Integrated product and tooling development via reverse engineering methodologies and rapid prototyping techniques

José M. G. Carvalho Ferreira
Universidade Técnica de Lisboa - Instituto Superior Técnico – Dep^{o}. Eng^{a}. Mecânica / PORTUGAL
mjcf@alfa.ist.utl.pt

Artur J. Santos Mateus
Instituto Politécnico de Leiria – Escola Superior de Tecnologia e Gestão / PORTUGAL
amateus@estg.iplei.pt

Nuno M. Fernandes Alves
Instituto Politécnico de Leiria – Escola Superior de Tecnologia e Gestão / PORTUGAL
nalves@estg.iplei.pt

Pedro M. C. Custódio
Instituto Politécnico de Leiria – Escola Superior de Tecnologia e Gestão / PORTUGAL
pcustodio@estg.iplei.pt

Abstract: The engineering design supported by computer aided design and computer aided engineering (CAD / CAE) allows optimising the product concept before manufacturing with assistance of computer aided machining (CAM), in management for rapid product development. For some product development processes the reverse engineering (RE) allows to generate surface models from points cloud captured by 3D-scanning technique, and consequently this methodology permits to manufacture parts and tools in a short development period.

In this research and development (R&D) work are presented some methodologies and technologies for rapid product development, i.e., by reverse engineering to reconstruct geometric models for CAD software assisted by CAE and rapid prototyping (RP) techniques to manufacture prototypes and tooling, to simulate optimise and validate the processes.

Key words: Product development; Rapid prototyping; Rapid Tooling; Reverse engineering; CAD / CAM / CAE.

1. Introduction

Now a days, the industrial structure come across progressive mutations owing the increasing product development diversity, the short product life time, and the increasing product complexity.

The gradual product lifetime reduction implies that industries need to develop new products faster, in a short time period. The necessary time period to develop each new prototype or tools should each time be lesser. This reality compels industries to adopt new methodologies and management attitudes for product development that directs them to reach innovative objectives. Till the present the software's CAD / CAE / CAM have in this logic a great diffusion. The sequence to develop products in CAD>CAE>CAM starts usually with the product geometric modelling, with a CAD software. Based in this geometric model one could apply software's CAE to simulate and optimise products [1-10]. After eventual model geometry redesign, if needed, one could produce optimised products with CAM technology. When necessary to validate the accomplished optimisation, now it is possible to recur to prototypes or tools manufactured by rapid prototyping or by rapid tooling technology [1-10].

Nevertheless, the mentioned methodology it isn't possible every time, mainly when the objective is to reproduce physical models (existing parts or tools) with no CAD data available. In this contest the reverse engineering methodologies and techniques [3,10] are absolutely necessary because allows capturing and digitising the object surface geometry to be utilised in CAD / CAE /CAM.

2. Product development sequence

2.1 Conventional sequence

The conventional sequence to develop products with CAD/CAE/CAM normally starts with the geometric modelling utilising a CAD system. The geometric model could be represented as a wire frame, or as surfaces, or as a solid structure, function of the software release and application requested for the model.

In recent years, the developed software's 3D-CAD are upgraded with parametric solids, feature based modelling and associative capacities between modules or between several applications.

Via conceptual modelling, the generated CAD information could be exported subsequently in standard format (IGES, STL, VDA, STEP, etc..) and imported in the same data format to CAE systems (allowing numerical model simulation) and/or to CAM systems (allowing to generate tooling trajectories). However this communication interchange it isn't every time well succeed owing eventual lost data information.

In a system that comprises data association (a unique data base) the design information could be shared between several applications automatically, such as: the geometry actualisation; the orthogonal projections changes; the computer aided engineering; and the computer aided manufacturing, without the need to transfer data manually, each time.

In actual CAD systems could exist two types of association: the manual one; and the automatic. With manual association, in particularly applications, the CAD system acknowledge that information was changed, but don't carry on with the related actualisations in others applications till the operator gives instructions about the procedures. With the automatic association, any executed changing in the model, either at dimensional level or topological level, independently of the application in which was realized, origins the appropriated changes in the applications utilising the same model, without the need of operator intervention. As an example, a changing in a geometric dimension, of a 2D drawing, is reflected in all others applications that utilise the changed data, as also in the case of a computer aided machining applications.

2.2 Non-conventional sequence

The product development conventional sequence isn't applicable when the goal is to reengineer (and eventually to simulate and to optimise) parts/tools already existents without information in CAD data format. Consequently, will be necessary to apply techniques that allows capturing the geometry of parts/tools, and to generate a conceptual numerical model that could be utilise by CAE and CAM systems. This process is regularly called reverse engineering (RE).

