Bake-Hardening Effects, Arbitrary Image Data and Finite Pointset Analysis Results made Accessible with envyo®

C. Liebold[1], David Zerbst[2], Dr.-Ing. Michael Hedwig[3], Steffen Hagmann[3]

[1]DYNAmore GmbH
[2]Daimler AG
[3]Dr.-Ing. h.c. F. Porsche AG

1 Abstract

In the recent past, a lot of effort has been made towards the closing of the simulation process chain for all different kinds of materials. Besides the regular transfer of resulting stress, strain, and history data, main focus from a material's perspective has been on the transfer of fiber orientations from process simulations for continuous fiber reinforced composites [1] together with various homogenization approaches for short fiber reinforced plastic materials [2].

In the following, three new features of the mapping software envyo® [3] will be presented. The first one allows for the mapping of resulting temperature-time curves from a preliminary simulation using the software tool THESEUS-FE OVEN, which is used to simulate paint-drying processes. This process also effects the degree of hardening, e.g. of aluminum structures and therefore leads to locally varying material properties such as the yield stress, strengths etc. It will be explained how these parameter variations can now be considered with the proper mapping and homogenization approach.

The second new feature allows for the identification of different parts and therefore material properties based on a portable graymap (*.pgm) format. Therefore, any arbitrary colored image can be translated into a grayscale representation given in the ascii based *.pgm format, using a third-party software such as GIMP. In the mapping input command file, the user can then define ranges between 0 and 255 which will be assigned to the various parts and therefore material properties. The applicability of the method will be investigated on a wood-forming use case [4].

Another new feature is the consideration of simulation results gained with the Finite Pointset Method (FPM) [5]. Based on a resulting HDF5® data container which stores the coordinates of the particles and their pressure results at specific simulation stages, load curves can be generated which will be used to calculate the component's deformation with LS-DYNA®, making use of the `*LOAD_SEGMENT` keyword.

2 Overview on the mapping tool envyo®

The mapping tool envyo® has been introduced to the LS-DYNA® user community officially in 2016 [6]. As shown in fig. 1, its intention is to transfer various source data onto a target mesh. The source data can be provided in different ways: as simulation result data based on a various number of discretizations, as arbitrary point cloud data based on a *.csv format, but also as image data which are readable in ascii format. The mapping tool transfers the various data onto the target mesh, which is a LS-DYNA® input file, and may be given in various discretizations as well. Besides the element definition, also different material models may be used on source or target side so that history variables have to be assigned to specific locations, direction dependent properties have to be recalculated and damage related parameters might have to be adjusted to a possibly different element size used on the target mesh. For short fiber reinforced plastics (SFRP), a homogenization step has to be applied, which allows to calculate the fiber orientation and the stiffness tensor from a fiber orientation tensor provided by a mold filling analysis. Other standard applications include the transfer of element thicknesses, stresses, and plastic strains, e.g. as a result from sheet metal forming analysis.

The information which is needed to start the program envyo® is provided in an ascii based input file which is in a first step read by the program. The first mapping command tells envyo® which mapping shall be performed and is usually based on the source and target data provided, e.g. `SHELL-SHELL`,

