Progressive Mechanical Indentation of Large-Format Li-ion Cells

Hsin Wang ^a, Abhishek Kumar ^a, Srdjan Simunovic ^a, Srikanth Allu ^a, Sergiy Kalnaus ^a, John A. Turner ^a, Jacob Helmers ^b, Evan Rules ^b, Clint Winchester ^b and Philip Gorney ^c

^a*Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*

^b*Naval Surface Warfare Center, Carderock, MD 20817, USA*

^c*National Highway Safety and Transportation Administration, Washington, DC 20590, USA*

Abstract

Large format Li-ion cells were used to study the mechanical responses of single cells of thickness 6.5 mm and stacks of three cells under compressive loading. Various sequences of increasing depth indentations were carried out using a 1.0 inch (25.4 mm) diameter steel ball with steel plate as a rigid support surface. The indentation depths were between 0.025" and 0.250" with main indentation increments tests of 0.025" steps. Increment steps of 0.100" and 0.005" were used to pinpoint the onset of internal-short that occurred between 0.245" and 0.250". The indented cells were disassembled and inspected for internal damage. Load vs. time curves were compared with the developed computer models. Separator thinning leading to the short circuit was simulated using both isotropic and anisotropic mechanical properties. Our study shows that separators behave differently when tested as a single layer vs. a stack in a typical pouch cell. The collective responses of the multiple layers must be taken into account in failure analysis. A model that resolves the details of the individual internal cell components was able to simulate the internal deformation of the large format cells and the onset of failure assumed to coincide with the onset of internal short circuit.

Keywords: Li-ion cells, indentation, mechanical deformation, simulation

Corresponding author e-mail address: wangh2@ornl.gov, Tel: 865-576-5074, FAX: 865-574-6098

1.Introduction

Li-ion batteries for mobile electronic devices are usually in the form of single cells or small cell packs, where mechanical abuses could occur by handling of the cells during transportation and storage. The end-users are not subjected to risks from mechanical abuse under normal conditions. Although the once in several million chance of self-induced internal short circuit event has always been a potential safety concern, recent advances in cell chemistry, safer electrolytes, separators [1], and battery management system (BMS) have kept this issue a low priority. The emphasis on more specific power in the mobile devices has led to current Li-ion cells to share the same designs with a light-weight pouch and thinner layers of current collectors and separators. They are vulnerable to mechanical abuses such as crushing, bending and dropping. For electric vehicle (EV) applications, the same designs for small cells were simply scaled up in dimension to make large format cells. The larger cells carry significantly more energy and also inherit the same mechanical abuse-intolerant characteristics of their smaller counterparts. For the same mechanical damage and same state of charge (SOC), a larger cell is more likely to go to thermal runaway because it has higher capacity and more current can flow through the short circuit spot to trigger thermal runaway. With the increasing number of electrical vehicles entering the active fleet, battery safety has become an important issue [2]. In addition to the safety of handling and transporting the cells, the EV users can be directly affected by the mechanical abuses and failure of the batteries. In order to avoid mechanical damages, the cell packs are located in the crush-safe zones and protected by extra armors. However, severe accidents can still lead to mechanical deformation of the cells, short circuit in the cells and potential thermal runaway.

Various studies can be found in the literature on mechanical testing of Li-ion cells[3].For small cells used in mobile devices, UL 1642 [4] describes four mechanical abuse tests that the cells with less than 5 grams of metallic lithium must pass, including crushing, impact, shock and vibration. These tests mainly focus on possible mechanical abuses during the transportation and storage of the cells. The passing criteria for these tests are: no fire and no explosion. For self-induced internal short circuit there is no standard test. Most techniques were developed to simulate an internal short circuit at a single layer due to manufacturing defects.Alternative ways to simulate such a defect require opening a live cell and putting a foreign object inside the cell [5] or embedding an “instigator” inside the cell [6, 7]. These methods work well in a laboratory environment and are not practical in production and for in-service evaluations.Nail penetration [8] or single-side indentation [9] usually can cause extensive damages to the cell before the short circuit event. Efforts to develop mechanical pinching [10] and torsion [11]tests have been made to modify the simple nail penetration or mechanical indentationtests in order to induce a small short circuit spot deep inside the cell. It is important to point out that none of the above tests can perfectly mimic an actual internal short circuit event. Theycan be treated as cell safety evaluation methods and are more effective in comparing cell-to-cell and design differences.

