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Reverse Engineering of a Physical Windmill Sail and Manufacturing the Curving Sail Die in CAD/CAM System

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الملخص:
يطبق هذا البحث مثالًا عمليًا متكاملًا لتصميم قالب ثني لتقويس أشرعة طاحونة ريحية لضخ المياه باستخدام محاكاة برمجة آلة التحكم الرقمي بالحاسب (CNC) باستخدام أنظمة التصميم بمساعدة الحاسب والتصنيع بمساعدة الحاسب (CAD/CAM) وتكنولوجيا التصنيع باستخدام الة التحكم الرقمي بالحاسب لتصنيع القالب. يتم استخدام نهج الهندسة العكسية لرقمنة أحد الأشرعة (الريش) المادية المتاحة لدوار طاحونة ريحية بواسطة نظام مسح ثلاثي الأبعاد للحصول على ملف السحابة النقطية. بعد ذلك يتم نقل هذا الملف إلى برنامج CATIA V5 ، ومعالجة البيانات المقاسة لإنشاء أسطح ونموذج CAD ثلاثي الأبعاد للشراع. أهم الدوافع لهذا العمل وقرار تصميم وتصنيع قالب أحادي العملية (يتكون من أربعة أجزاء لتناسب سعة ماكينة CNC المتاحة) لتقويس الأشرعة باستخدام نموذج الشراع ثلاثي الأبعاد نتيجة استخدام الهندسة العكسية ، كانت على وجه التحديد : (1) نظرًا لصعوبة تصنيع تقويس الأشرعة يدويًا بناءً على العمالة المتاحة ؛ (2) عدد الأشرعة المستخدمة لإنتاج وحدة واحدة من طاحونة ضخ المياه ؛ (3) وأهمية الأشرعة في تحسين كفاءة نظام الطاحونة الهوائية. استنادًا إلى نموذج الشراع ثلاثي الأبعاد الذي تم هندسته عكسياً ، تم استخدام التطبيق التفاعلي ثلاثي الأبعاد بمساعدة الكمبيوتر (CATIA V5) كنظام (CAD/CAM) متكامل لتصميم وبناء نموذج ثلاثي الأبعاد ، ثم محاكاة عمليات التفريز من خلال النماذج الرسومية ثلاثية الأبعاد. تم إعداد نموذج CAM لتشغيل أجزاء القالب ، وإجراء محاكاة مسار الأداة باستخدام CATIA V5 ، و برمجة جميع عمليات المعالجة ، ومن تم نقلها إلى مركز آلة (CNC سلسلة (Fanuc Series OM Model C) لتصنيع جميع أجزاء القالب. أخيراً، يمكن الاستنتاج أن رقمنة الشراع عن طريق نظام المسح لتطبيق RE ، ومحاكاة عملية المعالجة في بيئة افتراضية ضمن نظام CAD / CAM متكامل لتصنيع القالب، يمكن أن يقلل زمن التسليم وتجنب التعديلات الكبيرة على القالب أو كسر الأدوات نتيجة الأخطاء التي قد تحدث ، مما يؤدي إلى تقليل التكاليف ووقت التشغيل على الالة.

Abstract— This paper applies an integrated practical example for designing a bending die for curving water pumping windmill sails using simulation programming Computer numerical control (CNC) machines utilizing Computer-aided design and computer-aided manufacturing (CAD/CAM) systems and CNC machining technology to manufacture the die. A Reverse Engineering (RE) approach was used for digitizing one of the available physical sails of a windmill rotor by a Three-Dimensional (3D) scanning system to obtain a point cloud profile. This file is then transferred to CATIA V5 software and processed with the measured data to create surfaces and a 3D CAD model for the Sail. The most important motives for this work and decision to design and manufacture a single-operation die (consisting of four parts to suit the available CNC machine capacity) for curving the sails using the Sail's 3D model of the RE, specifically, were: (i) Due to the difficulty of manually manufacturing the curving of the sails based on the available labor; (ii) the number of sails used to produce one unit of the water pumping windmill; (iii) and the importance of the sails in improving the efficiency of the windmill system. Based on the 3D model sail reverse engineered, the Computer-Aided Three-Dimensional Interactive Application (CATIA) V5 was used as an integrated CAD/CAM system for designing and constructing the die 3D model, then simulating the milling operations through graphic models in 3D. A CAM model was prepared to machine the die parts, and the tool path simulation was performed using CATIA V5. All the machining operations were programmed, then transferred to a CNC machine center (Fanuc Series OM Model C) to machine all the die parts. Finally, Finally, it can be concluded that digitizing the Sail by a scanning system to apply RE, and conducting a machining process simulation in a virtual environment within an integrated CAD/CAM system to manufacture the die. These can reduce the lead time and avoid significant modifications to the die or breaking of the tools due to errors that may occur, which leads to reduced costs and CNC machining time.

