# THE DESIGN OF GRADED MATERIAL OBJECTS

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**Abstract**
Rapid Manufacturing utilizes the application of different materials in parts by stacking a sequence of layers. Based on the requirements of the part, mixtures of materials, so-called Functionally Graded Materials, can be used to compose the product functionality. This process depends completely on the availability of CAD information of the part geometry. Unfortunately, commercially available CAD-systems do not allow the design of graded material structures. TNO developed a computer tool which enables the user to specify Functionally Graded Materials. The system is based on a new approach to define the material composition at any point in the solid.

## 1 INTRODUCTION

Few new technologies have impacted product development as much as layer manufacturing techniques (LMT). Parts produced by LMT are based on adding material instead of removing, e.g. milling. The procedure is based on a 3D CAD model, which is sliced into thin layers by arithmetical means, which can than be made individually as a stack of cross-sections resulting in the 3-dimensional part, e.g. the stereolithography technique, see Figure 1. There are many different techniques to make the slices. Each technique has its own advantages and limitations.

In combination with 3D CAD it provides the product developer with a very powerful tool to optimize its design, and shortens the time needed to develop the product. New technologies such as concept modelers are able to produce prototypes with acceptable tolerances in a short time.

The highest benefit in all layer manufacturing technologies comes from the reduced time to market. It is followed by fast changes in design and flexibility in technical changes both in design and manufacturing processes. Layer Manufacturing Technologies limit these changes to data and not hardware modifications. Hence, improvement of quality and product maturity resulting from testing and field experience can still be introduced without high cost of changing tools or manufacturing processes [1, 2].

LMT enables the possibility to create physical prototypes automatically without any human intervention during the realization of the part. Expanding the number of materials and improving the material properties used in these layer manufacturing processes gave the opportunity to create better quality prototypes. Slowly the quality of the prototypes is improving and proved to have a functional quality.

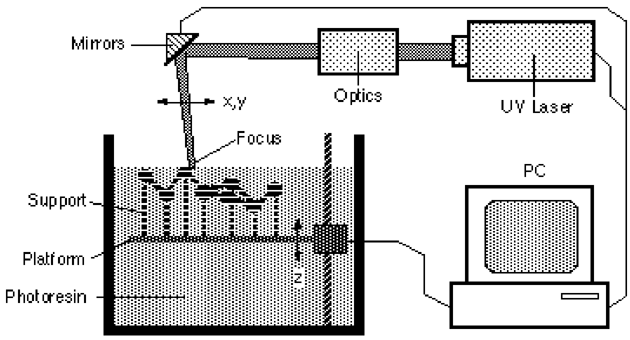


Figure 1 : Schematic design of a stereolithography apparatus.

This is why nowadays, for small series, layer manufacturing technologies are used to produce actual end production parts. Production of end parts with a layer manufacturing technology is known as Rapid Manufacturing (RM).

## 2 RAPID MANUFACTURING

Market potential for Rapid Manufacturing is growing quickly, as is demonstrated by initiatives like the Mobile Part Hospital Program of the U.S. Defense Department [3], and many other examples [1]. Every year, the operational costs of RM are decreased, so the break-even point of a production run of a certain product is stretched. Depending on the geometry and the function of the part, nowadays series sizes of up to 20,000 pieces can commercially be produced efficiently [4].

High potential is seen for parts with complex geometry and less demanding mechanical properties. Rapid Manufacturing techniques excel in mass customized part production. Many of the major manufacturers of hearing aids are in the early stages of using RP to mass customize their products in impressive volumes. Some of these companies produce more than 1,000 in-the-ear hearing aids per day [5]. To fit the patient's ear canal, each product is unique in its shape and size. The process begins with a silicone rubber impression of the ear. The impression is then digitized with an optical scanner and RM used for the rapid production of the hearing aid shell, see Figure 2.