Synthesising, the management of engineering product developed could be realised based on the two methodologies presented in figure 1, trough two information flows called "conventional sequence" and "non-conventional sequence".

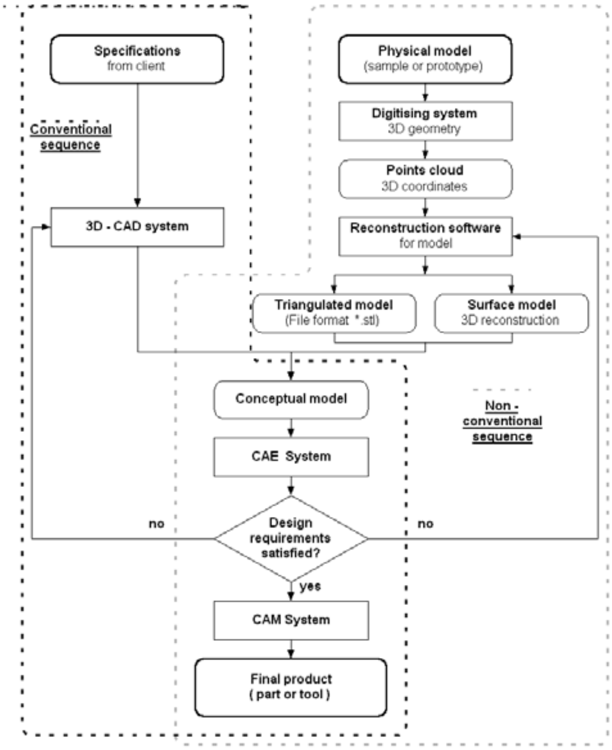

Figure 1 – Sequences to manufacture engineering products (parts / tools)

3. The reverse engineering methodology

The first objective of RE methodology is to generate a conceptual model (example: surface triangulated) starting from a physical model: a sample (part or tool); or prototype. In this sense the 3D-scanning digitising techniques aided by specialised software's for model reconstruction are necessary.

3.1 Digitising technique for 3D geometry

The usual 3D-scanning digitising technique to capture 3D geometries consist in generate a points cloud matrix (3D-coordonates) starting from a surface geometry of a physical object. The digital points cloud could be captured from different digitising techniques, classified in two main groups: the mechanical techniques (by physical contact sensors); and the optical techniques (by non-contact with the object). Related with the first one is normally utilised a coordinate measuring machine (CMM), or a CNC milling machine basis, equipped with physical touching probe sensors. Related with the second group, could be utilised also a CMM or a CNC milling machine basis, but equipped with laser beam probes associated to optical sensors (ex. CCD cameras) for non-contact coordinate measuring. For the second group also exists techniques utilizing computer tomography (CT) that allows to capture also the inside objects geometry, figure 2.

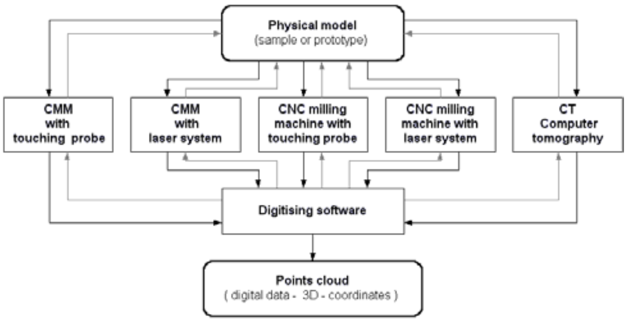

Figure 2 – Digitising techniques for 3D-geometries and generated data.

3.2 3D-CAD redesign from digitising data

The data generated during 3D-scanning, i.e., the digital points cloud data in x, y, z coordinates, is exported to a model reconstruction system software to be transformed in a conceptual model supported by a triangulated surface geometry or by a CAD surface data. When finish the conceptual model, the subsequent procedures are similar for the conventional and for the non-conventional sequence, described in figure 1.

4. The rapid manufacturing technology

4.1 Rapid tooling procedures

In design phase, the need to manufacture experimental parts faster compel to concept rapid tools capable to manufacture, at least, a limited minimum of products for validation. Now, are available a choice of techniques, equipments, and materials that allows rapid tooling construction. The rapid tooling techniques could be grouped in three main categories:

♦ Addictive methods: based in material addiction, as in rapid prototyping technique where the object is manufacture layer by layer;

♦ Subtractive methods: based in material removal, as in high speed milling (HSM) technique;

♦ Conformal methods: based in press conformation or material casting, as in the resin casting for replication of rapid prototyping models.

