

process2product simulation: Closing Incompatibilities in Constitutive Modeling and Spatial Discretization with envyo®

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Abstract

Within the automotive sector but also other industries, closing the simulation process chain from manufacturing towards the final crushing analysis becomes more and more important since it is well understood that the manufacturing process influences material properties such as initial damage, pre-stresses, induced plastic strains, differing thicknesses, or locally varying engineering constants. In LS-DYNA®, it is possible to consider such discontinuities using respective THICKNESS, BETA or ORTHO – options on element level, and *INITIAL_STRESS_SHELL/SOLID cards to introduce locally varying properties on an integration point level. What has been missing is a solution that is capable to link the various simulation disciplines within an easy-to-use routine, performing averaging, inter- and extrapolation for scalar and tensor properties of first and second order. Thereby, different discretization methods being used for the various simulation steps have to be taken into account for the homogenization procedures, history variables might have to be moved to different positions since they might have a different meaning for another material model or element type.

That is why DYNAmore GmbH recently introduced the envyo® mapping tool to its customers, allowing them to transfer and manipulate history variables between the different simulation disciplines for LS-DYNA multi-stage analysis.

In this paper, the mapping tool envyo® will be introduced and the methods behind it will be explained. Application examples from different disciplines such as additive manufacturing (AM), short- and continuous fiber reinforced plastics (S-/CFRP) modeling, sheet metal forming, and point cloud mapping will be presented. It will be shown that considering the process simulation results within further LS-DYNA analysis will improve predictability in many conceivable applications. Figure 1 illustrates the workflow within envyo®.

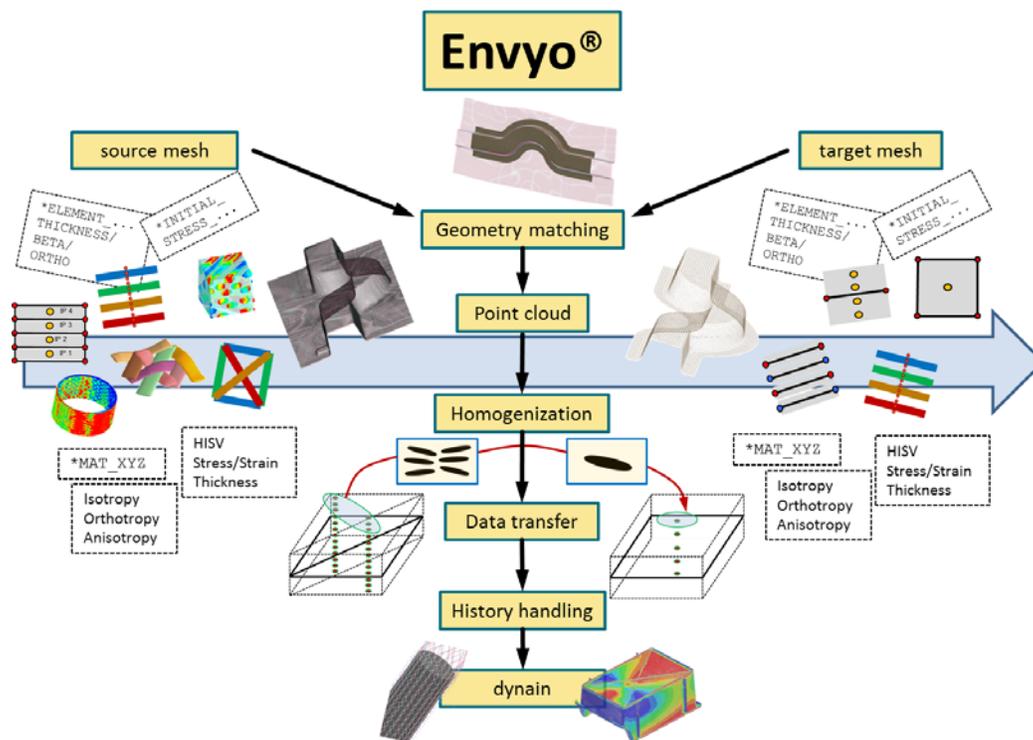


Figure 1: Illustration of the envyo® workflow from process2product.