SOLID-SHELL, MOLDFLOW-SHELL, MOLDEX3D-SOLID, and so on. After reading the input command file, an optional geometry matching algorithm is run. Geometry matching is either based on the iterative closest point algorithm [8] or on a 4-point congruent sets [9] algorithm, the former being more robust with provided nodal pairs, the latter being more general and working without a given point set, but is also more time consuming. Furthermore, the user may define standard transformation functions such as scaling, transformation, or rotation of the source mesh. Additionally, for some applications it is necessary to scale the unit system. This is done for all the variables given on the source side. In general, it can be said that a good match between source and target mesh is crucial for a proper data mapping.
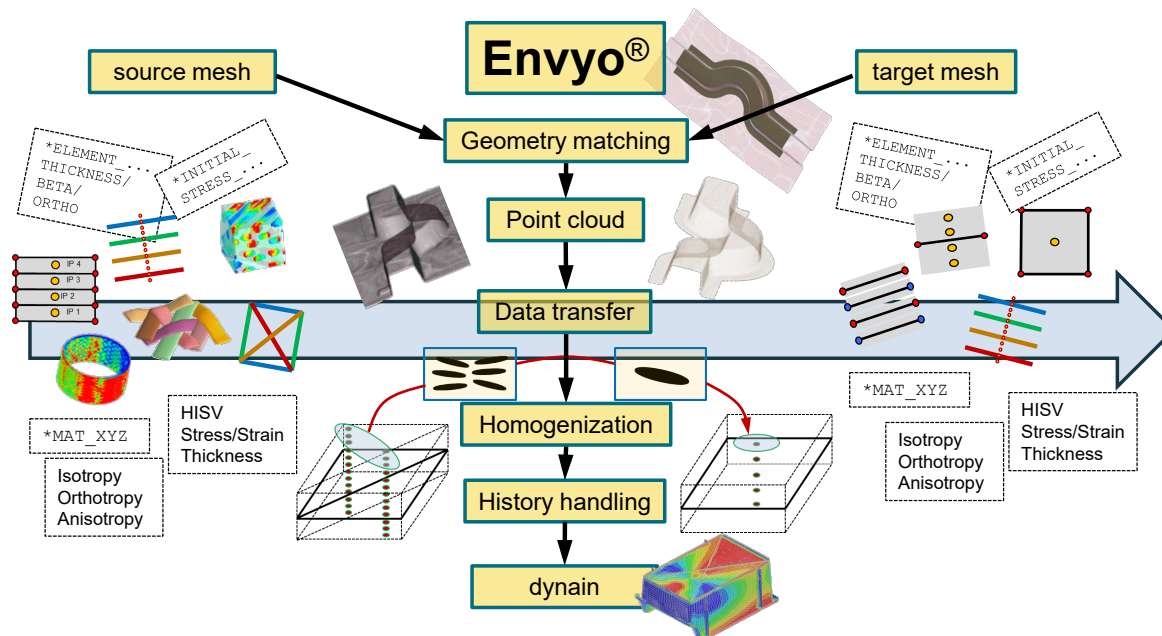

Fig.1: Overview on mapping capabilities within envyo® [7].

After mesh transformation, point clouds are being generated, depending on where the data which shall be transferred is being stored. That can be nodes, element centers, or integration points. To generate point clouds for the target side, the user usually provides information about the integration scheme that shall be used for the following analysis. Alternatively, this data can be read from the *SECTION cards provided in the input deck.

Afterwards, data is being transferred between the different point clouds, usually based on a closest point search. In addition, for standard SHELL-SHELL mapping schemes, scalar and tensorial averaging and interpolation techniques have been investigated in [10] and will be made accessible to envyo® users soon. In order speed up the search process, a bucket sort algorithm has been implemented and is used by default.

After the data transfer and depending on the mapping algorithm being used, homogenization, data manipulation and history handling are being performed on the transferred data. Finally, the resulting data is written to a dynain file which can be used for the following analysis.

In this paper, we will present some of the most recent developments in envyo®, namely the mapping of temperature over time curves and the calculation of the degree of hardening based on these data. Such temperature-time curves can be provided for example by the THESEUS-FE OVEN software and are stored in a HDF5® container. The other new feature being presented explains how one can gain access to image data in its finite element simulation, using an ascii based portable graymap (*.pgm) format. The advantage of this feature will be presented on the example of wood forming simulations. The last example will demonstrate how results from finite pointset simulations can be made accessible to structural analysis using the envyo® software. In this case, pressure data are being transferred onto the target mesh using the *LOAD_SEGMENT capability of LS-DYNA®.

3 Recent developments

In the following sections, the most recent developments will be introduced: the mapping of temperature vs. time curves and the calculation of a hardening parameter based on THESEUS-FE OVEN results, the mapping of portable gray map data and the mapping of pressure curves gained with the finite pointset simulation method.