4.2 Materials for rapid manufacturing

There are wide ranges of materials that are easily transformed and utilised in the manufacturing of rapid tools for preliminary tests. These materials could have a metallic structure (ex. Aluminium), or a polymeric matrix composite structure (resins with metal or ceramic powders).

5. The rapid tooling for reengineering

5.1 Tools reconstruction via RE

There are an extensive variety of situations were the integration of laser digitising in product conception sequence is advantageous. The tool reconstruction which support 3D-CAD don't exist prosecute in a more efficient way trough the integration of laser digitising in the conception stages (figure 3 (2)). If the tools wearing is inexistent will be possible to rebuild the correspondent tools from the existent without the need to reconstruct the 3D-CAD. This means that is possible, in simple cases, to generate a STL file (surface triangulated conception) from which are elaborated the machining files with dedicated software, figure 3 (1).

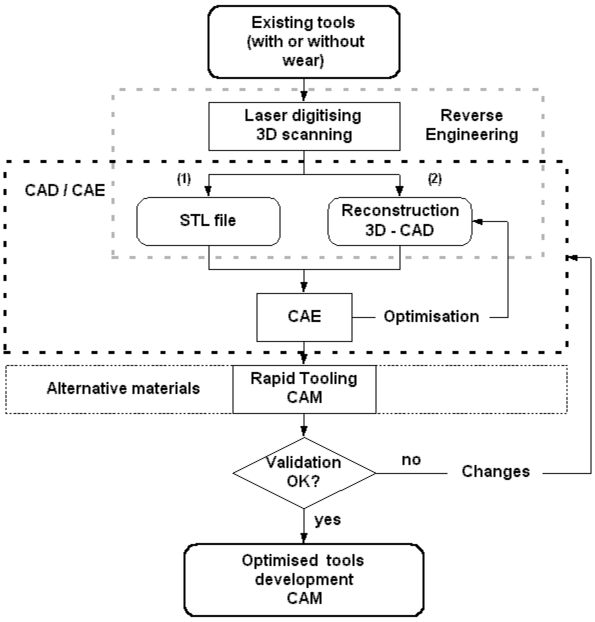

Figure 3 – Operating sequence for tools reconstruction. (1) Without changes / (2) With reconstruction.

5.2 RE for press tool reconstruction

In a R&D case studied it's requested to get the 3D-CAD geometry from an existent progressive stamp press tool. The tool was operating mounted in a press machine for cut / stamp Aluminium top profiles for autos roofs. Each tool was two modulus each with some simple and other more complex geometries. Characterising the tools, one have:

- One tool modulus for cutting;
- Other tool modulus for stamp.

The tool modulus wear is a problem that demonstrate to have a difficult resolution owing that it's requested to minimise the machine stopping production time, where the tool is mounted. The main problems to solve could be described as follows:

- The top profiles shows chipped edges, so the parts produced have a poor quality what manage to an elevated rejection index;
- The high wearing in press tools modulus;
- The tools were allocated from other factory, so don't exists any 3D-CAD support;
- The time for press immobility should be minimized, without affecting part production.

It's developed a methodology, based in utilising non-contact laser digitising linked with contact probe digitising, which one together has allowed minimising the immobility time, by means of:

- Selection and definition of techniques to correct and manufacture faster new tools;
- Digitising the existent tools – by laser 3D-scanning for complex shapes and a contact probe mounted in a CMM for simple topologic shapes to generate faster the whole geometry (the operation time for 3D-scaning digitising was only six hours in a week end day for minimising the immobility time and the associated costs);
- Reconstruction the 3D-CAD model by reverse engineering;
- Corrections made to the 3D-CAD model accordingly the tool geometry design;
- Manufacturing prototype tools (in polymeric resin) to evaluate the corrections and eventual working problems in the main standard tool.

Only the complex surfaces were digitised by a 3D-scanner with a laser beam and two optical CCD arrays. A contact-measuring probe digitises the simple geometries, as plan surfaces, edges and vertices. For simple geometric shapes digitising with laser triangulation scanning method it isn't necessary owing that is only needed few points (two to four geometry points) to reconstruct simple shapes (lines or planes), and in this cases more 3D data points will imply in a more complex geometry reconstruction process. Owing the surface complexity, one should choice and utilise the digitising technique more adequate and economic, figure 4.