Introduction

Within recent years, many users tend to consider the results from process simulation within further structural analysis. This trend has been primarily established for short fiber reinforced plastic (SFRP) materials where the results from Moldflow[®] or Moldex3D[®], namely the orientation tensor with its characteristic eigenvalues and eigenvectors have to be transferred onto a structural mesh, sometimes even taking homogenization procedures into account. For LS-DYNA as the receiving code, material models

*MAT_ANISOTROPIC_ELASTIC_PLASTIC (*MAT_157) or *MAT_4A_MICROMECH (*MAT_215) are not of much use without the local initialization of the fiber orientation tensor or stiffness matrix [1] – [3]. The same accounts for spring back analysis of continuous fiber reinforced plastics (CFRP). It has been shown that considering the results from a multi-layered draping analysis within the spring back analysis not just eases the initialization procedure of the fiber directions, but also improves the results of the following analysis for the case that fibers and fiber stresses are considered correctly [4] – [5]. Nevertheless, not everybody seems to consider results from process analysis for the following crushing simulation. In 2005, it has already been shown that the consideration of the thickness and plastic strains resulting from metal forming analysis are beneficial for the predictability of the structural simulation [6]. But since a proper tool and an output convention that allows mapping programs to interpret results from any software solution properly are missing, no solution has been completely established within automotive industry's OEMs or suppliers. Instead, several, software specific solutions exist which allow for data transfer within one software package, but not from one software package to another. Furthermore, a very general case which considers any arbitrary data given as point cloud data which can be results from casting- or any other simulation as well as experimental data, e.g. CT-scan results is completely missing.

Therefore, the mapping tool *envyo*[®] has been developed to overcome the gap between process simulation and advanced structural analysis for LS-DYNA. It allows to simply transfer history variables from one mesh to another, has specific history handling methods which allow for a change of the position as well as deletion of specific history variables. *envyo*[®] also allows for the consideration of direction dependent data such as vectors or tensorial data. This is crucial for a proper consideration of these results in the following analysis step with LS-DYNA.

The following paper will present the current development status for the mapping tool *envyo*[®], illustrated on specific examples. Examples will be given for short- and continuous fiber reinforced composites as well as sheet metal forming applications as well as data given from an arbitrary point cloud. An outlook will illustrate ongoing works for the process consideration within 3D printed components.

Workflow

The workflow of the *envyo*[®] mapping tool is already displayed in figure 1. The user has to provide the source and target mesh, preferably in LS-DYNA format. Other formats such as a binary HDF5 format can be considered as well as arbitrary csv – files for point cloud mapping. Further files such as orientation information should be provided for Moldflow[®] or Moldex3D[®] result mapping. These files are usually given as xml – files or element lists containing information such as the 2nd order fiber orientation tensor or eigenvalues and corresponding eigenvectors that shall be considered within the structural analysis. In addition to that, the user can provide a file that contains information about the sections files defined in the target mesh, which is common practice when dealing with large models. This is necessary to get the correct integration point position for the mapping process, in case that the thickness is not mapped in a first step.

The main mapping command is structured in way that it considers various discretization approaches, as long as mapping is done from an LS-DYNA mesh towards an LS-DYNA mesh. Otherwise, it refers to the type of data given in the source mesh and then to the discretization being used in the LS-DYNA target mesh. An overview

on available main mapping commands is given in table 1. The mapping input is provided by the user in an easy to define and editable ascii – format which is documented in [7] for various mapping cases.

Table 1: Overview on main mapping commands [7]. They follow the ASCII – input ENVYO=...

BEAM - SHELL
BEAM – ALE-MESH
BEAM – STACKED_SHELL
STACKED_SHELL - SOLID
STACKED_SHELL - SHELL
STACKED_SHELL - TSHELL
STACKED_SHELL – STACKED_SHELL
STACKED_SHELL – STACKED_TSHELL
SHELL – SHELL
SHELL – STACKED_SHELL
SHELL – SOLID
SHELL – SOLID(GENERATION)
SOLID – SOLID
MOLDEX3D_MUCELL - SOLID
MOLDEX3D - SOLID
MOLDFLOW - SHELL
MOLDFLOW - SOLID
PCL - SHELL
ABAQUS2DYNA
GCODE - PATH

After reading initial information such as source mesh with corresponding resultant thicknesses, orientations or history variables for specific LS-DYNA materials, target mesh and clustering the input in to parts which are considered for the mapping, envyo® may perform a geometry matching. Geometry matching is provided in two ways: with an “Iterative Closest Point” algorithm [8] or with the usage of the so called “4-Point Congruent Sets” algorithm [9]. After geometry matching has been performed, envyo® will create various point clouds, depending on where the data in the source mesh has been stored and to which position they will be transferred. Point clouds are generated for nodes, integration points as well as for element centers. These point clouds will be sorted internally using a Bucket-Sort algorithm [10] for quicker mapping operations afterwards. Once mapping is finished, the target mesh with assigned information from the source mesh will be passed to problem specific homogenization and history handling routines in order to consider the transferred data in a correct way. In a final step, a resulting dynain – file will be written as an output, which can be used for further analysis and shall contain all the requested data from the process analysis.