### 2.1 Mono material

The use of Rapid Manufacturing will give designers the opportunity to design products in a different way, no longer limited by the production techniques, like injection molding, deep drawing, etc. This new design freedom involves not only the geometry of the part, but also the material definition of the part can be done in a different way. However, most layer manufacturing technologies are designed

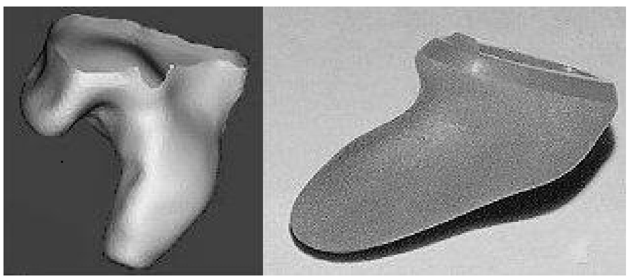

Figure 2 : RM manufacturing steps of a hearing aid.

to manufacture parts comprising only one material per production run. Only some techniques are able to process more than one material per layer, e.g. the LENS and DMD processes [6, 7]. This opens the possibility to build parts comprising two or more different materials.

### 2.2 Multi material

Multi materials in layer manufacturing technologies are yet not often used. Current state-of-the-art of the RM-machines (including controlling software), CAD-tools, and design methodologies don't enable the development and manufacturing of multi material products. However, market demands for multi material products forced TNO to solve these difficulties. Especially solutions were demanded to support the development of 2K injection molded parts (see Figure 3) and MIDs (Molded Interconnect Devices). Therefore a special multi material manufacturing machine has been developed, based on the principle of extrusion.

The design of a multi material part is done on a commercially available CAD system. Each material of the part is represented by one solid. These solids are exported in STL-format (standard triangle language). This format is commonly used on standard layer manufacturing machines. Unfortunately, this method is very cumbersome for parts comprising many different materials on different locations, since each material (and location) in the part require a separate solid. This methodology does not fully stretch the capabilities of RM-machines to its extent, because they are able to deposit numerous mixes of several materials in one layer. Therefore the solid-methodology used to describe multi material parts is not viable to describe parts containing many mixes of materials. These kinds of multi material mixes in functional applications are called Functionally Graded Materials (FGM).

## 3 FUNCTIONALLY GRADED MATERIALS

The concept of Functionally Graded Materials existed already before the idea came to explore this in combination with the Rapid Manufacturing technology. To get a full understanding of Functionally Graded Materials the history of Functionally Graded Material will first be discussed.

### 3.1 History of Functionally Graded Materials

Functionally graded structures can be seen in nature, in bio-tissues of animals, such as bones and teeth, and plants. For example a tooth and more specific dental crowns are an excellent example of the application of a FGM. It requires a high wear resistance outside (enamel), and a ductile inner structure for reasons of fatigue and brittleness. Further, it requires a translucent outer area and a specific set of color nuances for reasons of aesthetics [8].

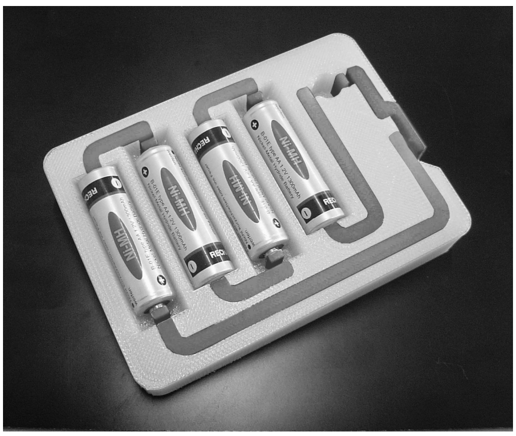

Figure 3 : Prototype of a 2 components MID part.

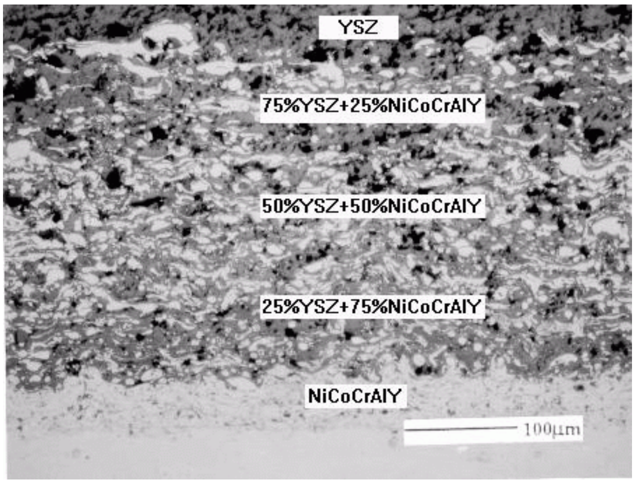


Figure 4 : Plasma sprayed functionally graded $ZrO_2$/NiCoCrAlY thermal barrier coating.