3.1   Mapping of electrophoretic deposition (EPD) simulation results

For the mapping of EPD simulation results, the user has to provide a source mesh given as an HDF5® THESEUS-FE OVEN result file which contains the mesh and temperature vs. time curves stored on the meshes' nodes. Making use of the Johnson-Mehl-Avrami-Kolmogorov, or JMAK equation which describes the transformation of one material's phase into another at a provided constant temperature, it is possible to calculate the hardening degree Y ($0 \leq Y \leq 1$) through numerical integration. The JMAK equation is given as:

$$Y = 1 - \exp\left(-\left(\frac{t}{\tau}\right)^n\right) \tag{1}$$

with

$$\tau(T) = t_0 \exp\left(\frac{Q}{RT}\right) \tag{2}$$

Thereby, R being the ideal gas constant and T the temperature. The parameters Q (activation energy for diffusion), t_0 (time constant), and n (Avrami exponent) can be derived from experiments which evaluate the yielding behavior of materials being exposed to different temperatures for a varying amount of time [11]. The derivative of eq. 1 provides the growth rate of precipitates at a constant equivalent temperature during a specific amount of time.

Figure 2 illustrates the growth of the hardening degree for a given temperature vs. time curve. envyo® maps these curves from nodal points on the source mesh onto the nodes of the target mesh. In a post-mapping step, the hardening degree is calculated and averaged for each element on the target side. Afterwards, it can be used to manipulate the yield stress or scale the provided yield curves, e.g. for the usage with `*MAT_PIECEWISE_LINEAR_PLASTICITY` (`*MAT_024`).
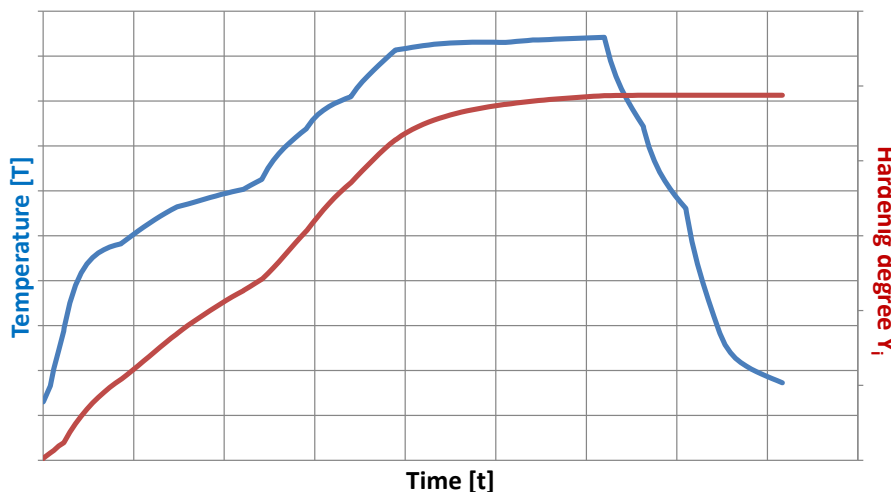

Fig.2:   Arbitrary temperature vs. time curve (blue) and the calculated hardening degree (red).

Besides the standard parameter such as source and target file name, the user has to provide the material specific hardening parameter t_0, Q, and n. As a further input, the gas constant R has to be provided for calculation of the hardening degree. For now, the temperature is assumed to be given in Celsius [°C] and is scaled automatically to be used for calculation in Kelvin [K]. The main mapping command for this option is `ENVYO=THESEUS-SHELL`.

3.2 Mapping of arbitrary image data on simulation meshes

Another recent feature that has been realized is the mapping of arbitrary image data onto finite element meshes. Therefore, a colored picture provided e.g. in a binary *.jpg format has to be converted into a readable portable graymap (*.pgm) file which is ascii based. For that transformation, the free software GIMP (GNU image manipulation program) can be used. The application in mind is the forming of wood veneers, which has distinguishable material characteristics based on the annual rings [4]. These characteristics are established during the growth of a tree. The so called "early wood" is created during spring time, when the tree grows. Wide vessels and thin cell walls causing lower stiffness and strength in these zones compared to the so called "late wood", which is created during the following deposition phase in order to stabilize the tree. By naked eye, early wood can be identified by its darker color compared to the late wood, which is lighter for hard wood species.