Referring to the workflow description, the mapping info file which is provided by the user and shall contain all the information envyo® needs to perform a proper mapping for the specific case, can be clustered in to specific areas, such as shown in table 2. At first, the user provides the main intention of the mapping, followed by the information, if transformation is needed. Then, some information has to be given about the source parts that shall be considered. Then, a list of target information has to be provided such as to which parts shall the data be transferred, which material model and element type will be used in the target mesh. Furthermore, envyo® needs to some information about the search algorithm (default is Closest Point, or nearest neighbor), and what sorting algorithm shall be used for a quicker mapping process (only Bucket-Sort available until know). Finally, the user has to provide information regarding which data shall be mapped: stress, strains, and thicknesses. Special homogenization approaches can be defined for modeling of short fiber reinforced composites as well as a switch

for history variable positions is available, which allows for moving, deleting or special consideration of the specific values for the case they are direction dependent.

Table 2: Wrap-up of the mapping_info.in - file [11].

\$-----
main mapping command ENVYO=...
\$-----
TRANSFORMATION OPTIONS
\$-----
MESHES
source files
target files
additional files containing orientations, sections,...
\$-----
ALGORITHMIC OPTIONS
averaging options
sorting algorithm
\$-----
TRANSFER OPTIONS
map thicknesses
map stresses (and histories)
map strains
\$-----
HOMOGENIZATION OPTIONS
specific target material (157, 215)
material properties for homogenization
list for specific history variable handling

All this information is provided in the so called mapping_info.in – file, whereas only the ending of the file has to be given properly since envyo® will not read it otherwise. From command line, this file will be called similar to LS-DYNA analysis with v0_201802_envyo i= mapping_info.in.

Geometry Matching Algorithm

Two geometry matching algorithms are available in envyo®: the “iterative closest point” (ICP) algorithm and the “4-Point Congruent Sets” algorithm. The latter is based on a random sample consensus (RANSAC) – algorithm, with an additional 4th point which is selected in a way that it lays within a plane with the three other randomly selected points. The connection of node#1 to node#2 is supposed to intersect at point e with the connection of node#3 to node #4. These points are selected on the mesh that shall be transformed, usually the source mesh – and then two corresponding pairs with approximately similar lengths between node#1 and node#2 as well as node#3 and node#4 are to be searched for in the target mesh. Another parameter that evaluates if the nodal pairs found are correct are the ratios r1 and r2 at the point of intersection e between node #1 and node #2 connection as well as the node #3 and node #4 connection. Matching pairs are tested for transformation, using the ICP algorithm. Two criteria evaluating the quality of the transformation are considered: the number of nodes within a specific distance to the target mesh and a mean-square error criterion, that only considers points within a specific range and adds a penalty for nodes found not in range of the target

mesh. The error will be evaluated after each transformation and the pair which provides the best match between source and target mesh is stored until the geometry matching ends with one of the following criteria: number of points within range satisfied, a mean-square error below a user defined value, or a user defined maximum number of iterations has been reached.

To have a quick evaluation of the best transformation, only the outer edges are considered within the point matching algorithm for a shell mesh. For solid meshes, the outer surfaces have to be identified first. If there is a specific angle between the normal directions of two neighboring segments, the connected nodes are considered as an edge and therefore used for the geometry matching algorithm. The resulting final transformation leading to the least error is used for the transformation of all nodes, direction dependent properties such as 2nd order stress, strain, and orientation tensors as well as vector-properties, given in a global coordinate system. Properties given in a local coordinate system do not have to be transformed.

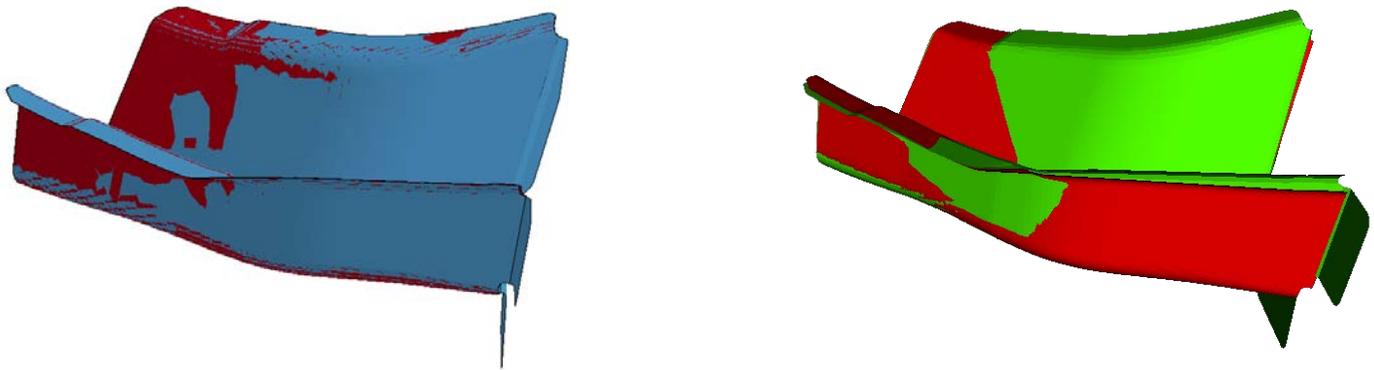


Figure 2: Comparison of two geometry matching algorithms as they are implemented in envyo®. On the left, the results of the more time consuming, but fully automatic 4-Point Congruent Sets algorithm and on the right results of the iterative closest point algorithm [12].

