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## Reverse Engineering based Methodology for Modelling Cutting Tools

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### Abstract

Reverse Engineering involves the use of techniques for extracting information about manufactured products. Assembled products contain usually hidden parts. Because of this, it is difficult finding RE procedures that involve the use of 3D-scanning techniques. However, 3D scanning technologies can help to capture information about their geometry for generating virtual models (VM), which can offer many possibilities for digital analysis. On the other hand, starting from a VM, it is possible to achieve the physical reproduction of the piece using additive manufacturing technologies. This allows performing functional tests or, simply, obtaining a physical high-scale model. All that permits improving the product through a redesign process. This work reports on the results of a preliminary study on the application of different 3D-S and AM technologies for generating VM and PHSM of a two edges mill. A comparison based on cost, result, difficulties-capabilities and runtime has been made.

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**Keywords:** Reverse Engineering; Cutting Tools; 3D Scanning; Modelling; Additive Manufacturing.

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### 1. Introduction

The machining is one of the most currently used manufacturing process, and within the same, conventional machining. The tools used for this type of conventional machining are known as cutting tools, and they have very different geometries and a short life.

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The variety and complexity of manufacturing processes have led to a major impact of the industrial sector on the GDP of developed nations. These processes are conventional machining requiring many cutting tool models which differ in composition, shape, dimension and tolerance, depending on the use and the material machined. The same model may have substantial differences, as the number of edges, the geometric characteristics, etc. Therefore, it is necessary to assess all the processes requirements with different cutting tools through systematic studies.

To conduct this study and to modify geometry without subjecting the functional testing tool, it is necessary to obtain the three-dimensional digital or Virtual Model (VM), because geometrical parameters required to define this model are sometimes impossible or too expensive to get. Reverse Engineering techniques seek to obtain them [1].

Reverse Engineering (RE) involves the use of techniques to retrieve information about manufactured products. Thus consists in analysing the procedure of design and manufacturing process of a product, not only with regard to geometries, but also materials and functionality [1, 2].

Currently, there are several RE techniques widely used and known but many of them still leave the object unusable to analyse or future use. Nevertheless, other alternative to this problem can be a kind of Three-Dimensional Scanning, which allows for obtaining a Digital or Virtual Model (VM). Getting the scan (VM) of an item makes it possible to redesign it, perform virtual testing, check its geometry and features, get conceptual physical models, or even perform functional prototypes for actual tests [3-5].

Different techniques can be used in the application of RE to recreate in detail the cutting tool geometry for further analysis and development. Accordingly, RE techniques allow for getting a VM of the cutting tool. This also enables to improve the product through a redesign process.

The use of RE in the Computer Aided Engineering is relatively new. There are some different applications to combine these two techniques [6-10], such as the physical reproduction of an element in the same or different material for performing functional tests or just obtaining a conceptual physical model. The latter is performed by Additive Manufacturing techniques (AM) [11, 12].

This study has carried out the digitization and subsequent physical reproduction of several cutting tools using 3D-P and Rapid Prototyping, providing a physical model, strictly conceptual, to analyse measured deviations resulting from the tolerance of the machines in the processes used. A comparison will be made between possible methods to perform each process, using different machines and software and taking into account costs, results, difficulties encountered and runtime.

## 2. Experimental Procedure

Although several methods could be used to carry out the experimental procedure, steps or general ideas for digitization and subsequent manufacture of a prototype can be established, Fig. 1. First of all, a starting model must be selected. Different problems can be observed in some models in their color, brightness, finishing or just their geometries. These techniques have limits and some models are not suitable for this purpose.

This model will be scanned to obtain the Virtual Model, the scanning being an important phase as the system obtains a point cloud the precision of which will define the quality of the model. On completion of the scanning, the cloud is processed and the three-dimensional surfaces are obtained. The VM is then created in the required format.

As soon as this VM is achieved, it is possible to modify some of its features and redesign the object if necessary. When the processing is completed, the VM can be used in the intended application.

The resulting model, whether modified or not from the starting one, can be reproduced by AM. Afterwards, the VM must be adapted to the appropriate format used by these techniques (STL). Once the format has been transformed, the three-dimensional model can be printed by AM technologies.