After transformation of the *.jpg image into a *.pgm file, envyo® can make use of the created ascii input file. For each pixel, it contains a grayscale value within the range of $0 \leq p \leq 255$, with p being the grayscale value. A value of 0 in this case means that the pixel is completely black, a value of 255 identifies a completely white pixel. The first entry in the file (see fig. 3) identifies it as an ascii based portable graymap file (P2). The next line contains a commentary created by GIMP. This is followed by the number of columns – in this example 803 and the number of rows – here 832. The forth line in the example indicates the range of grayscale values. Then, the grayscale values of each pixel follow.
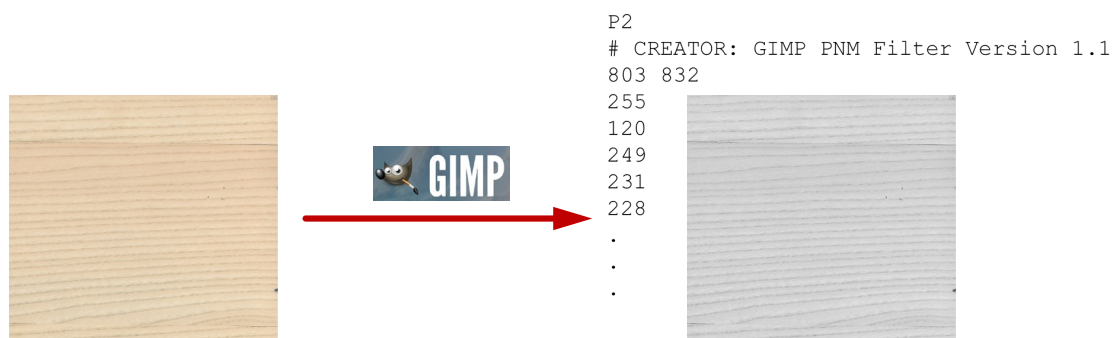


```
P2
# CREATOR: GIMP PNM Filter Version 1.1
803 832
255
120
249
231
228
.
.
.
```

Fig.3: *Transformation of an arbitrary image from *.jpg to ascii based portable graymap (*.pgm) format.*

With envyo®, the user can now define a grayscale range for each part ID which shall be established within the target mesh. The input is as follows:

```
PID#1=3 0 195
PID#2=4 196 255
```

In this example, element centroids which are found to be close to a pixel with a grayscale value within the range of $0 \leq p \leq 195$ are assigned part ID 3, if the pixel's grayscale value is within the range of $196 \leq p \leq 255$, the element gets assigned with part ID 4.

Furthermore, the user has to define the size of the image as $length \; x \; width$ so that the mid-points of the pixels can be calculated based on the number of provided columns and rows. The generated point cloud enables to perform the mapping process. It is possible to define more than just two part IDs. Nevertheless, the user has to ensure that the grayscale ranges to not overlap so that a clear assignment of the respective part IDs to the elements is possible. The different parts can now be linked to different material cards considering the different properties of early and late wood.

As shown in fig. 4, the specified grayscale range has an influence on the stress answer of the final component. In the provided example, superior properties (here: a higher stiffness) are assigned to the regions identified as late wood and therefore, higher stresses are calculated. Furthermore, one can see the influence of the chosen grayscale value for the separation into two parts. On the left side in fig. 4, the mapping results for different grayscale values are displayed. A larger grayscale value leads to a higher number of elements assigned with the properties of early wood and therefore, higher stresses can be observed for the designated late wood areas. The simulation results are given on the right side of fig. 4 and show the von Mises stress answer for a simple Nakajima test. Besides a varying stiffness,