Since the standard ICP algorithm searches for a minimum distance between all nodes, it might lead to insufficient results, in case that source and target meshes are not well aligned beforehand. Therefore, if the user chooses to use that algorithm for geometry matching, he may define up to ten nodal pairs in the source and target mesh that might coincide after transformation. Then the geometry matching is performed preliminary for these specific point sets, following a final optimization for all nodal points in the meshes. It can be stated that the ICP algorithm the way it is implemented needs a bit more preprocessing meaning, that the user has to define matching nodal pairs, but overall is quicker than the implemented 4-Point Congruent Sets algorithm, which therefore performs geometry matching without any user input and seems to be a bit more accurate, referring to the results shown in figure 2. It also shows the capability of both algorithms to consider outliers – in this case additional flaps on the source meshes (blue and green). These meshes are matched with the structural meshes (dark and light red) with a different element size and discretization. The outlying flaps are not considered in the mean-square error calculation.

Point Cloud Generation and Sorting Algorithm

Before the mapping is performed, several point clouds are generated. This is also dependent on the values that are supposed to be mapped. If thicknesses are mapped from source to target mesh, point clouds based on the element centers are calculated first, since those are needed for a proper thickness mapping. In that case, integration point clouds can only be generated, once the thicknesses on the target mesh are known. So the thickness mapping has to be performed before generating the integration point cloud on the target mesh. In order to calculate the integration point cloud, the user has to provide information regarding the integration rule used in the target mesh (Gauss, Lobatto), as well as the number of through thickness and in-plane integration points to be used. Integration point position of the source mesh is determined using either information being

stored in the *INITIAL_STRESS_SHELL or _SOLID card or can be determined by the provided LS-DYNA input deck that was used to create these results. In that case, such information is stored in the respective *SECTION – cards. envyo[®] calculates the integration point position in the way as it is described in the LS-DYNA User's manual [13]. Furthermore, point clouds might have to be generated for the nodal positions itself since values such as temperatures are stored on nodal coordinates. Sometimes, even orientation values are stored on nodal points. This is, for example the case for a specific Moldflow[®] output file that has to be handled differently since the 2nd order orientation tensor might be given referring to nodal IDs instead of element centers. Then, mapping has to be performed from nodal points to integration points in order to initialize history variables for *MAT_157 or *MAT_215 [14].