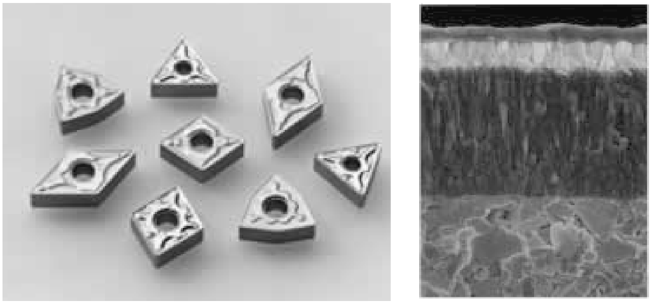

Figure 5 : Mitsubishi Materials Miracle Coated Indexable Inserts (left) and its surface structure (Courtesy of Mitsubishi Carbide).

In the technical world FGMs were first proposed around 1984-85 when Japanese researchers studied advanced materials for aerospace applications working on a space plane project. The body of the spaceplane will be exposed to a very high temperature environment (about 1700°C), with a temperature gradient of approximately 1000°C, between inside and outside of the spaceplane. There was no uniform material able to endure such conditions. Therefore, the researchers devised a concept to fabricate a material by gradually changing (grading) the material composition (see Figure 4), and in this way improve both thermal resistance and mechanical properties.

Nowadays there are already a significant number of commercial products being produced with graded materials. Mitsubishi Materials developed their Miracle Coated Indexable Inserts (see Figure 5), which are made of a carbide substrate that has a newly developed graded structure on the surface and CVD (Chemical Vapor Deposition) coated layers with a triple-structure [9]. By doing so, plastic deformation and damage resistance was successfully improved.

Most of the FGM applications are built as a coating on a surface build up by flame spray, CVD or spark plasma sintering. Therefore, all these applications have graded properties perpendicular to the surface but parallel to the surface the material composition is uniform.

Using Rapid Manufacturing for Functionally Graded Materials enables the creation of products with changing material properties in any direction.

### 3.2 Rapid Manufacturing and FGM

Most of the Rapid Manufacturing technologies generate the product point by point for each layer, like pixel representation of a picture. Examples of these technologies are the 3D Systems Thermojet® and the Objet machines

[10, 11]. Both machines generate the product drop by drop using a modified inkjet system. Both systems, equipped with one or more extra jets able to stack other materials, can build graded material parts comparable with printing a stack of color pictures on top of each other.

The FGM machine could be provided with information to "print" the desired graded material distribution. This could simply be solved by sending the machine a sheet of pixels for every layer (similar to printing color pictures).

These stacked layers of pixels are known as Voxels (volumetric pixels). The voxels originates from the medical field [12] as data representation of MRI and CT scans, see Figure 6. This is a passive application of data contained by the voxels. Modeling functionally graded material structures requires a more dynamic approach. A voxel representation for this purpose is not desirable since there is no relation between the individual voxels and each voxel must be modified in order to change the design.

In the next section some alternative commercially available data representations methods will be briefly discussed and a new approach to cope with the described problem will be introduced.

## 4 MODELING FGM STRUCTURES

The geometry of most products are designed on commercial CAD systems. These commercial CAD systems are mainly B-rep modelers. B-rep stands for Boundary representation, which implies that the system describes the solids only by the definition of the outer surface. The inside of the so called "solids" is not defined ("empty"), see Figure 7. Describing the material composition of the enclosed volume at any point is not possible with current CAD systems.