For large format cells, no formal mechanical abuse test standards or internal short circuit tests are available although many efforts can be found in the literature [12-14]. Mechanical testing to simulate damage in a crash situation is fundamentally different frominternal short circuit simulations. These tests need to cover variousexternally induced mechanical deformations.In most cases, the damages involve multiple layers and in some cases multiple cells. It is common to conduct mechanical deformation tests until battery failure (usually a voltage drop) is detected. The

final results are multiple layer short circuit and rapid local heating. Even with the minimal capacity, the resulting mechanical damage and localized joule heating are very difficult to pinpoint the final failure mechanism. In most accidents involving EVs, the field data are very hard to obtain, and are totally destroyed in the case of vehicle fire.

While the electrochemical behavior and degradation mechanisms could play roles in cell safety, the focus here is mechanically-induced damages which happen in a few seconds to a minute and result in thermal runaway. We investigate the evolution of mechanical deformation of the cell materials, especially the separators, leading to the final failure. Commercially available Li-ion pouch cells were progressively indented using a 0.5" diameter steel ball. The indentation was performed on single cells and on stack of three cells against a thick steel plate. Mechanical characterization experiments were conducted on cell components to measure properties and develop constitutive models for simulation of indentation tests. The computational models show good correlation with experiments until the on-set of the internal failure.

2.Experimental

The indentation tests were performed at the battery testing facility of the Naval Surface Warfare Center (NSWC) at Carderock, MD. A displacement-controlled test rig developed at Oak Ridge National Laboratory (ORNL) was used. The system consists of a steel frame, an electric motor-driven actuator and a load cell. It can impose displacement increments with accuracy of 0.0005 per revolution under displacement speeds between 0.01 inch/min and 12 inch/min. The tests were conducted on commercially available Li-ion NMC/graphite pouch cells with capacity of 25 Ahr. Thicknesses for electrodes are 58 μm for anodes and 57 μm for cathodes. The density of the

cathode is 3.2 g/cm^3 and 1.4 g/cm^3 for anode. The loading speed was $0.25''$ per minute. The reference indentation position ($z=0$) was set to the position when the sphere was in contact with the cell and the cell could not be turned by hand with light touch. The indentation was proceeded to the set depth (z negative values), until the force levels off, and returned to $z=+0.025''$ position at the same speed. The extra elevation above the reference allowed the cell to be moved to another position. The subsequent indentations were started from the $+0.025''$ position assuming the cell was flat and the initial $z=0$ position applied to all subsequent tests. There is a linear correction factor for the servo motor and actuator (under compressive load) on the targeted displacement, D_{Target} , and actual displacement, D_{Actual} , in which $D_{\text{Actual}} = 0.9373D_{\text{Target}} + 0.003$ (inch) The target displacements are used in the descriptions and the actual displacements are presented in all the results.

A total of five 25 Ahrcells were tested in this study and pictures of the cells are shown in Figure 1:

- 1) Figure 1(a), Cell No. 1: Eight indentations with $1.0''$ diameter steel ball on the single cell against the steel plate, with progressive depths between $0.025''$ and $0.200''$ in increments of $0.025''$. The final, 9th, indentation was carried until short circuit was detected. The test was used to determine the range indentation and increments needed for determining the onset of short circuit.
- 2) Figure 1(b), Cell No. 2: Eight indentations as for the cell no. 1. The same sequence of indentations was repeated at the lower part of the cell using 2 additional cells as backing material on top of the steel plate.
- 3) Figure 1(c), Cell No. 3: Five indentations of the single cell with depths of $0.100''$, $0.150''$, $0.175''$, $0.200''$ and $0.210''$.

4) Figure 1(d), Cell No. 4: Five indentations of the single cell with depths of 0.210", 0.220", 0.230", 0.240" and 0.245".

5) Figure 1(e), Cell No. 5: Two indentations with depths of 0.245" and 0.250". The final step induced internal short circuit and thermal runaway

Cell No. 1 was the initial test of indentation range to failure. Cell No. 2 was used to repeat the cell No. 1 and for additional 3-cell stack indentations. Cells No. 3 and No. 4 were designed to narrow the range of short-circuit failure. Cell No. 5 was used to determine the short circuit up to the accuracy of the equipment. The first two cells were discharged to 3.00V from the shipping state and recharged back to 25% SOC (2.5 Ahr) at C/3 rate. Open circuit voltage was monitored throughout the test for short circuit. The next three cells were tested with about 75% SOC.