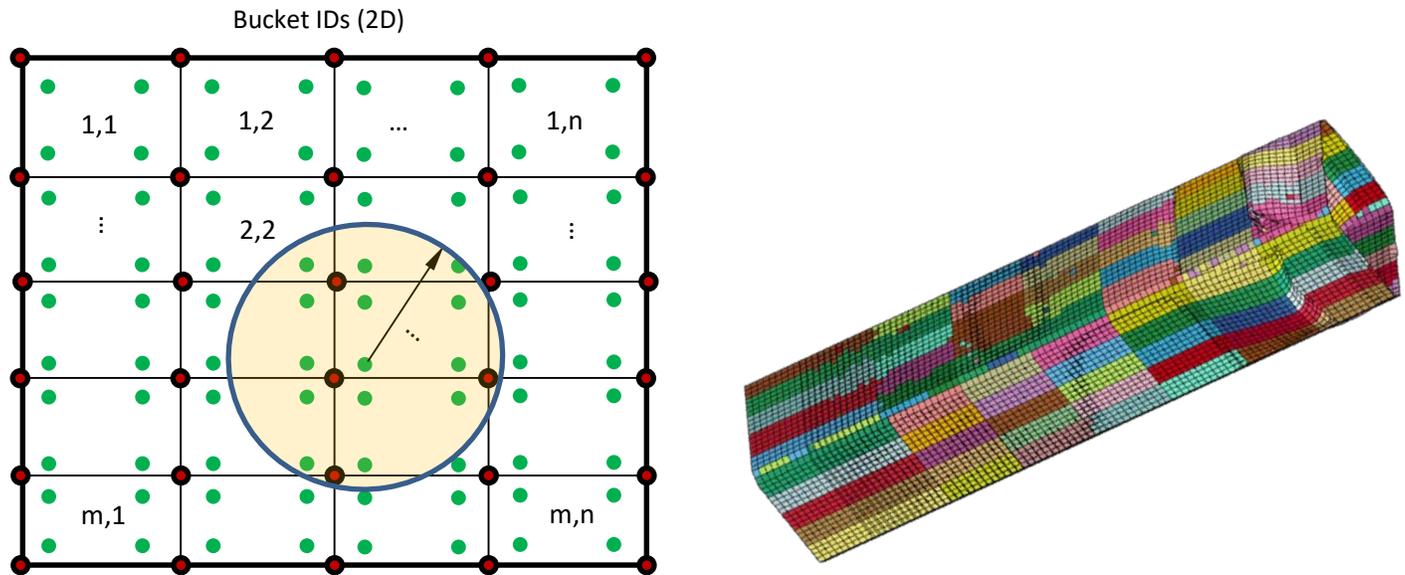


Figure 3: Illustration of the principle of the bucket sort algorithm (left) and results of a coarse clustering of the element center points (right).

A bucket sort algorithm is used to speed up the mapping process. Therefore by default, the generated points from the point clouds are added into a specific number of containers. The number of containers is determined by the maximum distance of all the available points in x, y, and z-direction over the average element length. In case that a specific search radius is defined by the user, for example for specific averaging routines, the size of the buckets is scaled with the specific search radius. Referring their positions in space, all the points are added to a specific container. When searching for the nearest neighbor, in a first step all the points within the same container as the source point are checked for minimum distance. Then all the containers perpendicular to that source container and diagonal to it are checked for further nodes, since they might actually be close to the search point then points belonging to the same container. The principal of the bucket sort algorithm is displayed in figure 3.

Interpolation, Averaging and Homogenization

At the time of writing, no averaging or interpolation procedures are performed during the mapping process. Instead, mapped values are written directly onto the target mesh's integration points, nodes, or element centers, taking into account the direction dependency of some of the values. Nevertheless, there is work in progress which considers several averaging techniques for scalar values as well as vectors and tensor data. For scalar values, several approaches are conceivable to improve mapping accuracy, such as the inverse distance weighted functions as they are proposed by [15]. Interpolation can be performed based on finite element schemes, with the goal to preserve energy when transferring data from source to target meshes. For vector or even tensor data,

averaging always implies the loss of information, e.g. averaging a $[1,1,0]^T$ – vector with a $[1,-1,0]^T$ vector leads to a vector pointing into x-direction only. Therefore, several techniques such as the interpolation of a specific set of tensor invariants such as proposed by [16] and the following calculation of the tensor might overcome some of the issues of loss of accuracy when performing tensor interpolation. Further techniques that will be investigated are proposed in [17] or [18].

When it comes to homogenization, there are some methods already implemented in *envyo*®, that are necessary to properly consider analysis results from injection molding in the structural response. In case that only the orientation tensor is being transferred, nothing specific has to be done. In case that the stiffness tensor shall be calculated from the resulting orientation tensor using **MAT_157* in the structural analysis, homogenization methods that are available are: Halpin-Tsai, Tandon-Weng, Voigt, Kukuri and Mori-Tanaka's theory. In order to perform a closure approximation which estimates a 4th order orientation tensor from a 2nd order orientation tensor, the user can switch between linear, quadratic and two hybrid closure approximation methods. To calculate the anisotropic stiffness matrix, the user has to provide fibers and matrix engineering constants as well as some geometrical parameters (inclusion shape, aspect ratio) and the fiber volume- or mass fraction. In addition to that, the user can provide direction and strain rate dependent plasticity curves, (e.g. 0°, 45°, 90° for

Table 3: Assigning material cards considering RVEs detected in process simulation.

\$-----	
UD 1	if one direction is detected, material card with ID = 1 is assigned
BIAX_30 30	if two directions are detected and they intersect at 30°, material card with ID = 30 is assigned
BIAX_45 45	same as above, for 45°
...	
TRIAX_30 300	if three directions are detected and the average angle between the braiding yarns and the reinforcing yarn is 30°, then material card with ID = 300 is assigned
TRIAX_40 400	same as above, for 40°
...	
ResinMatID 24	if no fibers are detected, resin properties are assigned to the specific integration point with material ID 24.

quasi-static and dynamic tests) – and an averaging scheme will be performed for missing curves corresponding to specific orientations that will be found in the target mesh after the mapping.