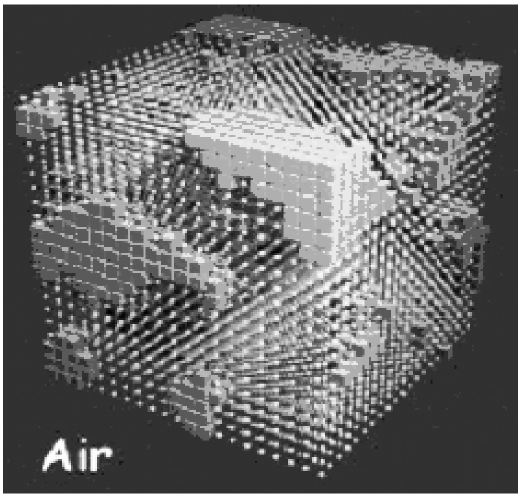


Figure 6 : Voxel representation of clouds.

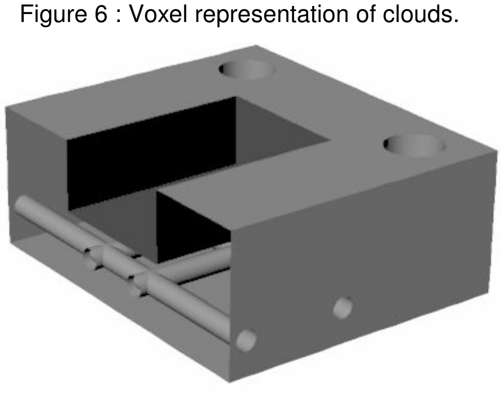

Figure 7 : Cut through a CAD solid model showing the "empty" inside.

An extensive inventory of mathematical models to describe FGM structures (see e.g. [13 14, 15, 16, 17]) resulted in four potentially suitable options:

- Voxels have, like pixels, no dimension and are quantified by a scalar. Akin to the way that a digital image is represented by an array of pixels, a volumetric dataset is made of voxels laid out on a regular 3D grid [18, 19]. Besides the problem that a grid of voxels don't show mutual coherence, the geometric accuracy of a solid represented by a grid of voxels is determined by the number of voxels. When accuracy is required, the use of voxels requires vast volumes of data storage and processing. Consequently, voxels are not the ideal entity to design and edit graded information. Nevertheless, they are very practical to use as neutral data format between the design system and the machine fabricating the part.
- FEM elements are used for Finite Element Analysis. Therefore a simplified model is used, consisting of many finite elements (tetrahedral, bricks, etc.) interpolating nodes in space. The size of these elements varies, so its position in the solid is not unambiguous. Although it was suggested that FEM elements could be used to model spatially varying materials distributions within FGM objects [20], the modeling method is inefficient for highly graded structures, so expected memory requirements and data processing effort are large.
- Particle system elements are objects that have mass, position, and velocity, and respond to forces, but that have no spatial extend. Because they are simple particles, by far the easiest objects to simulate. Despite there simplicity, particles can be made to exhibit the wide range of interesting behavior [21]. Since the particle show no coherence and there positions within a certain volume can change, particle system elements do not satisfy the requirements for graded structure modeling.
- Vague Discrete Modeling (VDM) elements have been developed so that the shape of a product doesn't have to be completely defined. A vague discrete model is vague in the sense that multiple objects are represented by one interval model, and that multiple shape instances can be generated based on certain rules. In this way global shapes can be defined while remaining the possibility to modify the shape in relation to, for example, constructive, functional, ergonomics or aesthetic reasons [22]. This model is still under development, and particle definition doesn't meet the requirements to define graded structures, due to the dynamic behavior of the particles.

Al these types of entities do have the major disadvantage of using a lot of memory, some of them are rather complex or do not have any relation between the entities, badly influencing the editing of these kind of formats.

To overcome the disadvantages of above mentioned data formats for the descriptions of FGM structures, TNO developed an alternative approach. The next section describes how this approach is implemented in the software program Innerspace™. Basically the approach is based on the assignment of certain properties to specific areas within the enclosed volume of a solid. These arbitrary properties determine the characteristics of any point in the solid.

