechanics of Materials, 86, pp.71-80.
[3] Lo, S.W. and Horng, T.C., 1999. Surface roughening and contact behavior in forming of aluminum sheet. Strain, 6, pp.7-0.
[4] Zhao, Z., Ramesh, M., Raabe, D., Cuitino, A.M. and Radovitzky, R., 2008. Investigation of three-dimensional aspects of grain-scale plastic surface deformation of an aluminum oligocrystal. International Journal of Plasticity, 24(12), pp.2278-2297.
[5] Romanova, V., Balokhonov, R., Zinovieva, O. and Shakhdjanov, V., 2016. Numerical study of the surface hardening effect on the deformation-induced roughening in titanium polycrystals. Computational Materials Science, 116, pp.96-102.
[6] Shimizu, I., Okuda, T., Abe, T. and Tani, H., 2001. Surface roughening and deformation of grains during uniaxial tension of polycrystalline iron. JSME International Journal Series A Solid Mechanics and Material Engineering, 44(4), pp.499-506.
[7] Baydogan, M., and Cimenoglu, H., 2003. Deformation induced surface roughening of austenitic stainless steels. ISIJ International, 43(11), pp.1795-1798.
[8] Furushima, T., Tsunezaki, H., Manabe, K.I. and Alexandrov, S., 2014. Ductile fracture and free surface roughening behaviors of pure copper foils for micro/meso-scale forming. International Journal of Machine Tools and Manufacture, 76, pp.34-48.
[9] Luo, L., Jiang, Z., Wei, D., Manabe, K.I., Zhao, X., Wu, D. and Furushima, T., 2016. Effects of surface roughness on micro deep drawing of circular cups with consideration of size effects. Finite Elements in Analysis and Design, 111, pp.46-55.
[10] Wilson, W.R. and Lee, W., 2001. Mechanics of surface roughening in metal forming processes. Transactions-American Society of Mechanical Engineers, Journal of Manufacturing Science and Engineering, 123(2), pp.279-283.
[11] Becker, R., 1998. Effects of strain localization on surface roughening during sheet forming. Acta Materialia, 46(4), pp.1385-1401.
[12] Ardelen, M., Beyerlein, I.J. and Knezevic, M., 2014. A dislocation density based crystal plasticity finite element model: application to a two-phase polycrystalline HCP/BCC composites. Journal of the Mechanics and Physics of Solids, 66, pp.16-31.
[13] Knysh, P. and Korkolis, Y.P., 2016. Blackbox: A procedure for parallel optimization of expensive black-box functions. arXiv preprint arXiv:1605.00998.
[14] Knysh, P. and Korkolis, Y.P., 2017. Identification of the post-necking hardening response of rate- and temperature-dependent metals. International Journal of Solids and Structures, 115, pp.149-160.
[15] Guannan, C., Huan, S., Shiguang, H. and Baudelet, B., 1990. Roughening of the free surfaces of metallic sheets during stretch forming. Materials Science and Engineering: A, 128(1), pp.33-38.
[16] Osakada, K. and Oyane, M., 1971. On the roughening of free surface in deformation processes. Bulletin of JSME, 14(68), pp.171-177.