Homogenization is also performed when detecting RVEs, e.g. from a braiding simulation with three yarns. Depending on the search radius and the braiding geometry, only one, two or three yarns pointing in the same direction might be detected. If only two directions are detected, the intersecting angle is calculated and a respective material card can be assigned. If three directions are detected, the intersecting angles between the braiding yarns and the reinforcing yarn are calculated and a respective material card can be assigned to the identified RVE. If only one fiber direction is found, UD – properties will be assigned to that specific direction. An input card could be defined as shown in table 3. This option also allows for thickness consideration, using the offset between the different layers and the corresponding **SECTION* information from the source mesh for thickness calculation in the target mesh.

The results of such a mapping procedure are also shown in figure 4. It can be seen that the blacked area in the right picture has been identified by the mapping procedure as a biaxial area, which is also shown in the result of the process simulation (right). The upper and lower parts of the target mesh are assigned the properties of a triaxial braiding structure. The fringe plot displays the thickness resulting from the mapping process.

Similar methods are available for the consideration of specific properties resulting from foam filling analysis. Thereby, the user may assign specific material cards for locally varying densities that can be determined for example with Moldex3D® mu-cell modeling capabilities.

Data Transfer

As mentioned before, data transfer within envyo® is straight forward and based on a closest point or nearest neighbor search. Found values on nodes, element centers or integration points are in a first step mapped without

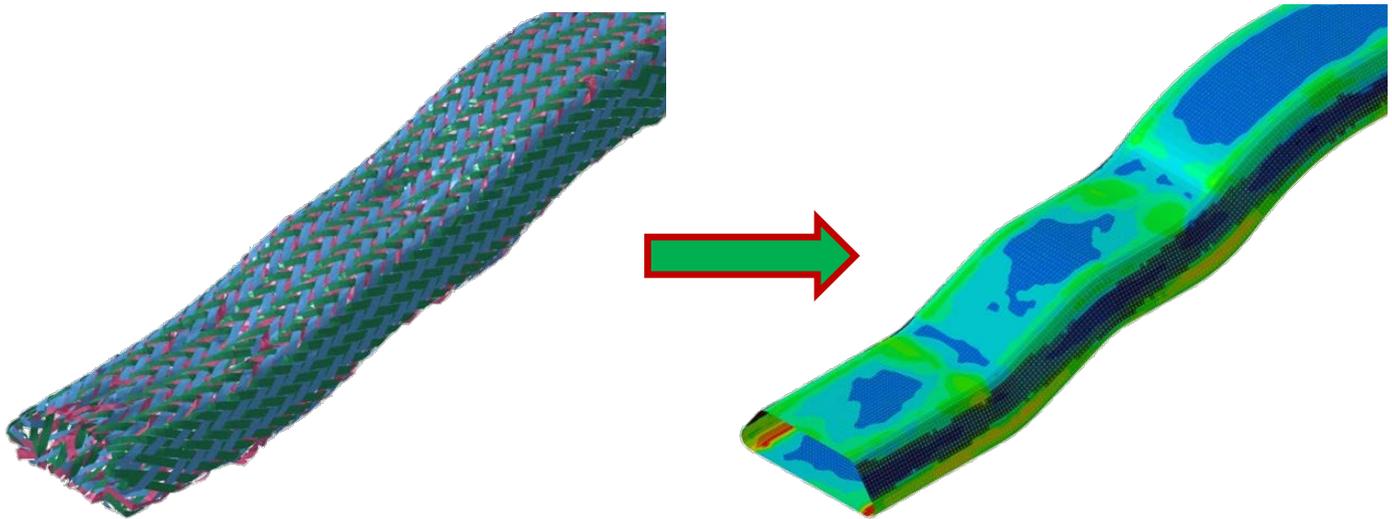


Figure 4: Identifying RVEs based on the process simulation result (left) and assigning thicknesses and respective material IDs on the target mesh. The blackened area displays the elements being assigned properties of a biaxial braiding (right).

any further history handling and averaging. After the transfer, process specific routines will take into account where the data is coming from and consider effects such as direction dependency or specific routines handling element size dependent properties such as damage variables. Further history handling and averaging techniques will be considered in the near future.

History Variable Handling

Special mapping capabilities are necessary to handle material model specific properties stored as history variables in LS-DYNA. A list of the history variables can be found in [14] or on [19]. Proper consideration of history variables is crucial in various cases: if the history variables are direction dependent, they have to be transformed from the formulation in the source coordinate system to the one that is used in the target mesh. This is usually a transformation from element coordinate system to a new element coordinate system for the case that different discretization methods are used in the source and the target mesh. Also common is the consideration of the element size. Simulations using e.g. the GISSMO – option in *MAT_ADD_EROSION need to be adjusted referring to the specific element in source and target mesh. Therefore, also the effective plastic strain has to be accounted for do properly estimated the element size dependent state of damage and triaxiality on the target mesh. Some of these methods have already been shown in [12]. And finally, it has to be considered that source and target mesh consider different material formulations and history variables shall be transferred, but they do have a different meaning on the same position in the target mesh. Therefore, a very general implementation has been implemented in envyo® which allows the user to switch the position of any history variable in the source mesh, erase specific history variables (set them equal to zero), or reduce the amount of overall history variables

in the target mesh. This method is shown in table 4. History variables not considered in this list will by default be transferred to the target mesh without further consideration

Table 4: Handling of any arbitrary history variable with envyo®.