Fig. 1. Chart-flow of the Experimental Procedure

### 3. Experimental results

For methodological development purposes, some cutting tools were selected as starting elements, Fig. 2.

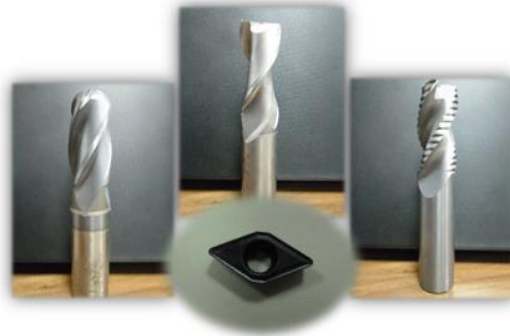


Fig. 2. Selected Tools for developing the methodology

#### 3.1. Digitizing. Obtain the Virtual Model

The scan for a VM is carried out using a 3D scanner [9]. The scan obtain the coordinates of multiple points of the surface and generates a point cloud.

Despite its complexity, the conversion of data acquired by a scanning system to a CAD model is a direct method, as opposed to a model created from scratch, which often requires major checks. This conversion can be done using a specific digitalization software or even with some CAD software like Catia®. However, it should be noticed that despite the plurality of scanning methods, not all of them deliver the same results.

Three different scanning techniques have been applied for collecting geometrical information of the tool: structured light; laser triangulation; and phase shift laser (Fig. 3). David® scanner and software (David® 3) was used for the first two techniques, and Faro® (Faro ScanArm® 2.7m) was used for the last one. Although these methods differ in many features, the concept and digitalizing stages remain the same and involve three main steps: exploration (acquisition of points); alignment (manual or automatic); and fusion or processing of the geometrical points pack for conversion into solid state.

To perform a proper analysis of the type of technique suited to each element scanned, aspects such as environmental conditions, the possibilities offered by the software used, scanning and processing times, and the resulting file size must be taken into account.

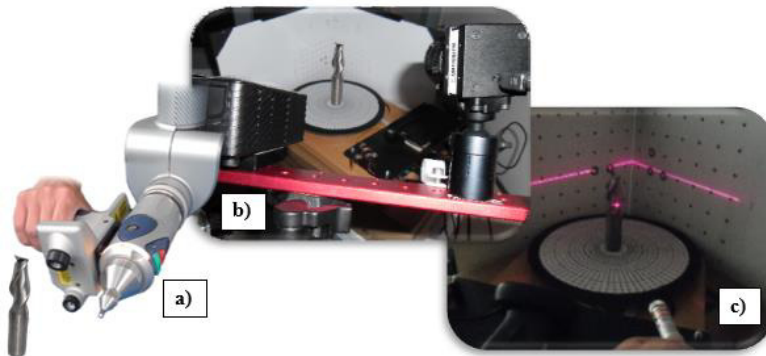


Fig. 3. (a) Phase Shift Laser (Faro®) (b) Structured Light (David®) (c) Triangulation Laser (David®)

The environment brightness of the place where the element is scanned is a very important factor to consider. In general, nearly all techniques provide bad results in bright environments. Therefore, working conditions in a space with the lowest possible lighting level must be privileged. It should also be mentioned that, in this case, the brightness of the element doesn't make the scanning easier. In some cases the element must be coated with a matte layer to ease the scanning process. The software, scanning and processing times are linked to the type of scanner used, as well as the available budget.

Some studies try to quantify the scanning errors in the different methods [13-14], relying only on the final quality of the model obtained. In this case, an initial analysis was carried out to select the best method to scan cutting tools. The best method analysis was realized in whole, comparing different items, from quality to price, (Table 1 and Fig. 4). Virtual Model accuracy depends on the resolution and the percent of dispersed points. The three most widely used methods were analyzed and the structured light was then selected for their excellent performance/price ratio for the cutting tool scanning application. The structured light scanning offers a good balance between quality, difficulty, run time and cost for the analysis of the above-mentioned cutting tools.