Keywords: **RE, CAD/CAM, CATIA, Windmill, tool path.**

1 INTRODUCTION

Reverse engineering is becoming a practical approach to generating a 3D virtual model of an existing physical component (part) for use in 3D CAD, CAM, CAE, or other software [1,2]. As the world's leading CAD/CAM software, CATIA can help users provide complete design capabilities and manufacture a windmill water pumping curving Sail die. At the same time, it provides the designer with capabilities to work in a 3D environment with embedded 2D drafting, technical specifications, and software system modeling as a fully integrated system. CATIA combines mechanical design, engineering analysis, and simulation processing functions to provide users with a strict paperless work environment to shorten design time, improve quality, and reduce production cost effects [3-6]. CATIA can build a working environment for the whole development process of digital enterprise [2,3,7]. CATIA software developed by the French company DASSAULT SYSTÈMES offers die and tool makers powerful virtualized functions to better suit the design and construction of dies and powerful automation capabilities to reduce Numerical Control (NC) programming and processing time dramatically. The NC codes can be generated using a CAD/CAM program and a virtual model of the piece [8-11]. In this study, the RE process with a CAD system was adopted to design, develop, and manufacture the die of a Rotor Sail of a water pumping windmill. To attain all the applicable dimensional data necessary to construct a CAD model or to design a part drawing, the use of digitizing or scanning may be needed. The 3D Acquisition with a noncontact technique was used to measure the Sail. The computer-aided design (CAD) allows the design in a computer environment, and computer-aided manufacturing (CAM) was used to manage program and production stages on a computer [12].
Process planning is a function in a series of manufacturing activities that define the production process and its parameters to transform material from its initial form into a shape according to the desired design [13-15]. In the ideal CAD/CAM system, the product design specification in the CAD database is automatically converted into a process plan for making the product. A 3D computerized numerical control (CNC) machine was used to machine the Sail's curving die scanned previously, and CAD/CAM program was prepared using CATIA.
Briefly, the main objectives of the paper are:

- Applying the various stages (steps) of RE starting from digitization to CAD model reconstruction.
- Creating manufacturing drawings and generating 3D models that are the basis for various RE applications, such as the CAM modeling available in CATIA for manufacturing sails curving die using CNC machines.

2 PROBLEM STATEMENT AND MOTIVATION

Within a project to manufacture a wind water pump to extract water from wells for irrigation and human uses, a limited number of these systems are expected to be marketed, especially in coastal agricultural areas and some pastoral areas isolated from the national network. The researchers aim within this paper to design and manufacture a die for curving the Sails while reducing the costs and the project time. This decision was taken (i) because of the importance of the Sails in raising the efficiency of the system and (ii) due to the lack of skilled labor to curving the sails within the required quality. The RE approach was applied to extract the dimensions and reconstruct a CAD model of a physical Sail to use it to design a suitable die for curving the Sails of the windmill expected to be marketed, then prepare a CAM model and program CNC machine as one of the RE applications. The researchers are also interested in contributing and providing a product that works with one of the renewable energies as a meaningful step towards the actual utilization of wind energy that is not harmful to the environment.

3 METHODOLOGY

Figure 1 illustrates the general process flow diagram (chart) for applying RE in this research paper. This flow diagram demonstrates the generated 3D CAD model obtained from the RE process to be used to design the die for manufacturing the Sails. Then the generated 3D CAD of the die was adapted and used to simulate the manufacturing process and program the CNC milling machine to manufacture the die of the Sail as an end application of the RE process.

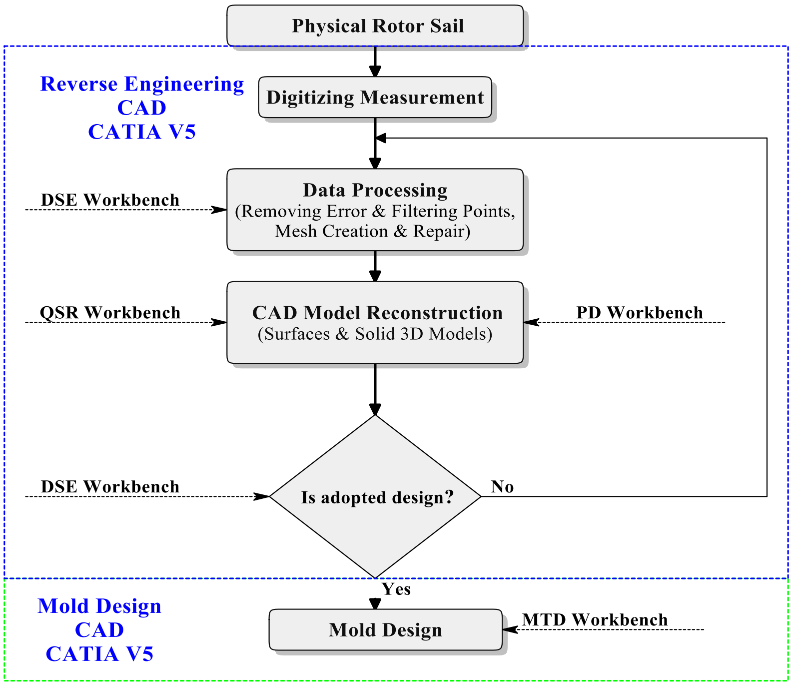

Figure 1. Sail RE process flow chart.

The CATIA modules were integrated to execute the design, construction, and simulation phases to ensure maximum digitization of the manufacturing process. In other words, the integration of RE, design, and manufacturing activities through computer systems is as follows:

- Several operations are needed to create the final surface by overlaying the point cloud with a Mesh. CATIA's Digitized Shape Editor (DSE) is used to achieve these operations.
- The surface model of the Rotor Sail is constructed by a quick surface reconstruction workbench (QSR) in CATIA
- The solid 3D model of the Rotor Sail is created by the part design workbench (PD) in CATIA.
- Die design is done using the CATIA die tooling design (DTD).
- The manufacturing process simulation was defined for the CNC machine in CATIA's advanced machining workbench (AMG).