\$-----	
NPLANE=4	define number of in-plane integration points in target mesh
NTHICK=5	define number of through thickness integration points in target mesh
INTEGRATION_RULE=GAUSS	define integration rule (Gauss or Lobatto)
MAP_STRESS=YES	turn on stress mapping (for history – handling)
INITIAL_STRESS=0.0	set all stresses equal to zero
MAP_THICKNES=YES	map thickness (otherwise, define thickness value)
HISV_HANDLING=YES	activate history variable handling
12 0 0 10	history variable 12 will be moved to position 10 on target mesh
15 200 1 11	history variable 15 which is the direction cosine (200) will be moved to position 11 on target mesh and is a scalar, direction dependent value (1)
16 201 1 12	history variable 16 which is the direction -sine (201) will be moved to position 12 on target mesh and is a scalar, direction dependent value (1)
18 0 0 --	history variable 18 will be set equal to zero
MAX_NUM_HISV=18	the maximum number of histories will be restricted to 18.

Similar procedures as shown in table 4 are available for any arbitrary csv-file, where the first three input values are considered as being the x, y, and z coordinates of a point in space and the following, comma-separated values are considered as histories. The expected csv-file format is as defined in table 5.

Table 5: Input layout for any arbitrary csv-file for history variable consideration with envyo®.

X-Coordinate, Y-Coordinate, Z-Coordinate,HISV#1,HISV#3,...,HISV#N

In figure 5, the influence of the various considerations when mapping from a fine source mesh (right) to a coarse target mesh are shown. The black curve thereby represents the stress-strain curve resulting from simulation on the fine mesh (0.5 mm). The light grey curves represent the experiments. The blue curves represent the results for the case that only stresses are mapped from the various fine meshes to the coarse mesh (10 mm element size), the yellow curves represent the results for the mapping of stresses and histories without any damage estimation, the red curves show the results taking into account only history variables, which consider the element size dependency, and the green curves show the analysis results with mapped stresses, strains, and history variables, taking into account the element size dependency. These results are obviously the closest to the results from the analysis with the fine mesh, regardless of the element size. Therefore, it is crucial to properly consider stresses, strains, element sizes and corresponding history variable when transferring results from process to structural analysis.

After handling the various history variables, the output file, or dynain – file will be generated.

Conclusion and Outlook

In this paper, the workflow of the recently developed mapping tool *envyo*® has been introduced. Special focus has been given to important topics such as geometry matching, point cloud generation, averaging, interpolation,