different strengths for early and late wood could be defined in the material card in order to increase predictability of both, forming and structural analysis. For the simulations, `*MAT_LAMINATED_COMPOSITE_FABRIC` (`*MAT_058`) has been used.
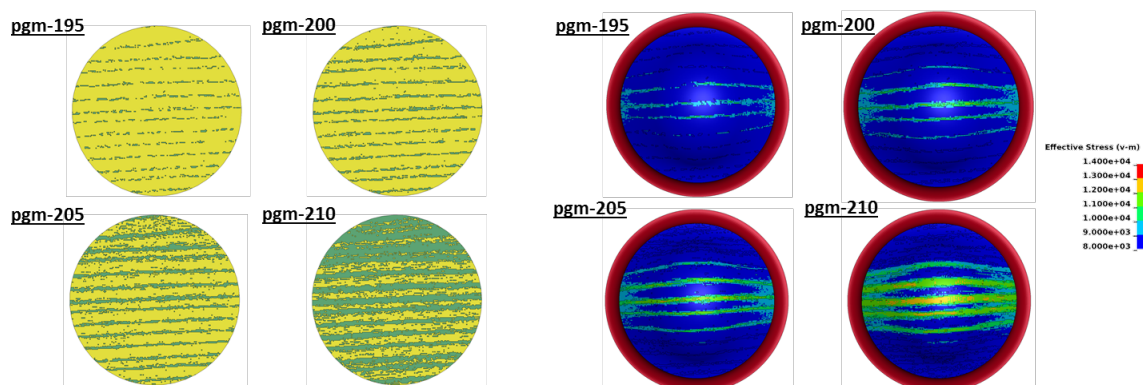

Fig.4:   Illustration of mapping results for different critical gray scale values (left) and the influence on the resulting simulation, in this case a Nakajima test (right).

The provided method cannot only be used for wood forming simulations, but also for any arbitrary image data being generated during a component's design process, e.g. an experienced blacksmith can identify weaker material properties in a technical drawing. A picture is taken from that drawing and based on the grayscale mapping method, envyo® can identify regions with varying material properties and therefore, forming or structural simulations can be run at an early stage of the design process taking into account processing parameters. In order to use this option, the user has to use the main mapping command `ENVYO=GRAYSCALE-SHELL`.

3.3   Mapping of Finite Pointset simulation results

The last method that has been implemented and tested is the mapping of results being generated with the finite pointset simulation method. At the top row of fig. 5, different simulation stages of such an analysis are illustrated. It can be seen that particles hit a plate (red line) after a specific amount of time and spread out along the plate. The simulation results are provided in a HDF5® based result file which stores the particles position and calculated static, dynamic and hydrostatic pressure. Within these simulations, the plate is assumed to be rigid and therefore, no structural responses are being calculated.

Due to that, a mapping is necessary which reads the resulting positions of the particles, searches for particles which are within a certain range of the target structure and transfers the resulting pressure information into load curves for usage with `*LOAD_SEGMENT` in a subsequent structural analysis. In the most general case, a unique load curve will be calculated for each shell element on the target mesh. In the most recent version of envyo®, all resulting pressure values of each particle for each time step are summed up and stored within a load curve which is then transferred. The envyo® input command allows for the filtering of particles to be searched for based on the "kob" parameter, which is a specific output of the FPM method. Furthermore, the user may define a starting state, a final state and a step size with which the states are considered. Another useful option allows for the output of parameterized load curves. A shortened example input file could contain the following case specific options:

```
LargeFile=YES
AllowCurveOutput=YES
PARAMETERIZE_LOAD_CURVES=YES
OUTPUT_OPTION=LOAD_SEGMENT_ONLY
KOB=5
SearchRadius=10.
FIRST_STATE=20
LAST_STATE=37
INTERVAL=5
```