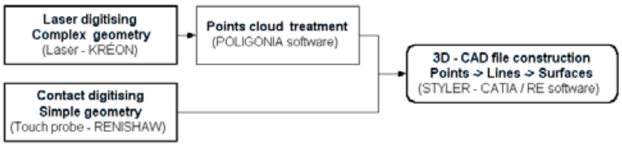

Figure 4 – Digitising techniques and reverse engineering to reconstruct 3D-CAD data for tools.

The intrinsic 3D-geometry for each tool modulus was evaluated and are selected laser digitising and contact digitising to capture the surfaces and conspicuous geometries. After capture the points cloud by 3D scanning they are manipulated (point alignment, suppression and generation of others) in

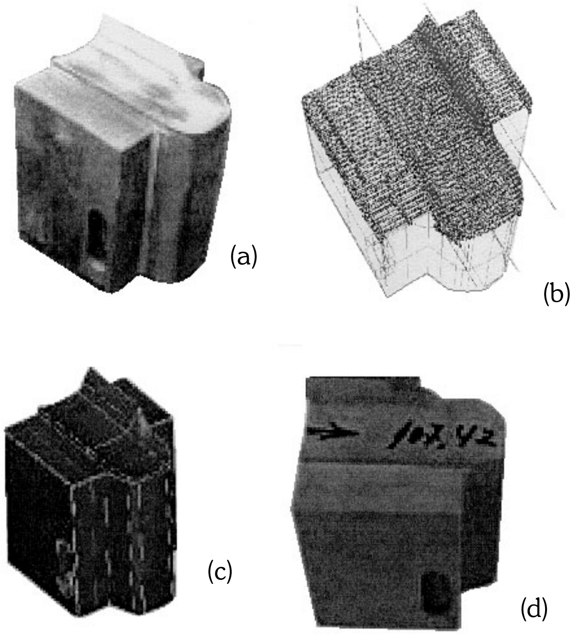

Figure 5 – Sequence to reconstruct a cut and stamp press tool. a) Press tool with wear; b) 3D-digitising with laser triangulation for complex surfaces and reference points captured from contact probe in a CMM; c) 3D-CAD; d) prototype tool manufactured in resin.

"Polygonia" software ("Kréon Industries" – France). The treated points cloud were reworked in a reverse engineering, surface generator "Styler" (Matra Datavision" – France), where the final 3D-CAD geometry is generated.

The tool modulus shown in the figure 5a was digitised with a laser 3D scanning and a contact probe mounted in a CMM, figure 5b. The 3D-CAD geometry data generated by reverse engineering (figure 5c) allowed manufacturing the prototype tool shown in figure 5d.

In table 1 are presented some characteristics from 3D scanning digitising, namely: the quantity of digitised points and treated; the file dimension; and the time needed to points cloud manipulation and treatment.

Table 1 – 3D-scanning digitising characteristics

Digitising by 3D-scanning	laser
Nr. of captured points	348481
Nr. of points after treatment	176240
Point file *.srf "Styler" [Mb]	5.5
Triangulate file *.bin "Styler" [Kb]	184
Surfaces file "Styler" [Kb]	90
Digitising time [min.]	45
Surface construction time [h]	3

The "Kréon" apparatus utilised for digitising by 3D scanning allows capture, in a general mode, the characteristics already described. The apparatus is composed by a sanning laser head with two CCD arrays mounted in a numerical controlled CMM base from "Charlyrobot", and have the configuration presented in figure 6. The principal characteristics are:

♦ Digitising area = 500x400 mm;

♦ Nr. Points get by each CCD = 600 points/second;

♦ Amplitude in X: 70 mm;

♦ Amplitude in Z: 107 mm.

After 3D-CAD data reconstruction, by reverse engineering methodology, the machining data to validate the tool was generated in the "CATIA Machinist" software and the production of this press tool was manufactured by HSM in a "DECKEL-MAHO" five axes machining centre. The selected press tool material is based in "Sika 950" hard resin that has good machining characteristics, allowing a faster production.

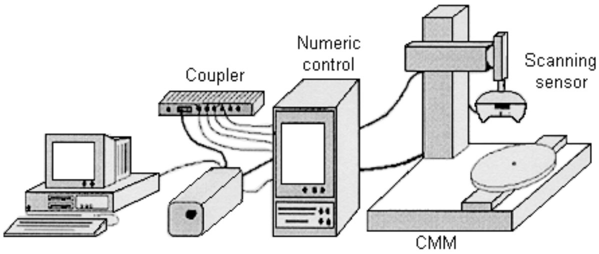

Figure 6 – 3D-scanning apparatus from "Kréon".