4 DIGITIZATION OF THE COMPONENT

The task for obtaining dimensional data of the physical Sail of a water pumping windmill rotor is executed with the BacesSCAN portable laser scanning system at the Trucks and Buses Company (T.B.Co.), composed of Baces3D three-coordinate measuring arm (7 axis M100). In Figure 2, the Baces3D arm is shown in a moment of its use while scanning the Sail. The point cloud file obtained from the Bces3d software digitizing machine is transferred to the CATIA used for performing the point processing operations and the CAD model reconstruction.

5 PROCESSING OF THE MEASURED DATA

Processing the measured data turns the point cloud or Mesh received from the scanner into a polygonal model, and the resulting Mesh is cleaned up and smoothed to retain its required shape and accuracy. The preprocessing work is executed as follows:

5.1 Removing Error Points

During the operation, clamps, fixtures, and other unwanted points would come into the measurement area (error points), making up a boundary buffer [16]. The Remove Command in DSE CATIA is used to remove these error points.

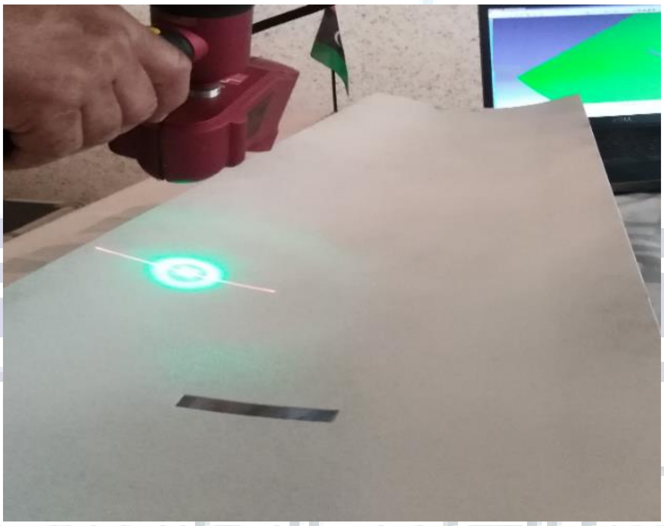

Figure 2. The Baces3D arm during scanning the Sail.

5.2 Filtering points

The cloud relating to the Sail consists of 9,999,96 digitized points, which is reduced to 140,83 points by applying the Filter Command in DSE CATIA, which displays only the points that determine the curvature of the Sail.

5.3 Creating and Repairing Mesh

Mesh is the triangle image of point clouds [16]. It's not a real surface, but it can improve the visibility of point clouds and the efficiency of surface modeling. Mesh is created by the Command of Mesh Creation of DSE CATIA with the radius of the little sphere set to 10 mm. The obtained Mesh has several discontinuities and large holes. The holes in the Mesh are repaired with the Commands Fill Holes, Mesh Smoothing, and Mesh Cleaning Commands of the DES workbench.

6 THE CAD MODEL CONSTRUCTION

After repairing the digitized points, the next step is creating (on these points) the curves on which the surfaces form the geometric model of the part. Planar curves are created with Planar Sections Command in the DSE workbench.

Figure 3 shows the planar curves that constitute the surface support on the repaired Mesh.

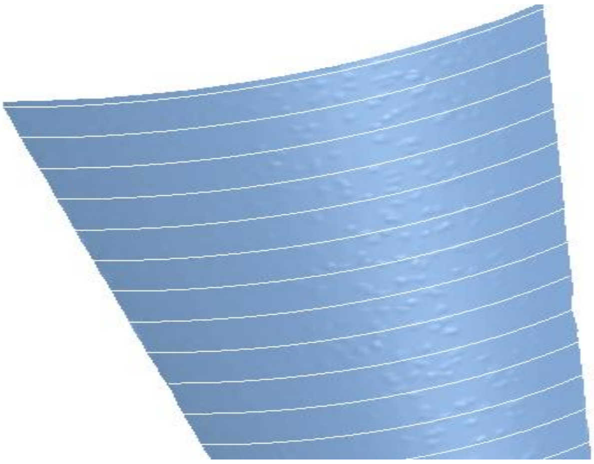

Figure 3. The planar curves on the repaired Mesh.

At this point, the fundamental problem is the choice of surfaces to interpolate the curves obtained to replicate the geometry of the physical piece as closely as possible. The surface of the Rotor Sail was created by Powerfit Command of Quick Surface Reconstruction workbench (QSR) in CATIA. From these obtained surfaces in Figure 4, a solid 3D model of the Sail is formed using the Part Design in CATIA.

After completing the CAD model of the Rotor Sail, Deviation Analysis Command in the DSE workbench is used to perform a deviation analysis by comparing the point cloud data (gathered from scanning the Sail) with the final CAD model.

Figure 4. Final obtained surfaces of Sail rib.

7 DESIGNING AND MANUFACTURING THE DIE

The researchers used various modules CAD/CAM integrated into CATIA for the design and development of the die and the simulation of its operation through 3D graphic models and carefully followed the CNC machine's programming.