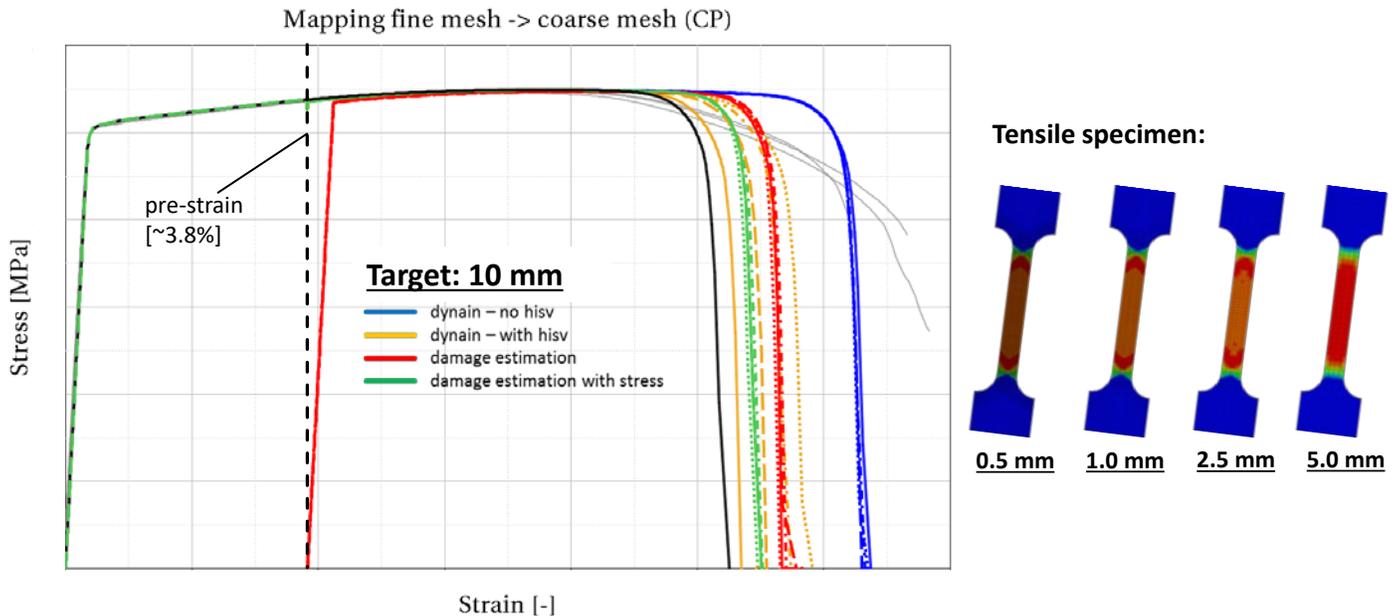


Figure 5: Stress-strain curves resulting from a 10 mm tensile specimen (left) with different initialized properties mapped from pre-loaded tensile specimen with smaller element sizes (right).

homogenization and history variable handling. Different methods have been introduced which are already implemented within the mapping tool or will be implemented in the near future. The small example from figure 5 also illustrates the necessity to properly consider history variables depending on the source and target material models, their direction dependency and the different discretization methods and element sizes in source and target mesh. Another application example which is under recent development is the applicability of *envyo*® for the warpage prediction of 3D printed parts using LS-DYNA. Therefore, a link between gcode – data, which is the native machine programming format for 3D – printers, and the LS-DYNA input file has been established. This allows for the generation of points which will be used as the load path of the heat source moving along this path with different velocities. Besides the point generation from gcode data for LS-DYNA, the velocities of the heat source are also generated, together with the on- and off functions for the heat source. The methods are similar to the once described in [20], considering a ghost material which will be activated at a specific temperature. This is illustrated in figure 6, showing the development of the 3D-printed part during the analysis and the temperature for each parts being activated layer by layer. This approach requires more calculation time the for example an approach which dumps the temperature onto the target mesh layer wise, such as it is proposed by [21], but therefore fully considers the move of the weld source as well as the resulting temperature development. The following extensions regarding 3D printed parts will consider initial stresses as well warpage in the following structural analysis. Furthermore, the load path with introduces anisotropy to the 3D printed part will be included in the mapping process and therefore, accuracy for predicting the structural behavior of such components will be increase.

Furthermore, several homogenization techniques and averaging methods will be implemented in the near future, allowing the user to fully control the mapping behavior with *envyo*®. Furthermore, a link shall be created which allows the user to define functions for history variable handling, such as in `*DEFINE_FUNCTION` in LS-DYNA.

The mapping tool *envyo*®, which is developed by DYNAmore GmbH in Germany available for both, windows and linux systems and test licenses can be requested directly from the developer.

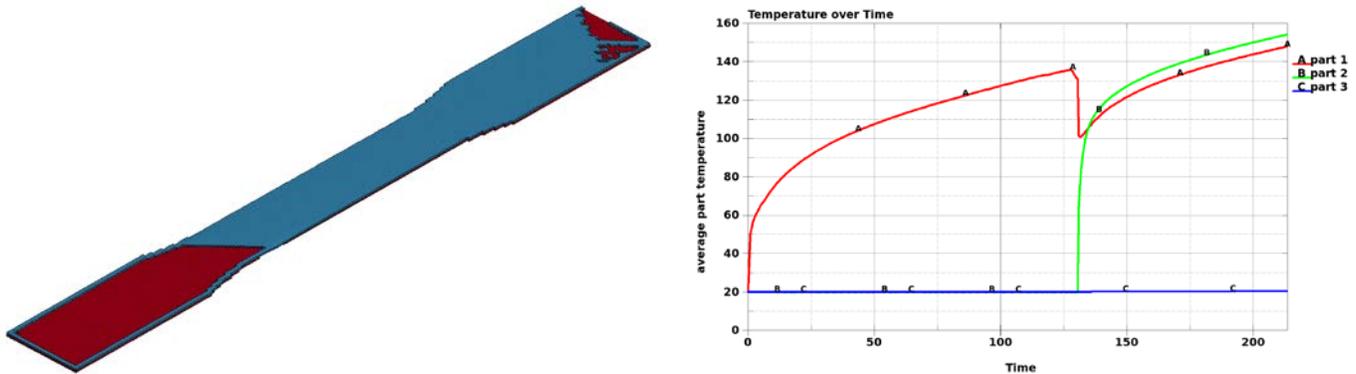


Figure 6: Additive manufacturing process simulation (left) with the binary output of the temperature development (right).

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