Sticking only to the quality of the process, a Phase Shift Laser technique could deliver better results. However, high hourly rates of the equipment rental are to be considered, as well as the significant setup time and the complexity of the point cloud post-processing, making this technique even more expensive. As a result, the Structured Light is generally recommended unless high quality is needed, requiring the Phase Shift Laser scan.

Table 1. Comparison of scanning methods.

	Phase Shift Laser	Structured Light	Triangulation Laser
Percentage of dispersed points	5	6	10
Quality of the points	Best	Good	Regular
Set-up	Complex	Simply	Regular
Post-Process	Regular	Regular	Complex
Price/Hour	Very high	Medium	Medium
Final Result	Best	Good	Poor

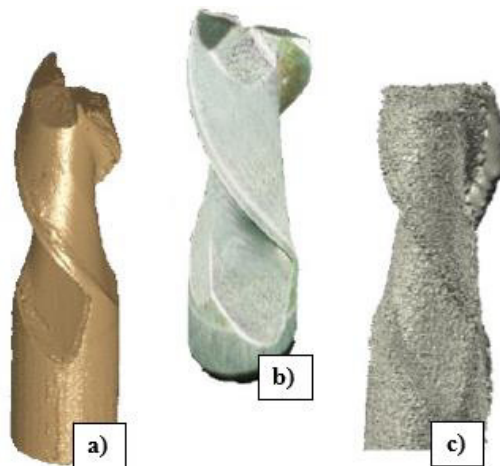


Fig. 4. Results of (a) Phase Shift Laser (Faro®) (b) Structured Light (David®) (c) Triangulation Laser (David®)

### 3.2. Structured Light Scanning process

The 3D structured light scanners project a light pattern on an object and analyse the pattern's deformation produced by the geometry of the scene (exploration). This must be done from various perspectives of the item, keeping it stationary.

To use this method, the size limit of the object should be taken into account. This procedure allows for working with items ranged between 10 and 500 mm. However, it is possible to scan bright objects, as opposed to allegations from other authors.

If the scanner has a positioning system, it will capture surrounding images and the software will perform the relevant alignments itself, having collected relevant information about the coordinates of each analysed point. Otherwise, the operator must provide to this methodology a supporting structure, a rotating base or pedestal. The core of this base will bear the item to scan, where axis will stay fixed. After setting several parameters to control the data collection, a first point cloud of the work piece front area will be obtained. This process must be repeated to accumulate enough images from different perspectives as those required. Finally, a manual alignment must be done.

Once collected from all sides of the cutting tool, the information is aligned and merged (fusion) to give as a result a closed three-dimensional model, Fig. 6. The latter can be usually processed and/or exported directly with the scanning software using a classic STL format. Otherwise, many CAD programs can convert the information to this format.



Fig. 5. Different perspectives of the analyzed object (left) and the result of the alignment (right)

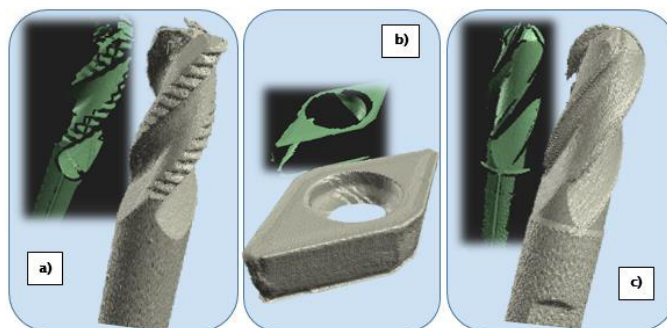


Fig. 6. Exploration and Fusion (Final model in STL format) of (a) a toothed endmill (b) a turning insert (c) a round endmill

### 3.3. Additive Manufacturing process.

From the STL Virtual Model obtained, it is possible to achieve a physical reproduction of the item in the same or different material, using Additive Manufacturing technologies. This allows for performing functional tests or just

obtaining a Physical High-Scale Model (PHSM) intended to observe the tool details. This enables to improve the product via a redesign process [3, 4]. During the last years, AM techniques have expanded significantly and changed mind-sets. This technique has an especial interest in designing cutting tools [8].