(a)

(b)

Fig. 1 (a) Cell No. 1 after 8 progressive indentations and final short circuit indentation; (b) Cell No. 2 after two set of indentations: single-cell and 3-cell, (c) Cell No.3 with 10 indentations; (d) Cell #4 with 5 indentations and (e) Cell No. 5 thermal runaway at 0.250"

The short circuit in cell No. 1 was local. The 8 previous indentations away from the final step were not affected. However, materials under the indenter were fused together after the short circuit event. Cell No. 5 went to full thermal runaway with large amount of smoke release. Although Cell No. 5 was destroyed, the onset of short circuit was preserved in Cell No. 4. It was determined that using 1" diameter sphere, the 25 Ahr cells could go to thermal runaway at $>0.245''$ deformation induced by compression. The tested cells were completely discharged and disassembled at ORNL for analysis of the internal configuration. Cell layers were examined for damage and indentations were photographed. The separators were digitally scanned against a black background to quantify the damage and thinning.

3. Mechanical Properties of the Cell Components

Mechanical properties of the cell components were determined by compression of stacks of electrodes in servo-hydraulic Instron load frame. Electrodes were cut into 17 mm x 17 mm square

samples (Fig. 2 (a) and (b)) to fit on flat platens (1 inch in diameter) that were placed in the hydraulic wedge grips. The number of layers in stack ranged from 19 to 28 with the average stack thickness of 3 mm. Within this range no correlation between stack height and resulting stress-strain curve was found (total of 19 experiments were conducted). Compression was performed under displacement control at 0.08 mm/s speed. The positive electrode was double coated aluminum foil with active material chemistry of $\text{Li}[\text{Ni}_{1/3}\text{Mn}_{1/3}\text{Co}_{1/3}]\text{O}_2$. The negative electrode was Cu foil double coated with Conoco Philips A12 graphite. Polymer/aluminum laminate of pouch material representing was cut into the same dimensions and tested under the same conditions. The resulting stress-strain curves are shown in Fig. 2(c-e).

(a)

(b)

(c)

(d)

(e)

Fig2. Setup for compression of stacked electrodes (a, b) and resulting stress-strain curves: (c) positive electrode; (d) negative electrode; (e) pouch material.

4.Simulation of Mechanical Deformation of Indentation Experiments

Indentation experiments were simulated using the FEM software package LSDYNA. The battery pouch geometry used for the simulation has a length (x-direction) of 80 mm, width (y-direction) of 80 mm and thickness of 6.54 mm. The displacement for 4 sides along the boundary are constrained in x-y direction i.e. motion along the z-direction is only allowed for those boundary nodes. The indentation test is conducted with a rigid sphere modeled as analytical surface moving downward at a constant speed. The contact between the rigid sphere and pouch cell was modeled as contact-entity feature with coefficient of friction as 0.3. The bottom surface of the cell model is constrained by a rigid wall.

Schematic of the single-cell and 3-cell model is shown in Figure 3(a) and (b). The pouch cell consists of 17 jellyroll layers along the thickness direction. Each jellyroll layer is composed of one negative electrode, one positive electrode, and two separator layers, as shown in Fig 3(b). In this

study, the components of the top 4 jellyroll layers are fully resolved, i.e. one element along thickness direction for each component. Remaining 13 jellyroll layers of the cell are modeled as a single homogenized material. On the basis of our previous study we have determined that resolving top four layers is an optimum solution [16].

The compressive stress-strain response of positive and negative electrode material were implemented into LS-DYNA using MAT-63 material model [20]. This constitutive material model is used for modeling crushable foam material. Due to high percentage of voids and a low Poisson ratio in electrode material it can be modeled similar to crushable foam material. MAT-63 material model has been used in previous battery deformation studies [3,12]. We did not consider component failures, so that a high value for tensile cutoff stress (1 GPa) is used for both positive and negative electrode material. The piecewise linear isotropic plasticity material model (MAT-24) [20] was used for separator layer. The active material constitutes approximately 80 percent volume in the jellyroll, so that we also used MAT-63 material model for homogenized material. Material properties for homogenized layer are calculated by Voigt average technique [21] based on properties of each constituent layer as per equation (1).