## 5 INNERSPACE™ PRINCIPLES

The best way of understanding what a modeling system for FGM structures should be capable to do is analyzing the situation from the point of view of a user.

Suppose a manufacturer of sweets developing a new kind of candy stick, see Figure 8. The instructions are:

- The candy stick should be sour at one end and sweet at the other end
- The candy stick should be red at the outside and white at the inside.

With these two instructions the model properties on each position have been described within the candy stick. The modeling system for FGM structures should now translate these desired model properties to material properties. The system must be able to give the value of the specified properties (sour, sweet, red, white) at any point so that the stick can be produced, realizing the correct material composition.

This example shows it is a waste of effort to define the properties of every point of the solid representing the candy stick. To describe the structure of the candy stick, in this example the candy stick manufacturer started defining properties in some specific areas. The same procedure will be used to find an automatic way to calculate the properties of the stick at an arbitrary point (see Figure 9).

These areas, where the properties are equal will be named "props". The areas between these props are described by the transition function from one prop to the other, so-called "distribution function". Finally, when calculating the distribution of materials it will be clear that the distribution functions are limited by the boundary of the solid, so-called the domain. Summarizing, the modeling system for FGM structures is defined by:

- domains
- props
- distribution functions

### 5.1 Domains

Ultimate freedom of volumetric property distribution can be created with multiple domains. Every distribution function is valid in a specific domain. The props used by the distribution function, are not necessarily located in the domain.

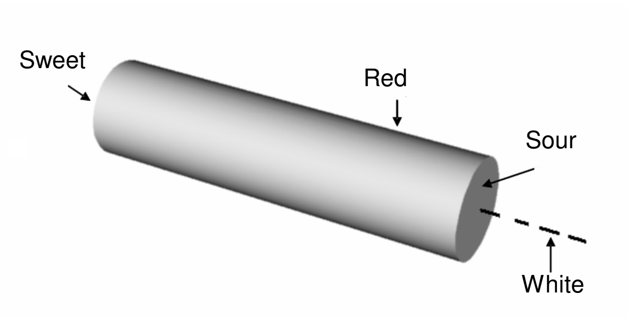


Figure 8 : Candy stick with desired properties.

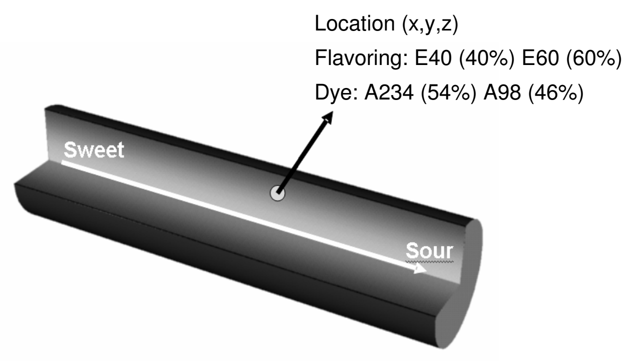


Figure 9 : Example of local properties in candy stick.

### 5.2 Props

For reasons of simplicity two types of props have been defined:

*ISO prop*

ISO props are areas with constant properties. They can be defined by a point, line or surface. ISO prop areas of the same type may not intersect or touch each other, since this causes an internal conflict. For example a point can't be at the same time defined as sour and sweet. The example of the candy stick has four ISO props of two types, taste (sweet, sour) and color (red, white). Properties of the same type are able to influence each other, while properties of a different type are independent of each other.

*Vari prop*

For more advanced property distributions ISO props are not sufficient, therefore Vari props has been defined. Both props have the same behavior. The ISO prop however describes an area with constant properties, while the Vari prop describes an area with variable properties. An arbitrary Vari prop is dependent on one or more ISO or other Vari props. When the local property of a point belonging to the Vari prop is needed, the value of the local property is calculated in relation to the involved props. The involved props are not distributing their properties into the domain, but exclusively to the Vari prop.

### 5.3 Distribution functions

A distribution function describes the quantity (e.g. percentage sweetness) of a property as a function of the distance. In order to specify effective distributions two distribution functions are defined:

*Absolute distribution function*

The absolute distribution function is affected by the distance to a prop. This function gives the relation between a relative distance and a percentage of the property. The distance is a given value by the user, see Figure 10.