The PHSM can be obtained through several techniques of Rapid Prototyping (RP), among which the extrusion or Fused Deposition Modeling (FDM) has been studied. This method builds the solid result by depositing melted plastic layers along the section of the item. The process is repeated until all layers have been printed. This technique also helps getting an element with good quality of detail at a low cost, the latter being functional and used as a prototype depending on the required mechanical properties. Through this study, it is possible to obtain quick results and know the faults of the element in use [11, 12].

There are currently a lot of FDM machines in the market. The possibilities to obtain a PHSM depend on the machine. In the same way, the material is limited for the machine. Even if PLA and ABS are the most frequently used materials, new materials have recently been introduced to the market. Furthermore, a special software is required to manage the model and the print conditions. The software being usually supplied with the machine, a large number of specific software (Cubex®, MakerWare®...) and generic software like Kisslicer® is available. The generic software is only recommended for special users with special requirements. A comparison between these software have been done, Table 2.

Table 2. Comparison of different 3D-Prototyping software.

	Cubify®	Kisslicer®	MakerWare®
Changing parameters (speed and temperature)	Null	Very good	Medium
Changing support structure	Poor	Very good	Medium
Post-Process	Complex	Medium	Medium
Price/Hour	Medium	Free	Medium
Final Result	Medium	Good	Medium

#### 3.4. Obtaining the Physical Model via Fused Deposition Modeling

PLA and ABS, the most frequently used materials for these printers, have been used. ABS has a main problem: Its high rate of thermal expansion, which means that it expands and contracts with temperature changes quite easily. Layers closest to the extruder are warmer and contract causing tension in the lower layers. PLA, however, does not have this disadvantage, but its machining is more difficult. The general defects analyzed in two materials confirm that there are no major differences. In both cases general quality is the same and defects are similar.

To obtain a cutting tool prototype, PLA has been chosen as solution, as the rough results do not differ too much in both cases and its energy performance is better owing to the lack of a warm printing plate.

The choice of a suitable software to this process depends on the possibilities offered to change print settings. The most important factors in manufacturing are the temperature and extrusion speed, the diameter thickness of the deposited wire, the internal structure, and the possibility of creating support areas under cantilever sections. For this reason, Kisslicer® software was chosen as the best option, because it offers possibilities to modify more parameters than the other two.

Physical models can be obtained in different scales and different materials and colours as shown in Fig. 7, in order to analyse any particular detail if needed. In the same way, it is possible to obtain a Physical High-Scale Model.



Fig. 7. Some physical models with different materials and scales. Wear detail

Once the physical model is obtained the deviation between its geometry and the theoretical can be known. Also the deviation between the VM and the piece obtained with FDM can be measured to know the deviations in the print model.

### 3.5. CAE applications

Measurements have been made in both digital and physical model, making it possible to use the proposed methodology for defining geometry of cutting tools. It can make both virtual testing, with the digital model, such as real extrapolating this methodology to other additive manufacturing techniques to make real tests.

3D virtual models could be used, for example, to perform simulations using Finite Element Simulation methods and study the behavior of the tool on a type of material to be machined, Fig. 8. The information collected by this analysis makes it possible to redesign the cutting tools in order to increase their performance.

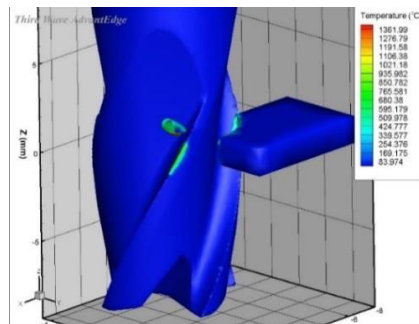


Fig. 8. Finite Element Simulation with the Virtual Model obtained

## 4. Conclusions

A general methodology has been exposed to obtain a physical model of cutting tools using 3D Scanning (Reverse Engineering) and Additive Manufacturing techniques.

Several tools geometry have been digitally collected. The capabilities of different 3D-scanning techniques have been compared. It has performed an analysis of the different methods of acquisition and processing point cloud, optimizing the scanning process for Structured Light Scanner, which offers the best quality/price final ratio.

