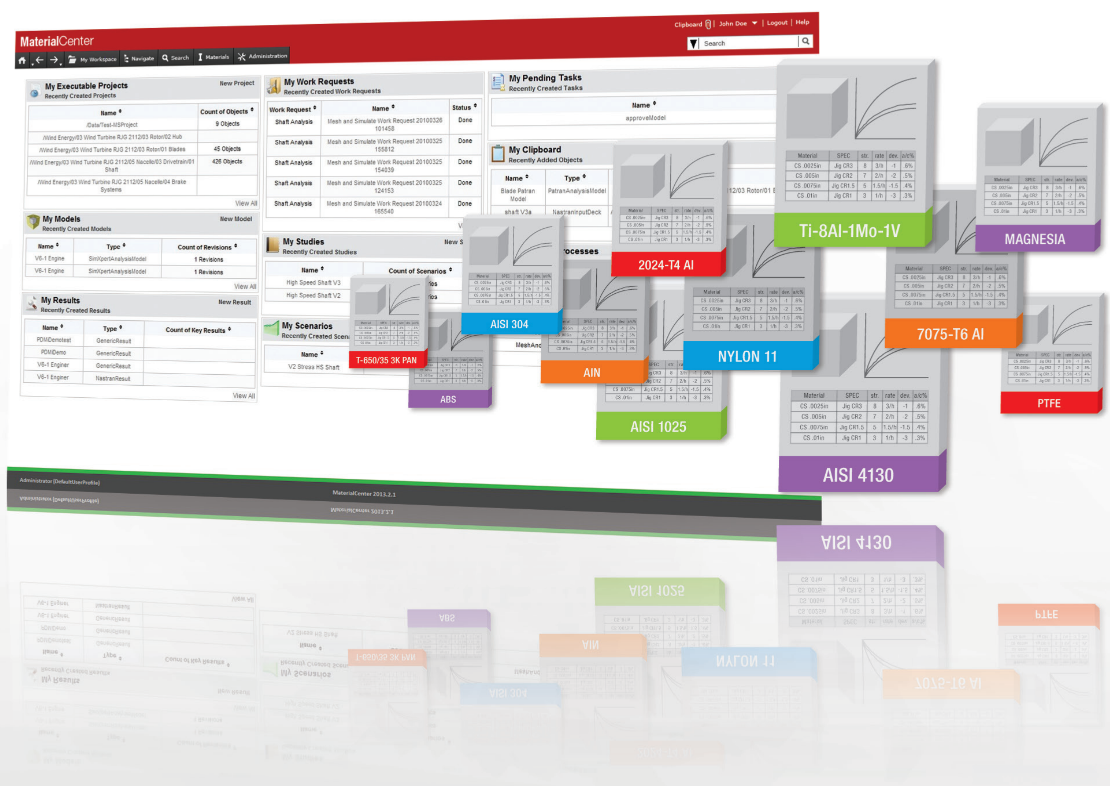
Left of Test

Manufacturing Variability Affecting Material Properties



MSC Software

Executive Summary

Materials property data is an essential resource for global manufacturing entities to strengthen product design, manufacturing processes, after market performance, and, ultimately profitability. This data, primarily the properties as a function of processing throughout life cycle stages, varies from metal to nonmetals, composites, ceramics, polymers, etc. It may come from a variety of validated and non-validated sources like: licensed and non-licensed global laboratories, outsourced suppliers, or even measurement of product performance over a period of time.

Leading materials researchers and engineers have identified the followings as the some of the key indicators behind poor product design and after market performance of commercial products

1. Improper implementation of governance to perform proper "Left of Test"(LOT).
2. Inaccurate study of manufacturing variability that affects material properties.
3. Lack of experimental-analytical correlation / comparison of material properties.

LOT strategy – Pre-Test (processing) stage, of a simple collection capture of manufacturing process characterization and uncertainty quantification of material behavior, can result in significant variation of properties.

This paper presents an innovative approach extending the traditional "Right of Test" (ROT) approach to include a systematic back-end approach to capture the manufacturing process data, apply a statistical measure to properly quantify and characterize the manufacturing effects on the "as produced" material properties (LOT).

MSC Software's MaterialCenter (MC), one of the components of Product Lifecycle Management (PLM), has optimized the process of material data and process management and addresses "Left of Test" and "Right of Test" with relation to lifecycle stages. This commercial off the shelf (COTS) solution, in use for over 20 years (former name mVISION), applies a combination of methodical principles, robust techniques and state of art information system.

Materials Lifecycle Management

Management of materials lifecycle provide linkages between items, attributes about information items as well as the information items themselves of "Left of Test," Actual Test Cycle and "Right of Test." Thus, directly addresses the issue of the traceability of data in complex environment. This is because the system stores the pedigree of the information creation process for each process steps. The data, stored as an information structure, is interpretable both by people and by computers, defining the exact context of each item of information.