$$E_{33} = \left[\frac{v_-}{E_-} + \frac{v_+}{E_+} + \frac{v_{sep}}{E_{sep}} \right]^{-1} \quad (1)$$

where E and v are elastic moduli and volume fraction for individual components, which are used in Eq.1 to calculate the value for E_{33} . For negative and positive electrode material the value of E was 0.515 and 0.467 GPa, while for separator material value for E was 0.5 GPa [REF]. Based on thickness of component layer volume fraction for negative electrode, positive electrode and

separator was 0.41, 0.52 and 0.07 respectively. Poisson ratio for electrode material and separator was 0.01 and 0.3. The value for E_{33} was determined as 0.495GPa

Fully integrated solid elements are used to mesh the battery cell. The different constituents of the resolved top 4 jellyroll layers are perfectly bonded with each other. Contact at the top surface in the homogenized layer is tied with nodes at the bottom surface of resolved layer using “contact tied surface to surface” keyword.

Simulation configuration for a stack of 3 cells is also shown in Figure 3(a) and (b). For the top cell, the first four jellyroll layers of the top cell are fully resolved similar to single-cell and the remaining structure is treated as one homogenized material. Bottom 2 cells are modeled as one single material. Contact interface is used between individual cells.

Fig.3. Simulation of indentation test (a) Mesh of the single-cell and 3-cell with a spherical indenter (b) Schematic along the thickness direction of the cell(s).

5.Results and Discussion

5.1 Load and Displacement vs. Time Results

For a single cell indentation on a steel plate, Figure 4(a) shows the results of eight indentations in Cell No. 1. The compression was stopped once the preset indentation depth was reached. The hold time depended on the load recovery time at each depth and was on the order of 10-30 seconds but not fixed. Overall, the load vs. time plots followed the same trend. The curves related to the initial 10-20 seconds are non-linear and followed by relatively linear responses all the way to the set depths. Once the compression stopped, we observed a slow recovery of the load due to the relaxation of the multiple layers. The cell was partially charged with an open circuit voltage of 3.50V. The voltage was monitored continuously during the indentation. No voltage drop was observed during the eight indentations.

Figure 4(b) shows the final indentation on cell No. 1 at the speed of 0.25” per minute. No depth was set and the system is programmed to retract at 1” per minute once a 0.1 V voltage drop is detected. The cell voltage dropped from 3.5 V to 0.2 V within a few seconds followed by heating and small amount of outgassing of the cell. With limited capacity, no thermal runaway occurred. However, localized heating and melting were observed when the cell was opened. The folding and bending of the of the pouch did not occur before short circuit and was mainly due to the volume expansion during outgassing as shown in Figure 3 (a).

Cell No. 2 was first used to repeat the single cell vs. steel plate test as Cell No. 1. Eight indentations were made and the results are shown in Figure 4(c). Beside the initial contact uncertainties in the steps 1-2, the Load vs. Time curve repeated very well with the non-linear and linear portion overlapping in each step. No short circuit was observed to the last step. The maximum load values after step #3 were consistent with Cell #1. Cell No. 2 was used again with two more cells as background material on top of the same steel plate. The 3-cell stack was subjected to the same 8 indentations and the results are showing in Figure 4(d). With thicker backing materials, the first 4 steps had very small compressive load (< 50 pounds). Starting from

Fig.4(a)Cell No.1:Load, Displacement vs. Time curves of the eight indentations on a steel plate; (b) Indent-to-short circuit test; (c) Cell No.2: Eight indentations on a steel plate; (d) Eight indentations on a 3-cell stack on steel plate; (e) Load, Displacement vs. Time curves of the multiple indentations in Cell No.3-5 against a steel plate

step No. 4 the load values increased linearly with indentation depth. The final maximum load at 0.200" depth is about 1/3 of the single cell which is equivalent deformation in strain unit.

However, the initial steps in the 3-cell stack showed highly non-linear responses. Figure 4(e) is the Load vs. Time plot of cells No. 3-5 in an attempt to pin-point the indentation limit for short circuit. The plot shows 11 steps at from 0.100" with 0.025" increments until 0.200" and 0.010" steps until 0.240". The final increment 11 was 0.005". It was determined the critical indentation limit for this commercial NMC cell is 0.245". The large tolerance for compression is an overlooked safety feature for Li-ion pouch cells, i.e. not all mechanical deformations are critical.