The final press tool was manufactured starting with a more performing CAM software, also by high speed milling in a "DECKEL-MAHO" five axes machining centre, starting from a steel block that was thermically treated for hardening, after rough machining. Finally the surfaces and edges were rectified and finished by grinding. The comparison between times for programming and machining is expressed in table 2.

Table 2 –Comparison between programming and machining times

Time in hours			
Tool - Sika 950		Final tool – steel	
Programming CAM	1.5	Programming CAM	3
Machining HSM	7	Machining HSM	21

5.3 RE for foundry part and tool reconstruction

Other R&D case study allowed optimising a casting part and to manufacture the respective rapid tools for sand casting, i.e., the pattern-plates and the core-box made by RP-SLS technique. The initial casting was a steel cable link without 3D-CAD data, as represented in the figure 7.

Figure 7 – Original casting part of a steel cable link.

The 3D-scanning digitising of casting geometry was performed with a "3D Scanners" apparatus belonging to the Modelling Prototype Laboratory (MPL) of Institute Superior Técnico of Lisbon. The digitising of each symmetric geometry half, by laser triangulation (without contact), allowed generating the points cloud in coordinates (x, y, z), as shown in figure 8.

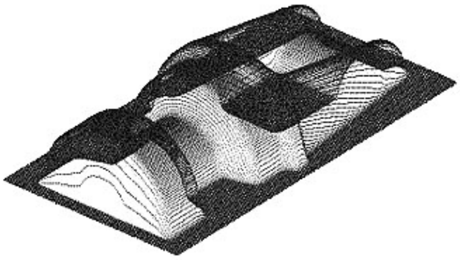

Figure 8 – 3D-digitising geometry / points cloud.

After the points cloud captured by 3D-sanning with the "RiScan" software ("3D Scanners" - UK) is utilised the software "RiTools" ("3D Scanners" - UK) for the digital image data treatment.

The generation of the surface model, starting from the points cloud data of the casting, was accomplished by reverse engineering with assistance from "CopyCAD" software ("DELCAM" – UK). The points cloud treated file was imported in CopyCAD software in *.ris format. The CopyCAD software allows regenerating closed scan-lines from the points cloud data, as shown in figure 9.

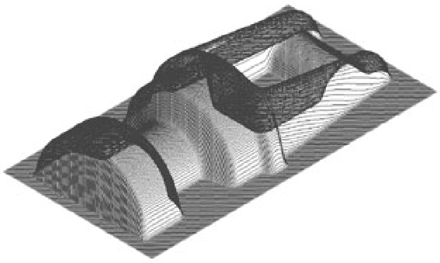

Figure 9 – Scan-lines / CopyCAD software.

The surface reconstruction only is possible when the model is faceted. From the scan-lines was generated a model faceted by triangles, as shown in figure 10, with defined tolerance parameters and surface normal per triangle indicating the external direction.

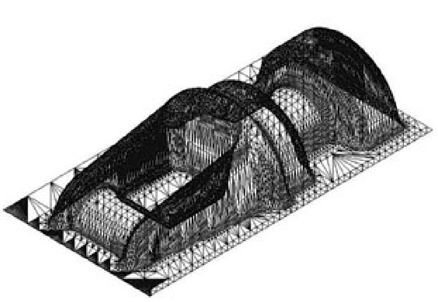

Figure 10 – Polygonal structure represented by triangles.

From the triangulated structure was performed the 3D-CAD surfaces generation in the reverse engineering CopyCAD software. The modelling process has as objective to generate a surfaces model, figures 11 and 12, that is convertible in a 3D-CAD solid model by reverse engineering methodology.

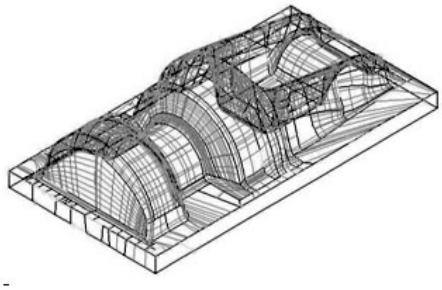

Figure 11- Surfaces model represented by Bézier lines.

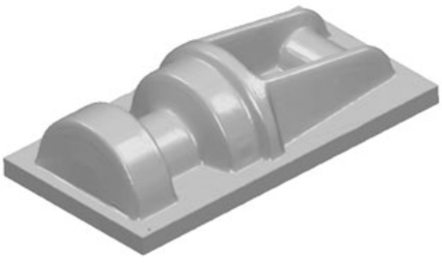

Figura 12 – Shaded surfaces model.