*Relative distribution function*

The relative distribution function is affected by the relative distance of two props. From a given point the shortest distance is calculated to both props. The relative position is used to calculate the values of the properties, see Figure 11.

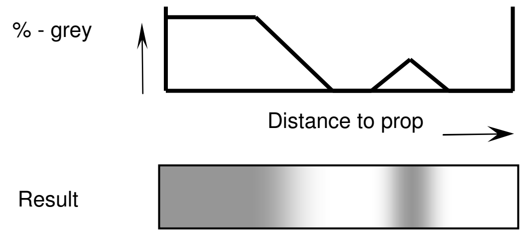


Figure 10 : Example of an absolute distribution function.

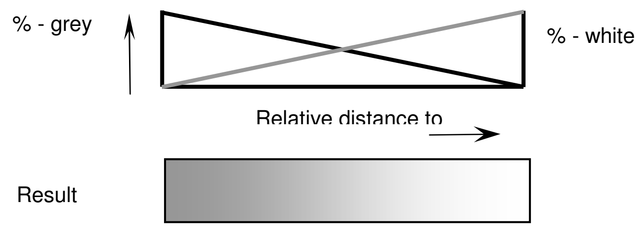


Figure 11 : Example of a relative distribution function.

Since all properties are defined by distribution functions and not by discrete elements like voxels, the resolution of the prop determination in theory is unlimited, and therefore can be tuned to any application.

An other example will be discussed now, in detail to demonstrate more extensively the capabilities of the developed method to define adequately a complex functionally graded structure. This graded structure can represent any type of product with graded material structures. An example is a dental crown with different properties, a hard wear resistant outside, graded to a stress absorbing ductile inside. For simplicity this example consists of simple cylinders demonstrating all the previously described available functionality.

Suppose a small cylindrical bar 1 (see Figure 12), completely enclosed by a bigger cylindrical bar 2. Both cylinders represent a domain. First will be focused on domain 1 represented by bar 1. In this domain two properties are created (as in the example with the candy stick) but with the distribution Function 1, displayed in Figure 13, a more advanced graded structure is generated (Figure 14).

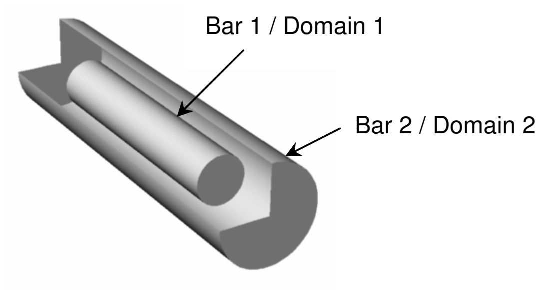


Figure 12 : Configuration of 2-bar example.

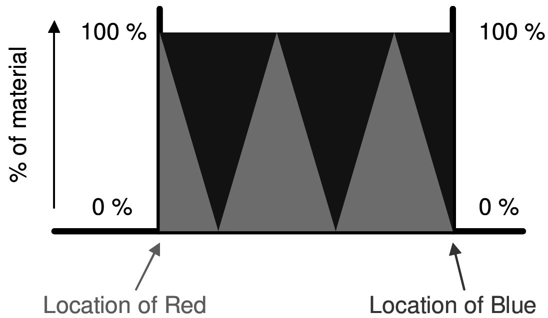


Figure 13 : Function 1 determines the distribution of the properties (colors) of domain 1.

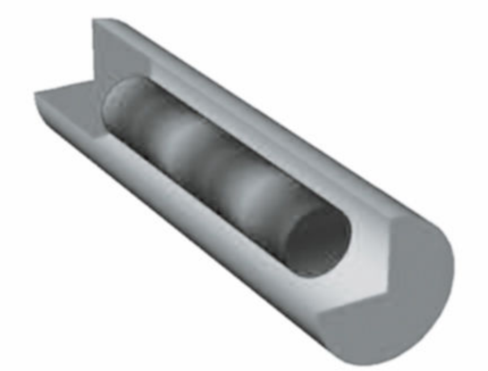

Figure 14 : Result of distributing the properties in bar 1.