The command `PARAMETERIZE_LOAD_CURVES` activates the output of parameterized load curves with the options `&sfa` (abscissa scale factor), `&sfo` (ordinate scale factor), `&offa` (abscissa offset), `&offo` (ordinate offset). If this option is active, the user has to ensure that the mentioned parameters are defined in the LS-DYNA® input command using the `*PARAMETER` keyword. The `OUTPUT_OPTION=LOAD_SEGMENT_ONLY` turns off the output of nodes and elements to the defined mapping result file and only outputs the generated `*LOAD_SEGMENT` cards and corresponding load curves which can then be included into the LS-DYNA® analysis using the `*INCLUDE` keyword. The commands `FIRST_STATE`, `LAST_STATE`, and `INTERVAL` define the range of states that should be considered for the mapping – not by time but by a simple integer value for the respective states to be used. The `KOB` parameter filters for particles which fulfill a finite pointset analysis specific criterion and with the `SearchRadius` option, only pressure values of particles within a user defined distance to the target element's centroids are considered for the mapping and pressure-time curve generation. It has to be noted that the `SearchRadius` option is a scale factor for the automatically calculated element size dependent search radius.

The last options which need to be explained are `LargeFile` and `AllowCurveOutput`. They have been implemented to avoid memory issues for the case that the finite pointset simulation result files are too large to be read into memory all at once. Therefore, if the `LargeFile` option is activated, reading and mapping will be performed separately for each simulation result state. The `AllowCurveOutput` option allows for the output of the transferred pressure values into separate curve files in order to avoid excessive memory usage due to the necessity to store the mapped results. Instead, after reading and mapping of the last simulation stage, the generated curve files will be copied into one file and erased from the computer's storage. With that method, it has been possible to read and map a 250 gigabyte (Gb) finite pointset result file to a LS-DYNA® analysis. Nevertheless, it should be mentioned that the calculation time for such a mapping has been measured as approx. 80 hours and 45 minutes.

For the small example shown in fig. 5, the calculated structural response (bottom) derived from the pressure-time results of the finite pointset simulation results (top) corresponds quite well to the observed distribution of particles.
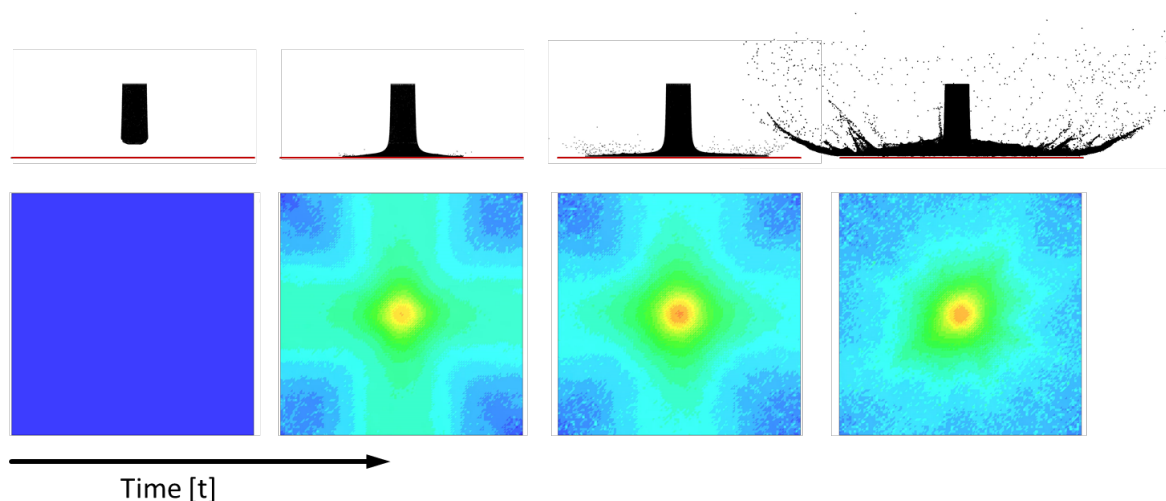

Fig.5: *Finite pointset simulation results (top) and von Mises stress answer for a simple pressure plate example (bottom).*

The mapping of finite point set analysis results can be activated using the main mapping command `ENVYO=FPM-SHELL`.