MC manages complete materials process, from physical test to design allowables (integrated process management, automated traceability, robust workflow and approval processes, etc.). It is also designed to handle next generation needs through the enablement of ICME (Integrated Computational Materials Engineering) and virtual allowables. Fig.1 presents the lifecycle stages.

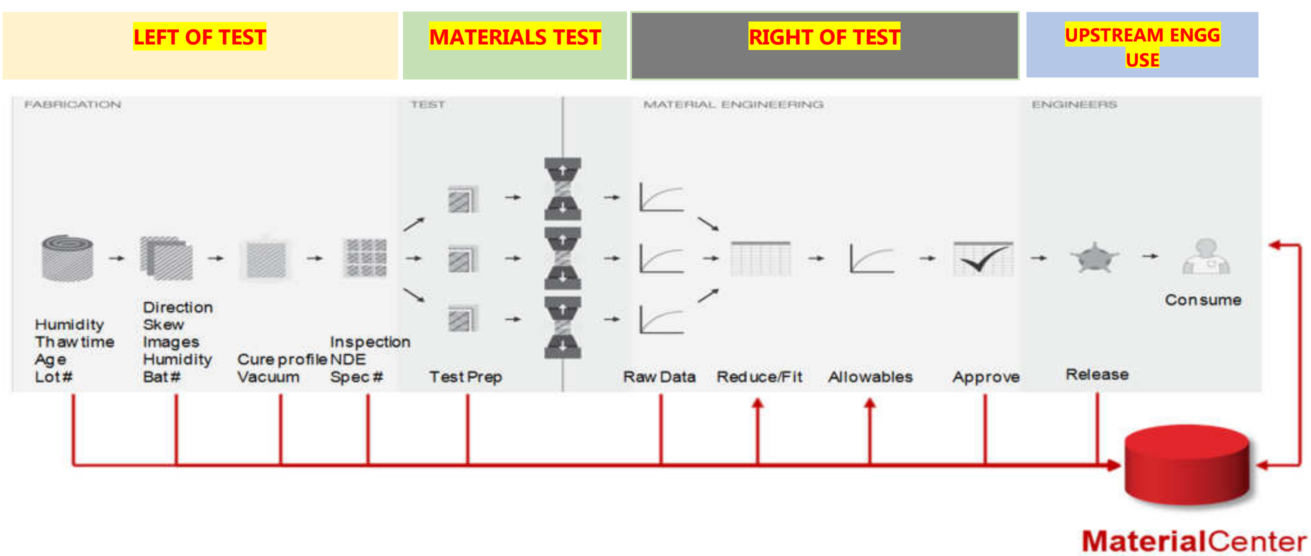


Fig. 1: Materials Lifecycle stages

Left of Test

Material characterization is a process that requires longer lead time. In the Aerospace industry, it begins much earlier than a program/platform is initiated or conceptualized. Development of a new material system is always years ahead of its use/application in new commercial projects. It is not uncommon during a program for the need to expand the test matrix for a material system to account for variation in material definition, manufacturing process, off nominal conditions, etc.

This approach works well for traditional materials using traditional manufacturing method (e.g. sheet metal stamping, forming, forging or tailor welded blanks). However, the response and performance of several modern materials platforms are not influenced, rather determined by inputs to and process parameters of the manufacturing process. In other words, the manufacturing process prescribes to a great extent the material characterization. The variability of material process allows the materials performance to be tailored and optimized as it is used in a design. The material itself becomes a design variable in the design process. Examples of material system include chopped fiber injection molded composites (CFRP, RTM, etc.), layered composites, and materials created via additive manufacturing. All these materials are highly dependent on the manufacturing inputs and process.

In additive manufacturing world, path printing direction of 3D printed parts can be used to tailor the product performance, but can also introduce variation in the "as manufactured part". The introduction of variability needs to be accounted for and the number of parameters increases as compared to traditional manufacturing methods. For example, in order to study the variation between 2 "identical" 3D printing machines, one needs to examine the followings:

1. Variation of raw material stock
2. Shelf-life of organics
3. Process variation of thermal or cure cycles, etc.

All of the above introduces statistical variation of the "as manufactured" material behavior and have a significant unplanned effect on the outcome of simple coupons to manufactured parts.

Understanding the variability in manufacturing and process parameters is critical to determining quantifiable material properties.

Framework of LOT

The suggested starting point for such an approach is to begin with a material characterization test development program. Subsequent approaches scales from materials to parts and components and finally a complete assembly. Additionally, this approach is not limited to only modern material systems, but can be applied to traditional material and component development programs.