7.1 The Die Design

The design and development of compound die are essential phases in sheet metalworking. The minor error in the design can result in heavy manufacturing losses through die failure, part geometry distortion, and production risk [17]. When designing a die, different factors must always be taken into consideration. The choice of possible solutions to problems related to the production of a part must be made, taking into consideration the characteristics of that part (e.g., shape, size, material), the characteristics of the machines available (stroke, size, load, etc.), and the number of pieces to be manufactured [18]. Medium and large production quantities require the use of dies, while for small production, one must decide whether it is convenient to design and make the die based on the number produced. In this case, the expected production quantity is small. Nevertheless, the decision was taken according to an economic and technical point of view to design and manufacture a single-operation die as shown in
Figure 5(a) for curving the sails, instead of manufacturing a typical die system that can perform simultaneously different types of processes, such as, blanking and bending to produce the sails as shown in
Figure 5(b).
This decision was also due to the difficulty of manually manufacturing curved sails based on available labor, the number of sails used to produce one unit of the windmill, and the importance of the sails in improving of the efficiency of the windmill.

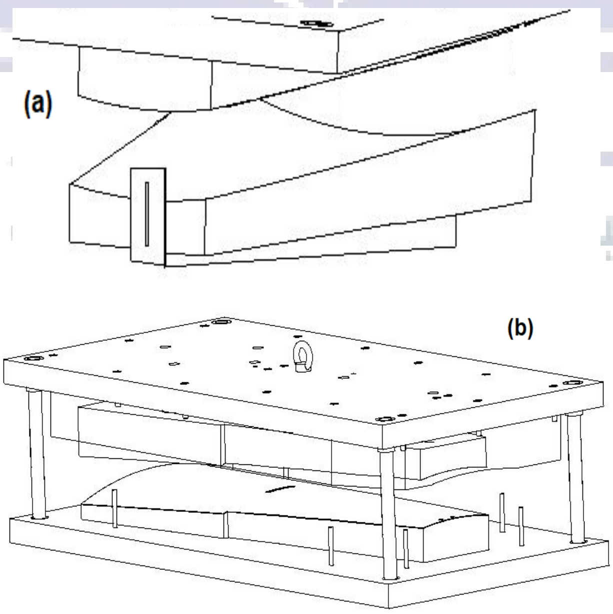

Figure 5. (a) A single-operation die; (b) Typical die system.

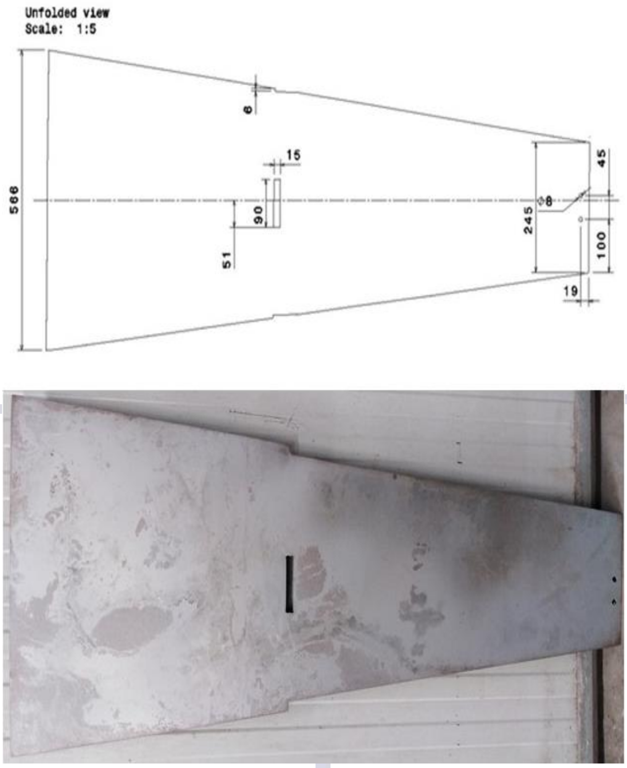

Figure 6. The Sail sheet metal blank.

Before implementing the die design, once the operating cycle is established, it is essential to determine the development (unfolded) of the sheet metal piece to understand how much material was needed to make it. This development is determined as shown in Figure 6, which will be manufactured using a laser cutting machine. The design is executed using the CATIA Die Tooling Design (MTD) as shown in Figure 7, and the die is designed with four parts to suit the capacity of the CNC machine operating table.

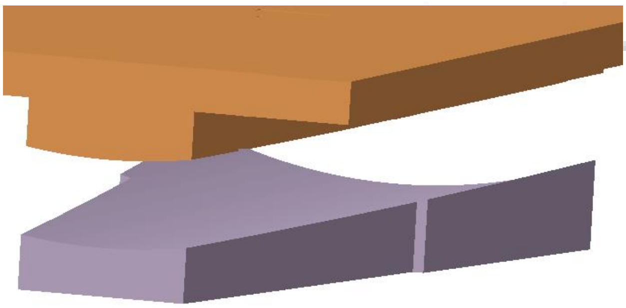

Figure 7. The 3D model of the sails curving die.