4 Conclusion and outlook

Three recently implemented new features for the mapping tool envyo® have been introduced and their usability has been demonstrated using small examples. Nevertheless, there is still some work to do.

Further enhancements for the `THESEUS-SHELL` mapping could include a transfer of temperature vs. time curves onto the nodes of a target LS-DYNA mesh. Similar to the `FPM-SHELL` approach, a following analysis, e.g. with the usage of `*MAT_GENERALIZED_PHASE_CHANGE (*MAT_254)` would allow for the calculation of the phase changes directly within LS-DYNA®, avoiding the approximated solution with the JMAK equation. Instead, the simulation result could be used directly within a further structural analysis.

If this mapping enhancement is realized, it should be considered to allow for the output of binary based lsda `dynain` files as well. They can be read in by LS-DYNA® as well and reduce the size of the input deck significantly. The main drawback is that they are no more human readable.

Due to the large calculation times needed for the mapping of finite pointset analysis results, there is a need for parallelization of the mapping process. In a first trial version, a parallelized mapping has been realized for the well-established `MOLDFLOW-SHELL` mapping feature in envyo® and it shows that the time needed for the mapping process only can be reduced significantly. The parallelization has been realized based on a shared memory approach, comparable to LS-DYNA's® smp capabilities. After successful testing, parallelization will be added to further features such as the sorting and transformation algorithm as well as the post-processing of mapped data.

Another enhancement regarding the generation of curve data might be the calculation of running averages for the resulting curves in order to create a smoother load distribution in the analysis file. This would also allow for an easier identification of similarities between the different curves and therefore, a clustering method could be developed.

5 Literature

[1]   Vinot, M., Holzapfel, M., "A Multiscale Strategy for the Simulation of Braided Composites with envyo®", Conference Proceedings, 15th German LS-DYNA Forum, Bamberg, GER, 2018.
[2]   Lauterbach, B., Erzgraeber, M., Liebold, C., Haufe, A., Helbig, M., "Simulation of Short Fiber Reinforced Plastics with LS-DYNA Considering Anisotropy, Rate Dependency and Rupture", Conference Proceedings, 11th European LS-DYNA Conference, Salzburg, AUT, 2017.
[3]   DYNAmore GmbH, "envyo® User's manual - DRAFT", GER, March, 2019.
[4]   Zerbst, D., Liebold, C., Gereke, T., Clauß, S, Cherif, C., "Modeling inhomogeneities of veneers with a grayscale mapping approach", ECCOMAS CompWood, Conference Proceedings, SWE, June, 2019.
[5]   Fraunhofer ITWM, "FPM – Finite Poinset Method", Kaiserslautern, GER, 2019.
[6]   Liebold, C.: "Workshop envyo®: Mapping and Data Management along the Simulation Process Chain", 14th LS-DYNA Forum, Bamberg, GER, 2016.
[7]   Liebold, C., Haufe, A.: "An Interface for Different Modeling and Discretization Approaches Linking Process- and Structural Analysis", NAFEMS 18 DACH Conference, Bamberg, GER, May 2018.
[8]   Besl, P., McKay, N.: "A method for registration of 3-D Shapes", IEEE transactions on pattern analysos and machine intelligence, Vo. 14., No. 2, Feb. 1992.
[9]   Aiger, D., Mitra, N., Cohen-Or, D.: "4-points Congruent Sets for Robust Surface Registration", SIGGRAPH 2008.
[10]   Usta, T.: "Evaluation of Various Averaging and Interpolation Methods for Scalar and Tensorial Finite Element Data Mapping", Master thesis, Institute for Structural Mechanics, University of Stuttgart, GER, Sept. 2018.
[11]   Greve, L., Krabbenborg, G., Eller, T. K., Andres, M., Geijselaers, B.: "Characterization and modeling of the deformation and fracture behavior of a bake-hardenable aluminum sheet alloy depending on the state of hardening and pre-strain", Crashmat, Freiburg, May 2018.