Traditional material development test programs implement a multistep workflow/work instructions to manufacture, prepare, and test coupon specimens. Data is measured and recorded for each step of the development/manufacturing process for the test specimen. Often times this information is recorded on a "Traveler," a single document that "follows" the coupons from raw goods to tested specimen. In addition to the Traveler, other recording and monitoring tools may be employed to track related data such as humidity, material out time, etc.

Traveler data is often disconnected and unrelated to the "as tested data." Often at times the data is recorded on paper and, if one is lucky, transcribed to an electronic format (like Excel). If the data (or metadata) is stored electronically, it will be in a system other than a proper materials data management system and the information will be "disconnected" from potential downstream uses, such as correlation of the manufacturing data to materials performance and variation of manufacturing effects.

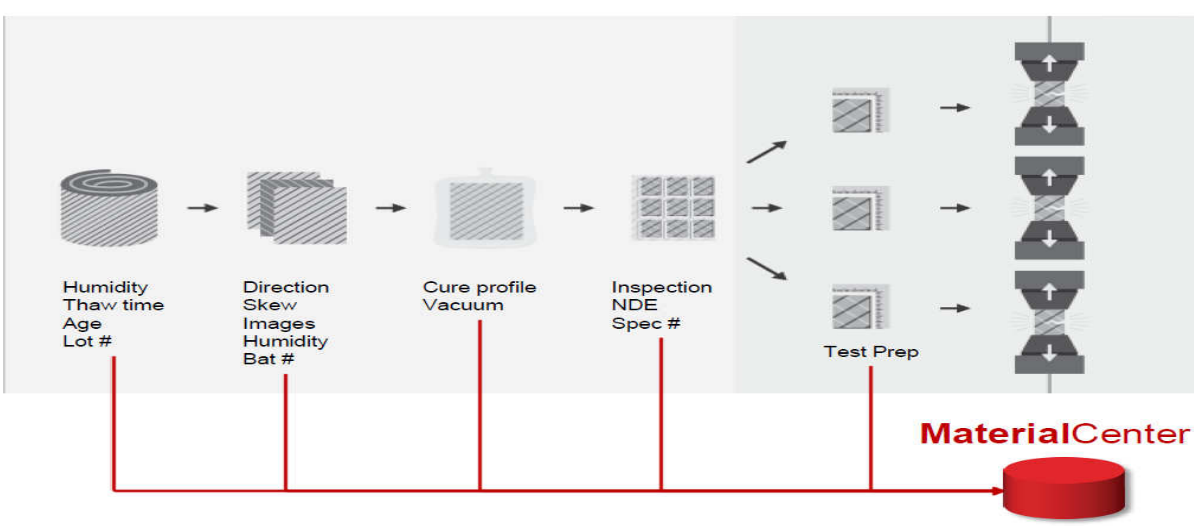


Fig. 2: Left of Test (LOT) – Framework and phases

Fig. 2 presents the framework and phases (steps) of LOT stage. This provides a direct interface to record the test preparation data directly into the same system that manages the material data management (e.g. a single repository maintaining the data from the "Left of Test" with data from the "Right of Test" with full traceability).

Some of the key steps (phases) in the LOT stage may include the followings:

1. Test Environment: Information on Temperature, Effects of humidity, Thaw time, Age and Lot number of the Test specimen.

2. Boundary Conditions: Direction of applied mechanical / electrical load affects microstructural characteristics of the specimen.

3. Profile/Schedule: Definition of thermal (heating /cooling) profile causing changes in specific heat is recorded along with cure profile/pressure schedule.

4. NDE: Nondestructive evaluation may include thermal imaging, phased array ultrasonic, eddy current testing and optical laser backscatter.

Above steps have been identified as the key contributor in determining the following material property sets during the different stages of the lifecycle.

A. Mechanical properties: Microstructure properties change during processing stage or use. The followings are the most difficult to characterize:
    a. Grain distribution and texture;
    b. Fatigue initiation;
    c. High strain rate.

B. Physical properties: Physical state of materials may vary and pose challenges. The most difficult data collection include the followings:
    a. Heat of transformation - Gibbs Free Energy and Enthalpy;
    b. Surface and grain boundary;
    c. Surface tension and Gibbs-Marangoni effect.

C. Uncertainty in modeling: Assumptions on boundary and processing conditions may carry a high level of uncertainty.

Complete electronic documentation of each step results in tighter statistical band of material end properties. It can also provide multilevel benefits

i. Streamlines the workflow of the Traveler into a single master document;
ii. Manages the work instructions of operators;
iii. Records all essential data related to manufacturing processing steps that may result in variability;
iv. Stores and continually updates the central material data and process management system;
v. Lifecycle stage data provided to other corporate stake holders.

Right of Test

Traditional material characterization begins with testing materials, often times in batches (typical of coupon level testing of various composition) to account for variability in material performance. Once experimental measurement is completed, materials test output data is recorded. Key recorded data are usually as follows:

1. Pictures of Test Set up;
2. CT Scans & X-ray microscopy;
3. Post Failure micro-scans;
4. Strength (Yield strength, Tensile strength, Ultimate failure strength);
5. Young's modulus;
6. Density.