As 3D-CAD technology to transform the surface model in a solid model is utilised the "Pro/Engineer – version 20" software. To proceed with this transformation the following phases are utilised:

♦ The 3D-CAD surfaces are exported in standard IGES format from CopyCAD software;

♦ The 3D-CAD surfaces is imported in Pro/Engineer software in standard IGES format;

- The 3D-CAD surfaces are linked together in the Pro/Engineer software;
- The 3D-CAD solid model is generated from the surface model completely closed, figure 13.

Figure 13 – 3D-CAD solid model ("Pro/Engineer").

In the course of this second R&D work it's performed two computational simulations, i.e. the structural simulation by finite element method (FEM) to optimise the casting part weigh, and the solidification simulation through the finite difference method (FDM) to optimise the casting process.

To concretise the first objective, the simulation was performed with FEM software "Pro/Mecanica" to determine the casting part stress-strain behaviour when in hard work.

The simulation analysis accomplish resulted in a reference data that allows performing others FEM stress-strain simulations iteratively in order to optimise the casting part, i.e. to decrease part weigh, to increase the security coefficient, and to homogenise the stress-strain field, without affecting the manufacturing process by foundry and the part performances at work.

The reference analysis, from the first simulation by FEM to determine the stress (Von Mises) field I, has presented the result shown in figure 14.

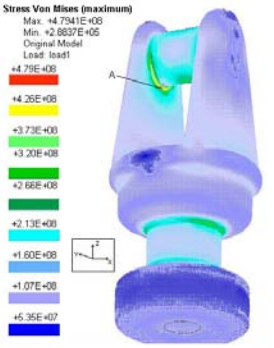

Figure 14 – Equivalent stress field I (Von-Mises).

One could verify that the main stress concentration (maximum stress zone) is located in the zone A.

The resulting data from this first FEM simulation and the value of the design parameter: radius of concordance r in A zone (which dimensional changing implies variations in the associated stress field), are presented in table 3.

Table 3 – First stress-strain simulation results

Parameters	Numerical values
Maximum stress [Mpa]	479
Maximum strain [mm]	0.127
Weight [N]	30.37
Radius A [mm]	1.5

In the first geometric model redesign there is incremented the concordance radius in A zone from 1.5 mm to 2.5 mm, with the main objective to reduce significantly the maximum stress value in this location. Accordingly with this modification is performed the second FEM simulation, from which have result the equivalent stress field II represented in figure 15.

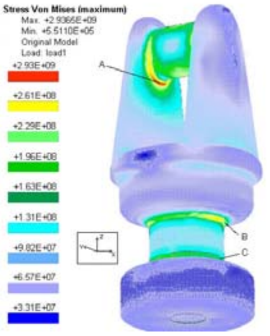

Figure 15 - Equivalent stress field II (Von-Mises).

The related results from the second FEM simulation and the design variable r are described in table 4.

Table 4 – Second stress-strain simulation results

Parameters	Numerical values
Maximum stress [Mpa]	294
Maximum strain [mm]	0.116
Weight [N]	30.40
Radius A [mm]	2.5

As one could analyse from figures 14 and 15 the 1 mm increment in the concordance radius implies a stress field local homogenisation, i.e. the critical zone extent is enlarged, but the maximum stress suffer a reduction of 185 Mpa. A similar behaviour has the strain field that presents a maximum value of 0.116 mm.

Consequently, in the persecution of an intermediate solution have been imposed tree new changes in the initial casting geometry. The first chance consists increasing the longitudinal hole diameter d1 (inside the minor diameter / vertical cylinder), though there exist two stress zones in B and C the maximum of each one are minor then the maximum stress in A zone. The second change consists in a new hole in the basis (d2 = 60 mm, h2 = 20 mm) concentric with the base cylinder. The third change consists in a new horizontal hole (d3 = 10 mm) inside the horizontal cylinder passing through the vertical rods. These changes have the main goal to reduce the casting weight maintaining the performances at work inside acceptable limits and allowing a classical foundry manufacture with cylindrical sand cores. Accordingly with these changes have been performed the last FEM simulation, from what have result the equivalent stress fields III presented in figure 16.

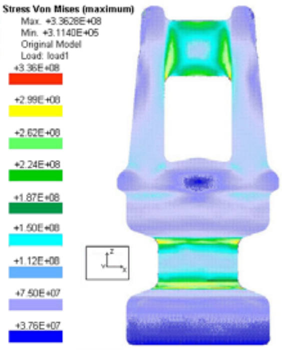

Figure 16 – Equivalent stress field III (Von-Mises).