7.2 The Die Manufacturing

CAM is a transition point from thinking like a designer to thinking like a manufacturer by applying parameters within the process that include values such as depth of cut and tool overlap. As the eternal goal of CNC machining, high efficiency and high precision milling need to balance many constraints for selecting the most reasonable processing parameters [19]. CATIA creates the operations and tool paths needed to mill the geometry of the Sail die. Figure 8 displays the workflow diagram, starting with a 3D model of the Sail die that was designed and approved, then the CAM processes, simulation, and manufacturing of the die parts on the CNC machine until the die testing and the beginning of the production stage.

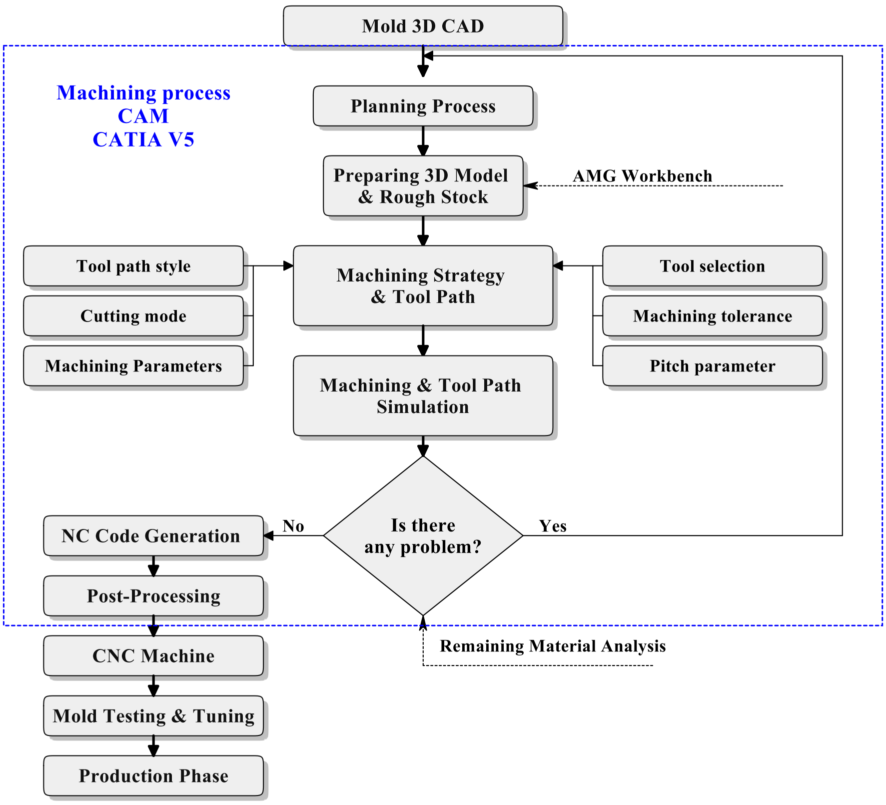

Figure 8. The CAM Process workflow diagram.

7.2.1 Preparing of 3D Model & Rough Stock.

The 3D CAD models of the two parts of the lower die with Stock dimensions of (635mm x 370mm x 110mm) and (465mm x 498mm x 110mm) are prepared within the CATIA assembly design workbench as CATproduct file.

In the same way, the two parts of the upper die with Stock dimensions of (635mm x 370mm x 90mm) and (465mm x 498mm x 90mm) was prepared as CATprodct file. After that, the CATproduct files were transferred for both the lower and upper parts to the machine mode of the CATIA advanced machining workbench to generate the CATprocess files. The CATprocess file screenshot for the lower part of the die in

Figure 9 shows the dialog box and the working tree, including the Product List (lower die Parts and Stocks) and the Process List at the top of the work tree, where the production process is created. Then the workpiece coordinate system and the post-processor type of the machine are Identified to generate NC code.

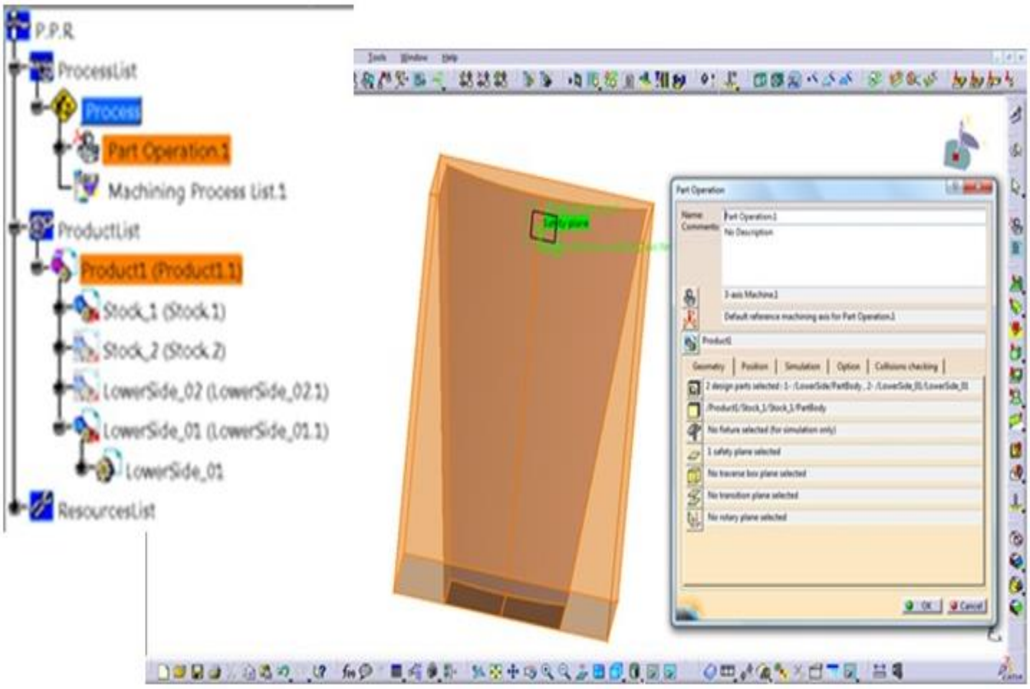

Figure 9. Preparing of 3D Model & Rough Stock.