Statistical variability of the recorded information is examined and mean material properties interpolated / extrapolated. The approved and released property data is forwarded for upstream engineering activities like product design, development and simulation work.

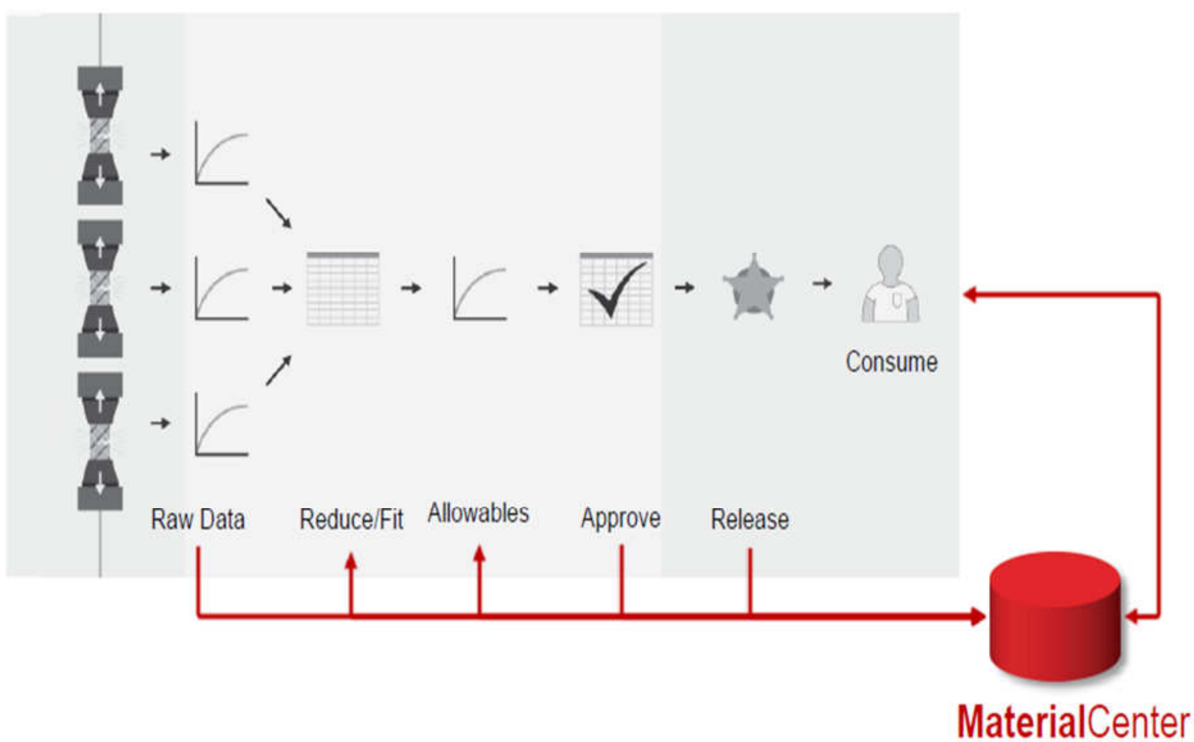


Fig. 3: Right of Test (ROT) – Framework and Process flow

This approach is known as “Right of Test”. The underlying assumption of the influence in the manufacturing process during “Left of Test“ is considered within sufficient tolerance limit.
Fig. 3 presents the frame work and process flow of ROT

In summary, LOT stage materials processing information is the key to ROT fulfillment. Inaccuracy in that stage impact the followings:

a. Inaccurate material property sensitivity matrix (e.g. mechanical and physical properties);
b. Huge effort to linearize (curve fit) the tested materials data;
c. Arrange additional budget to retest materials;
d. Improper basis for follow on analytical Design of Experiments (DOE) to predict material properties in the virtual world.

CONCLUSIONS

The material data and process management system act as the materials "backbone," addressing the lifecycle for all aspects of materials management. This covers the full scope of materials lifecycle, such as materials development program, material usage for such things as a product development (design, development, simulation, validation and release) and all across the life of the product from concept to sustainment.

The new approach defines LOT stage to be more important and process driven than ROT. The key enablers in LOT are:

1. Replacement of outdated traveler
2. Complete electronic documentation of collection/capture of manufacturing process
3. Characterization of manufacturing processes and steps that effect material behavior.

All of these significantly impact the statistical variation of material properties computed in ROT stage. Thus, it is essential to put more stress on "Left of Test" and capture the manufacturing, process and raw material characteristics in order to determine meaningful engineering property matrix. The variation of these effects can be statistically accounted for and used to determine a prediction of material behavior and performance resulting in a tighter statistical band for engineering properties.

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