The last FEM simulation related results and the design parameters r, d1, d2, h2, and d3, are presented in table 5.

Table 5 – Third stress-strain simulation results

Parameters	Numerical values
Maximum stress [Mpa]	336
Maximum strain [mm]	0.133
Weight [N]	25.46
Radius A [mm]	2.5
Diameter d1 [mm]	25
Diameter d2 [mm]	60
Height h2 [mm]	20
Diameter d3 [mm]	10

A brief analysis from the achieved results indicates a tendency for a stress field local homogeneity and a considerable weight reduction. The optimisation has allowed reducing the weigh 16% and an increase in security coefficient of about 40%. The strain field from the final product don't present a significant value.

As the objective of the new casting geometry is to maintain a good performance when in work, it's important not only analyse the stress-strain fields but also to estimate the porosity and the metal density location induced by the casting process to compare these characteristics with the stress concentration zones. It's important that in the more stressed zones the casting material has the great density and don't present porosity in these locations to contribute for a good performance in hard work situations.

The simulation of casting process to analyse the cooling and solidification behaviour as performed with "AFSolid" software (from American Foundrymen's Society), what allows to characterise diverse casting parameters.

The solidification simulation process was carry out after modelling the risering and feeding systems linked to the optimised casting part, which assembly was transformed in a surface triangulated file (*.stl), as represented in figure 17.

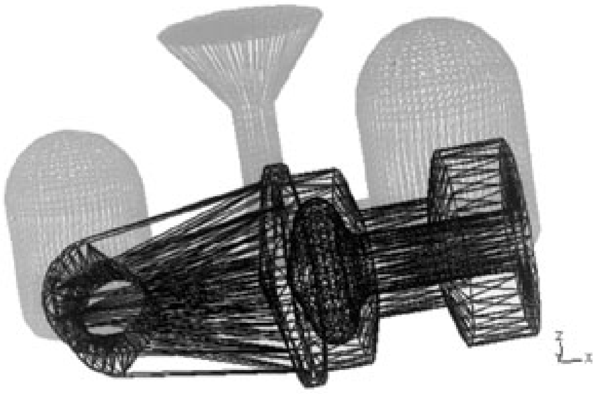

Figure 17 – Casting model with risers and feeder system (STL format).

The main objective of solidification simulation analysis is not only to verify the risering and feeding systems, but also have give information about lack of density in casting and risers zones. The porosity and shrinkage zones, internal to the casting part, are indicated in figure 18.

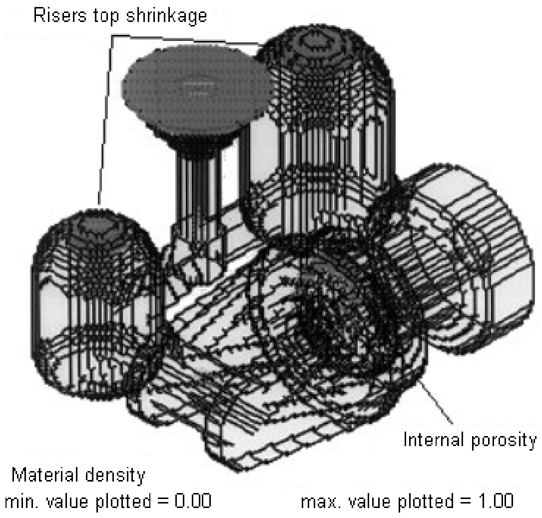

Figure 18 – Porosity zones inside casting and risers.

After simulation analysis it's verified that the porosity zone inside the casting part isn't coincident with the main stress zone (the A zone, linking an horizontal cylinder to the two lateral rods). Its also verified that this zone, together with the B and C stress zones presenting a great internal density. That analysis allows confirming that the more stressed zones present the higher density and are porosity free that in theory are structural zones more resistant.

After optimising the casting by simulation methods where design and manufactured the necessary foundry tools. These tools for sand casting, two half patterns and a core-box, were made faster with rapid prototyping technology by selective laser sintering (SLS) technique, in polymeric material (nylon powder filled with glass micro-spheres), as shown in figure 19.