7.2.2 Machining Strategy

A machining strategy is a methodology used to compute an operation to carry out a geometrical entity in its final form [20-22]. It is vital to adopt a reasonable machining strategy and choose accurate machining parameters considering the machining efficiency and quality [23,24]. Some CAM strategies described were used to create all parts of the Sail die through CATIA.

The manufacturing operations strategies for the lower part of the die are displayed sequentially in the following Figures:

Figure *10***.** The first operation is to achieve external contour using Z level in AMG workbench, Z-level contouring tool path, with a flat end mill tool of diameter 20mm, the machining tolerance parameter 0.1mm. The cutting mode set to the upward mode (Climb in CATIA) because it facilitates the cutting conditions, and the constant stepover distance of 7mm.

Other settings need to be set for CATIA software, also called machining parameters which are applied for the software as follows (for Mild Steel workpiece):

spindle speed (n) = 1200rev/min; feed motion (f) = 600mm/min; Offset on part = 0.0 mm.

Figure 11. The roughing operation is performed to reach as close as possible the desired rough shape with a high level of cutting material flow and tool path series as smooth as possible [25].

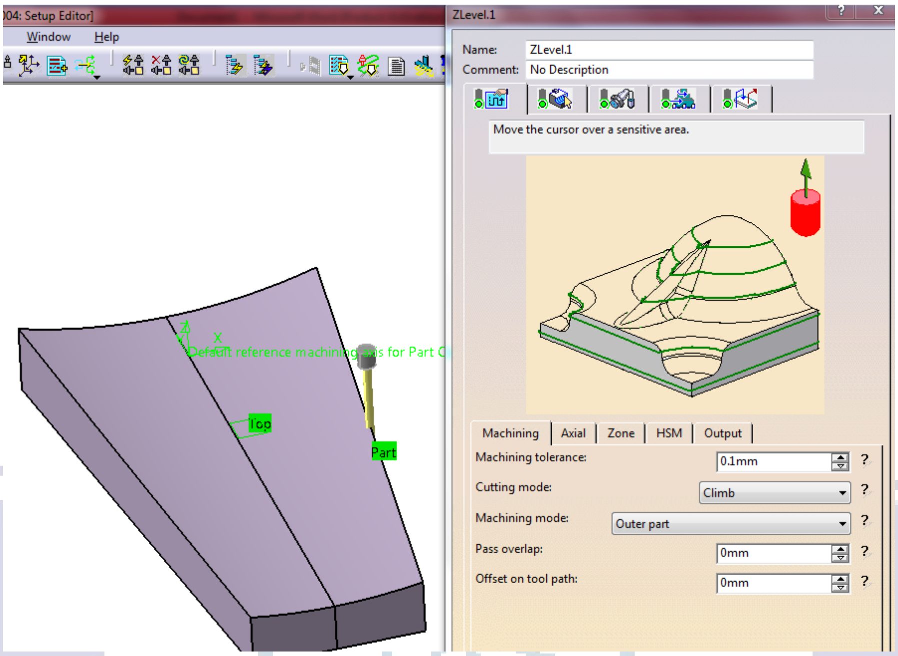

Figure 10. "Z-level" milling strategy of lower Sail die.

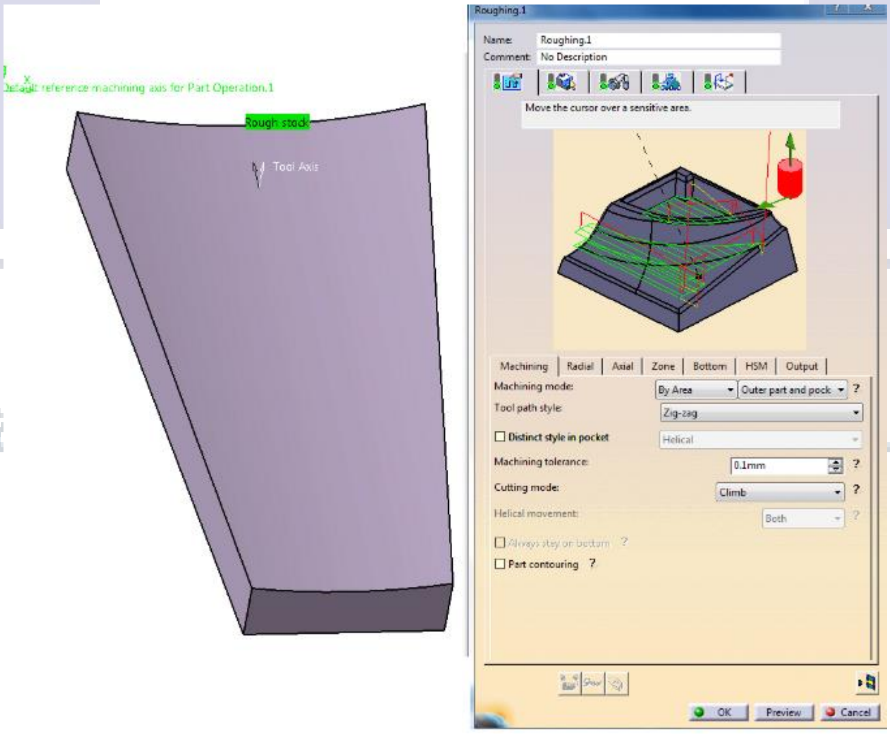

Figure 11. "Roughing" milling strategy of lower Sail die.