These models have made it possible to start a methodology aimed to redesign cutting tools. It is possible by modifying their geometry to improve their performance. However, changing the files of these applications remains too difficult, even though their conversion to other more editable formats. Even so, there are certain advantages awarded by STL files, such as measurements in shape or geometry, as well as obtaining the possible deviations from the real model, for comparison therewith.

Also, a physical model of the tools were achieved using a Fused Deposition Modeling (FDM) technique. The different materials and their use were analyzed and no major differences were found in the model quality. In addition, a Physical High-Scale Model (PHSM) was obtained using a generic software and PLA material.

Several measurements have been done in both virtual and physical model to check the obtained deviations in each process. It is found that the deviations in the digitalization are negligible compared with those obtained in Fused Deposition Modeling.

The methods described in this paper include many applications for manufacturing. However, these technologies are still under development. Depending on the type of the item and the available budget, it would be necessary to devote some time prior to the development of the target, by thinking and testing methods that would give better results.

This work reports the development, from a three-dimensional scanning, of a conceptual model printing to learn strategies and to achieve the desired printing quality of a piece, since these models can be manufactured from metallic materials, frequently featured in cutting tools to achieve functional prototypes.

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## References

- [1] X. Yea, H. Liu, L. Chen, Z. Chen, X. Pan, S. Zhang. Reverse innovative design - an integrated product design methodology. *Computer-Aided Design*, 40 (2008) pp. 812–827.
- [2] T. Váradya, R.R. Martin, J. Cox. Reverse engineering of geometric models - an introduction. *Computer-Aided Design*, 29 (1997) pp. 255-268.
- [3] R. Stark et al., Product analysis automation for digital MRO based on intelligent 3D data acquisition. *CIRP Annals - Manufacturing Technology*, (2013) pp. 123-126.
- [4] J. Wang et al., A framework for 3D model reconstruction in reverse engineering, *Comp. and Ind. Eng.* (2012), pp. 1189-1200.
- [5] J. Vagovský, I. Buranský. Evaluation of Measuring Capability of the Optical 3D Scanner. *Procedia Engineering*, 100 (2015) pp. 1198-1206.
- [6] C. Tian, D. Xiaoming, Z. Jianming, Z. Xinjue. Point-Based Data Analysis for Extracting Parameters of Cutting Tools. *Tsinghua Science and Technology*, 14 (2009) pp 47-55.
- [7] E. Kouhi, S. Masood, Y. Morsi, Design and fabrication of reconstructive mandibular models using fused deposition modeling, *Assembly Automation*, 28 (3) (2008) 246-254.
- [8] E. Bagci. Reverse engineering applications for recovery of broken or worn parts and re-manufacturing: Three case studies. *Advances in Engineering Software*, 40 (2009) pp. 407–418.
- [9] A. Dumitrache, T. Borangiu. IMS10-image-based milling toolpaths with tool engagement control for complex geometry. *Engineering Applications of Artificial Intelligence*, 25 (2012) pp. 1161–1172.
- [10] M. Paulic, T. Irgolic, J. Balic, F. Cus, A. Cupar, T. Brajljih, I. Drstvensek. Reverse Engineering of Parts with Optical Scanning and Additive Manufacturing. *Procedia Engineering*, 69 (2014) pp. 795 – 803.
- [11] J. Zaragoza, H. Medellín. Design for Rapid Prototyping, Manufacturing and tooling: Guidelines. *Proc. ASME 2014, Quebec, Canada* (2014).
- [12] H. Singh, F. Rayegani. Cost Optimization of FDM Additive Manufactured parts. *Proc. ASME 2014, Quebec, Canada* (2014).
- [13] H.Y. Fenga, Y. Liua, F. Xib. Analysis of digitizing errors of a laser scanning system. *Precision Engineering*. 25 (2001) pp. 185–191.
- [14] A. Isheil, J.P. Gonnet, D. Joannic, J.F. Fontaine. Systematic error correction of a 3D laser scanning measurement device. *Optics and Lasers in Engineering*, 49 (2011) pp 16–24.