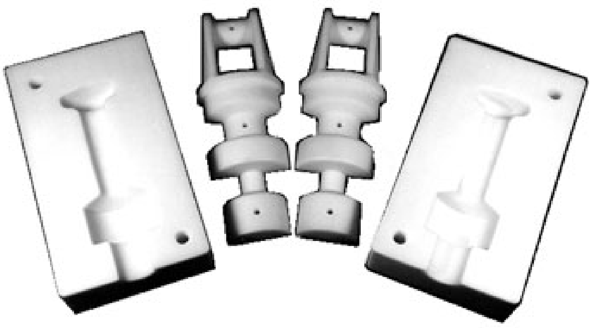

Figure 19 – Two half patterns and a core box made by RP-SLS in nylon powder.

6. Conclusions

The product and tools development via integrated reverse engineering is a recent methodology in research and development phase that in the actual stage, integrated with new rapid manufacturing technologies, allows manufacturing time reduction and associated costs for product and tools development and management. For these production methodologies and technologies the 3D scanning digitising is the initial activity to capture the products geometries.

The resulting parts and tools from the analysed methodologies and technologies, were the reverse engineering process, the computational numerical simulation, and the rapid prototyping and/or rapid tooling are integrated, presents a product quality upgrade.

This R&D work demonstrates the benefit from utilising the reverse engineering methodologies and rapid prototyping techniques in production process, specially when exists parts and tools without 3D-CAD support.

Therefore the reverse engineering process integrated with the recent rapid prototyping and/or rapid tooling technologies, were is granted by numerical simulation the process and product optimisation to increase the final product quality, lead to increase the competitiveness in the industrial field.

7. Acknowledgements

The authors acknowledge the experimental facilities for the first case study to the “Moliporex” industry – Marinha Grande / Portugal (www.moliporex.pt). This research and development work was performed in the scope of “Programa Operacional Ciência, Tecnologia e Inovação” (POCTI), from “Quadro Comunitário de Apoio III”, which is sponsored by FEDER and Portuguese founding’s.

8. Bibliography

1. FERREIRA, J.C. **Intégration des techniques de prototypage rapide et de simulation de la solidification dans les fonderies portuguaises**. 1998, revue Hommes et Foundry. vol: 282, pp. 28-32.

2. FERREIRA, J.C, **Rapid prototyping and advanced emerging technologies in the portuguese foundries**. 1998, revue Foundrymen, vol: 91, part 12, pp. 379-382.

3. FERREIRA, J.C, **Design analysis via simulation aided by reverse engineering to optimise castings**. 1999, NAFEMS World Congress’99, edition The International Association for the Engineering Analysis Community, New Port - Rhode Island, E.U.A, vol.1, pp.47-58.

4. FERREIRA, J.C. MATEUS, A.S. **Production of EDM electrodes via rapid prototyping**, 1999. IWK’99 Congress, edition TU Ilmenau, Germany, vol.3, pp.390-395.

5. FERREIRA, J.C, MATEUS, A.S. **Solidification simulation to test casting electrodes shape before rapid prototyping**. 1999, IWK’99 Congress, edition TU Ilmenau, Germany, vol.3, pp.93-98.

6. FERREIRA, J.C, ALVES, N.F. **Image processimg after 3D-scanning for quality control of rapid prototyping pieces**. 1999, IWK’99 Congress, edition TU Ilmenau, Germany, vol.1, pp.445-450.

7. FERREIRA, J.C, MATEUS, A.S. **Computer simulation to optimize rapid tooling for cast EDM electrodes**. 2000, 8th International Conference on Rapid Prototyping, edition The University of Daiton Press, Japan, pp.335-340.

8. FERREIRA, J.C, MATEUS, A.S. **Computer simulation before rapid tooling to produce EDM electrodes**. 2000, 9th European Conference on Rapid Prototyping and Manufacturing, edition The University of Nottingham and Authors, Greece, pp. 1-10.

9. FERREIRA, J.C, ALVES, N.F. **Modelização dos Processos de Solidificação de Peças de Fundição antes do fabrico Rápido de Protótipos e Ferramentas**. April 2000, 6° Encontro Nacional de Mecânica Computacional, vol.II, Aveiro, Portugal, pp. 1193-1201.

10. ALVES, N.F., FERREIRA, J.C. **Aplicação da engenharia inversa integrada com a simulação numérica na indústria de fundição.** May 2000, Semana da Engenharia Mecânica do Instituto Politécnico de Setúbal – Escola Superior de Tecnologia, Setúbal, Portugal, pp. 1-6.

Address for mailing

José M.G. Carvalho Ferreira, Instituto Superior Técnico – DEM-STM, Av. Rovisco Pais, 1049-001 Lisboa, Portugal, tel.+351218417644, Fax.+351218419058, e-mail: mjcf@alfa.ist.utl.pt.