The deformation of a single cell could tolerate before short circuit was over 90% of the thickness and multiple-cell stack makes the module and pack highly compressible to mechanical deformation. Under compressive loading, the separators can be thinned extensively without failure. Our observations indicate that the final failure occurs when the electrode layers collapse and shear forces cause separator failure and contact of the opposite electrodes.

The cells were opened to analyze their internal state after the indentations. Figure 5 are optical images of the opened cell stack and separators. The polymer separators were white in color and become transparent when stretched. When placed on a black background, the thinned areas appear black. The first three steps show little thinning with little increase in darkness increasing indentation depth. Starting from step #4 the thinning becomes notable to naked eye. The thinning was anisotropic in the intermediate steps #4-#6 where the thinning areas are shaped as ovals instead of circles. The anisotropic behavior of the separator was demonstrated in tensile tests were performed in different directions. The ratio of the maximum tensile stress in separator was 1:15. Tests for the through thickness compression behavior of the separator were not performed and its material model for simulations was derived from the tension tests, only.

Fig.5. Images of the opened cell and separators at various depths

5.2 Simulation results

The load displacement curve comparison between simulation and experiments (Figure 4) for case of single cell and combination of 3 cells are shown in Figure 6. The experimental plot is taken for indenter displacement of 0.2 inch and values in the curve are adjusted such that at zero load there was zero displacement. There is a relatively good agreement between the experiments and simulation results for both 1 cell and 3 cell stacks, illustrating the validity of the material models and material parameters presented in the previous section.

Fig.6. Load vs. Displacement curves for (a) single cell indentation; (b) indentation of stack of 3 cells

As discussed in the experiment section, there was a change in color of the separator as indentation progressed due of its thinning. This change in thickness is represented in simulation by z-strain (thickness strain). In Figure 7(a) we compared the deformed region of separator layer in the top of cell at indenter displacement of 0.1 and 0.2 inch. With increased indenter displacement, the area of deformed portion increases. After a critical deformation, the separator fails causing the contact of opposite electrodes, which may cause the short in the pouch cell. The area of the deformed plastic region of separator obtained from test and simulation is plotted in Fig. 7(b). Area is measured using software ImageJ [19]. The correlation of area is tested using a linear fit, R^2 value is 0.9952, and this measure of R^2 for linear regression implies a good agreement in measure of area obtained from test and simulation.

Fig.7(a). Thinning of top separator layer with indenter displacement, top experimental and simulation images are at indenter displacement of 0.1 inch while the bottom one are at indenter displacement of 0.2 inch; (b). Area of deformed region obtained from test and simulation

To model the anisotropic behavior of the separator, we used Barlat constitutive model [17] (Mat-36 in LSDYNA). This constitutive model is commonly used to model behavior of sheet metals under plane stress condition [18]. Stress-strain curves given in [17] were used as input for this material model. The other material constants were Elastic Modulus = 0.5 GPa and Poisson's Ratio = 0.3. We did not get any notable difference in the load-displacement curve compared to the isotropic model.

5.3 Simulations with failure criteria

In the previous section we have simulated the indentation of cell without any failure criteria for cell components, With increasing indentation, separator layer thickness is reduced, and when the thickness is sufficiently reduced, separator fails and causes the short circuit in the cell. We modeled this failure behavior by maximum strain (Strain in thickness direction) criteria for separator layer elements. In this criterion, an element is deleted when the strain in the element is equal to or greater than a predefined value. We varied the predefined value for strain to get a good match with experimental finding (Fig.8) and found the strain value to be 0.65. This value is dependent on the FEM mesh discretization. The separator thickness represents the characteristic length of the problem, and since our elements are of this size, the failure criteria may be transferrable to other configurations.

As previously discussed, we have considered isotropic and anisotropic material models for the separator. We simulated the failure (short-circuit) of the cell using these 2 models. For Isotropic we have 2 cases, in the first the mechanical properties in all the direction were same as manufacturing direction and in the other the properties in all the direction were same as Transverse direction value. The value for failure strain was 0.65 in all the cases. Since, Separator is stronger in Manufacturing direction (MD) compared to Transverse direction (TD) failure load was higher for MD as compared to TD case as seen in Figure 8. Anisotropic model predicts the failure load and displacement value in between these two isotropic models for the same failure strain in separator. By changing the failure strain for any of these cases (isotropic/anisotropic) load-displacement curve similar to experiment result can be obtained. However, as shown in Fig 7 the maximum strain at indentation of 0.2 inch is close to 0.6, hence 0.65 can be correct value, so the anisotropic model

was better in prediction for load-displacement curve compared to isotropic model. In the present study we have guessed the value for failure strain, but in future studies we can perform bidirectional tension test on Separator to obtain the value at which Separator will fail and use that value for Simulation