Without the tool change, the Zig Zag tool path style, the machining tolerance parameter 0.1mm, the cutting mode set to the upward mode, and the stepover length parameter of 7mm. The other machining parameters:
spindle speed (n) = 1000rev/min; feed motion (f) = 300mm/min; Offset on part = 0.5mm.

Figure *12***.** The Finishing operation using Sweeping Command achieves the final die shape up to the geometrical quality specified. It is done with a ball nose end mill of diameter 10mm, Zig Zag tool path, the machining tolerance parameter 0.1mm, the cutting mode set to the upward mode, and the stepover length parameter 4mm.

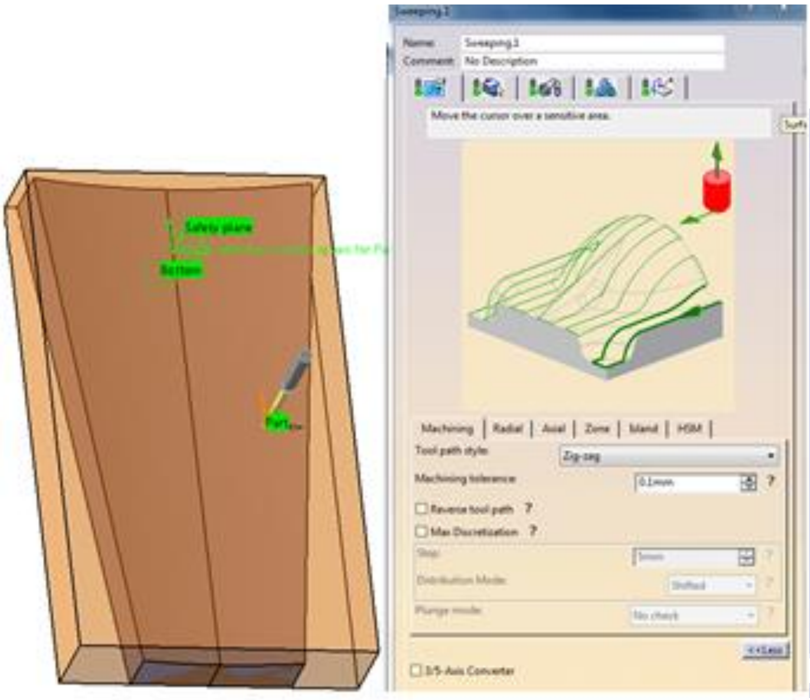

Figure 12. "Sweeping" milling strategy of lower Sail die.

The other machining parameters: spindle speed (n) = 1600rev/min; feed motion (f) = 300mm/min; Offset on part = 0.0mm.
Table 1 summarizes the parameters comprised within the CAM process of all the die parts. The generated code can be further edited on a computer or directly at the CNC machining center.

Table 1. Machining parameters applied in preparing CAM process of the die parts.

Parameter	Z-level	Roughing	Sweeping
Tool path style	....	Zig Zag	Zig Zag
Cutting mode	upward	upward	upward
Stepover	7	7	4
Machining tolerance	0.1 mm	0.1 mm	0.1 mm
Tool type	Flat End mill	Flat End mill	Ball Endmill
Tool diameter	20 mm	20 mm	10 mm
Offset on part	0	0.5 mm	0
Feed motion	600 mm/min	300 mm/min	300 mm/min
Spindle speed	1200 rev/min	1000 rev/min	1600 rev/min

7.2.3 Machining Simulation and Results

Once the CAM process is completed and all the required parameters of the CATIA are set, the resulting tool path can be simulated. Figure 13 shows the tool path simulation of the roughing operation used to see the graphical representation of the path taken by the tool. The tool path simulation of the Z-level and the sweeping operation is shown in Figure 14 and Figure 15.