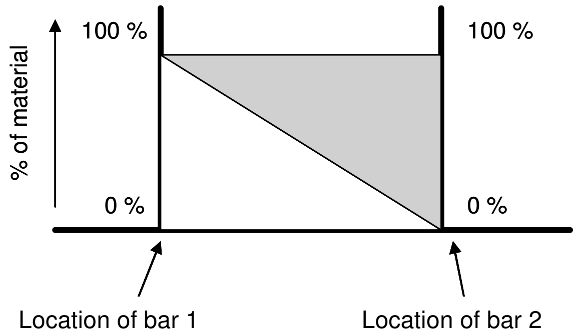


Figure 15 : Function 2 determines the distribution of properties of domain 2.

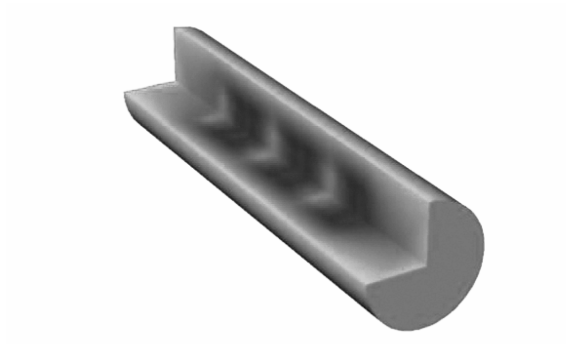

Figure 16 : Result of executed sequence of operations.

The properties created in domain 1 will be extended towards the outside of domain 2 by Function 2 (Figure 15). To achieve this, bar 2 is defined as an ISO-prop and bar 1 as a Vari-prop dependent on the same ISO-props as used to create the property distribution in domain 1. The result is displayed in Figure 16

## 6 DISCUSSION

However this research was initiated to support other internal projects, the system is now used at different pilot locations. Based on our own and third party feedback, results of this research show that initial project requirements are met. The use of the Innerspace™ program gave some remarkable response of which some highlights will be discussed here:

- The system gives the opportunity to define graded structures that range from very simple to extremely complex. Far more complex than the human mind can imagine, although it is questionable whether this complexity is needed. This resulted in the conclusion that the capabilities of the developed model (program) are sufficient for al experimental graded material setups foreseen at this moment.
- Although the graded distribution of properties is a 3-dimensional distribution, it could be experienced by the user as a more dimensional problem. A typical complex and regular problem is the optimization of the heat conductivity behavior in certain areas of a given product geometry and the mechanical strength in the same areas. The optimization parameter is the composition of the graded material distribution. This requires a new approach of design optimization.

## 7 CONCLUSION

This research, finding a solution to define graded material property distributions in a CAD like environment to be able to send graded material information to Rapid manufacturing machines for graded materials, succeeded.

The developed system covers the need of Research and Development centers in the field of experimental graded material and machines and is likely to cover both beginners as experienced user requirements

The creation of complex graded material distributions in complex geometries is far beyond the capabilities of the human brain and therefore can only be applied in full potential if it is supported or even driven by computerized optimizations in the future.

The design of Functionally Graded Material parts (with Rapid Manufacturing technologies), and on a limited scale the production of these parts, has become possible. The creation of Functionally Graded Material products with Rapid Manufacturing therefore is now a reality.

## 8 SUMMARY

This paper describes the state of the art of Layer Manufacturing Techniques (Rapid Manufacturing) in relation to its capability to process mixed material for product manufacturing. Further it is shown that RM-machines can process multiple materials within layers of which parts are built off, but CAD-systems are not able to define these structures. To bridge this gap, a modeling approach has been developed. Basically this approach is based on the assignment of certain properties to specific areas within the enclosed volume of a solid. These arbitrary properties determine the characteristics of any point in the solid. This model has been implemented in the TNO software program Innerspace™, and its capabilities are demonstrated by two examples. Feedback from pilot users proved that Innerspace™ satisfies initial research requirements.

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