Fig. 8. Load-displacement curve with failure criteria for separator layer

5. Conclusions

Progressive indentation tests have been carried to systematically study the mechanical deformation of Li-ion cells. Indentation test was performed on a single cell and 3-cell stacks. The indentation depth limit for the 1" diameter sphere is about 0.245" which corresponds to 90% of the cell thickness. Load-displacement curve obtained from test was compared to those obtained by simulation. By detailed analysis we found thinning of separator, which might be one of the

potential reason for short due to mechanical indentation. Using an anisotropic material model for separator the shape of deformation observed is similar to the experimental findings.

Acknowledgements

The authors would like to thank Edgar Lara-Curzio and Donald L. Erdman III for their supports on building the initial testing rig. We would like to thank James Barnes for his help in establishing collaboration with NSWC. NHSTA and DOE VTP are the main sponsors for this work. Oak Ridge National Laboratory (ORNL) is managed by the UT-Battelle LLC, for the Department of Energy under contract DE-AC05000OR22725.

References

- [1] J.B. Goodenough and Y. Kim, Chemistry of Materials, 22-3, 2010, 587-603.
- [2] L. Hollmotz, M. Hackmann, in: 22nd International Technical Conference on Enhanced Safety of Vehicles (ESV), (2011) 11-0269.
- [3] E. Sahraei, J. Meier and T. Wierzbicki, Journal of Power Sources, 220, (2012) 360-372.
- [4] UL, in: UL 1642 Standard for Safety for Lithium Batteries, UL, 1999.
- [5] Battery Association of Japan, Presentation at UN Informal Working Group Meeting, November 11–13, 2008, Washington, DC.
- [6] M. Keyser, D. Long, Y.S. Jung, A. Pesaran, E. Darcy, B. McCarthy, L. Partrick and C. Kruger, in: Advanced Automotive Battery Conference (AABC), January 25-28, 2011, Pasadena, CA
- [7] R. Takata, C. McCoy, D. Ofer, R. Stringfellow, B. Barnett and S. Sriramulu, Proceedings of 44th Power Sources Conference, Curran Associates, Inc. Red Hook NY, (2010) p12.

- [8] J.P. Peres, F. Pertion, C. Audry, P. Biensan, A. de Guibert, G. Blanc, M. Broussely, *Journal of Power Sources*, 97-8 (2001) 702-710.
- [9] L. Florence, in: *Battery Power*, Dallas, Texas, 2010, p. 576.
- [10] W. Cai, H. Wang, H. Maleki, J. Howard, E. Lara-Curzio, *Journal of Power Sources*, 196 (2011) 7779-7783.
- [11] F. Ren, T. Cox, H. Wang, *Journal of Power Sources*, 249 (2014) 156-162.
- [12] E. Sahraei, R. Hill, T. Wierzbicki, *Journal of Power Sources*, 201 (2012) 307-321.
- [13] T. Wierzbicki, E. Sahraei, *Journal of Power Sources*, 241 (2013) 467-476.
- [14] R. Spotnitz, R. Muller, *The Electrochemical Society Interface*, 12 (2012) 57-60.
- [15] H. Wang, S. Simunovic, H. Maleki, J. N. Howard, J. A. Hallmark, *Journal of Power Sources*, 306 (2016) 424-430.
- [16] Crash Model for Advanced Automotive Batteries
- [17] Barlat, F., Lian, J.: Plastic behavior and stretchability of sheet metals. Part I: a yield function for orthotropic sheets under plane stress conditions. *Int. J. Plast.* 5, (1989)51–66.
- [18] D.Banabica,, H.Aretzb, D.S.Comsaa, L.Paraianua:An improved analytical description of orthotropy in metallic sheets *Int. J. Plast.*Volume 21, Issue 3, March 2005, Pages 493–512)
- [19] ImageJ <http://rsb.info.nih.gov/ij/docs/>
- [20] "LS-DYNA Keyword User's Manual Volume II Material Models" Version 04/06/16 (r:7556), Livermore Software Technology Company, Livermore, CA, April 2016.
- [21] Voigt W. 1928. *Lehrbuch der Kristallphysik*. Teubner.