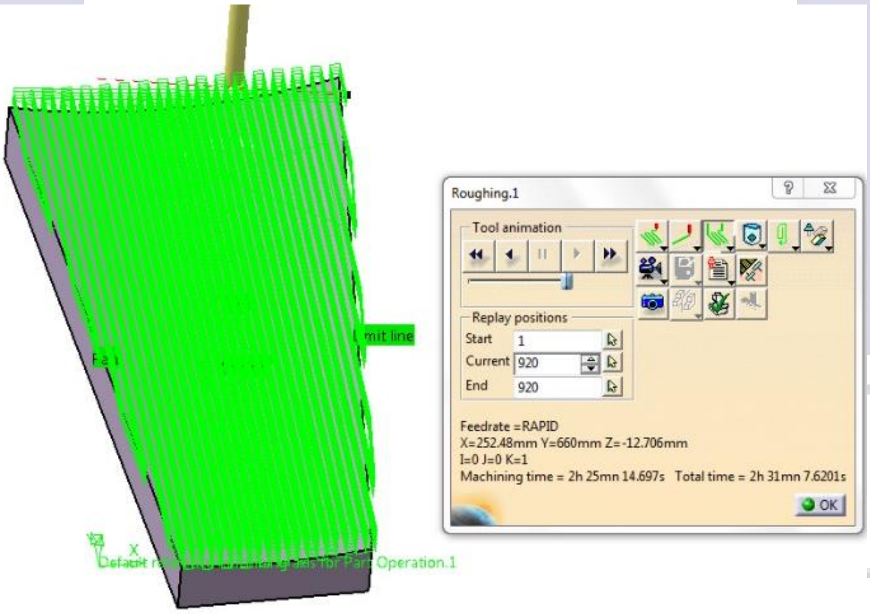

Figure 13. The tool path "Roughing" simulation.

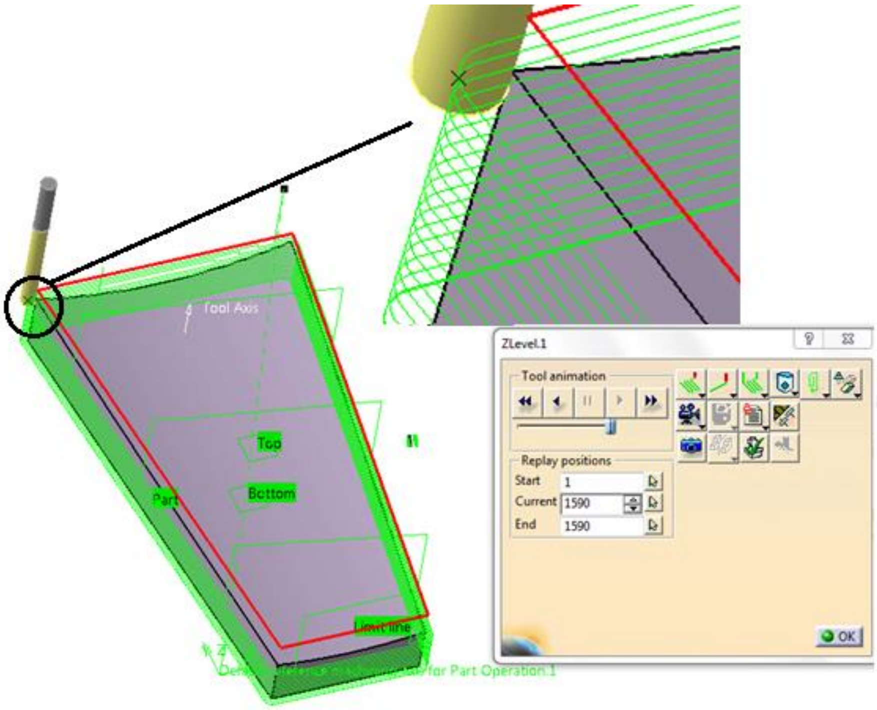

Figure 14. The tool path "Z-level" machining simulation.

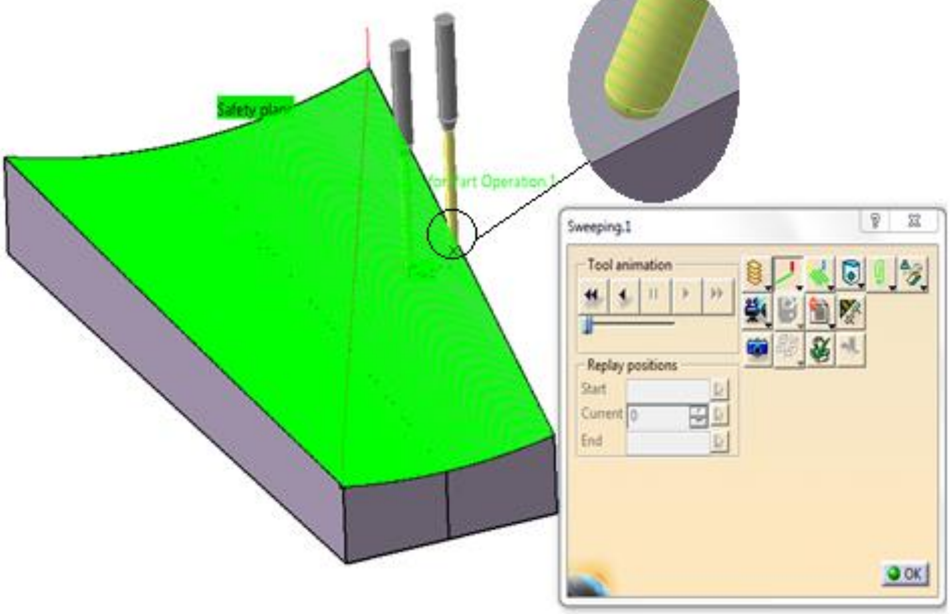

Figure 15. The tool path "Sweeping" machining simulation.

CATIA can also display a video simulating the three operations, as shown in Figure 16 and Figure 17. With this simulation, one can easily observe the movement of the tool and identify any inefficiency in the machine's operation. If any inefficiency is recorded, the previous settings are modified to obtain the best solution.

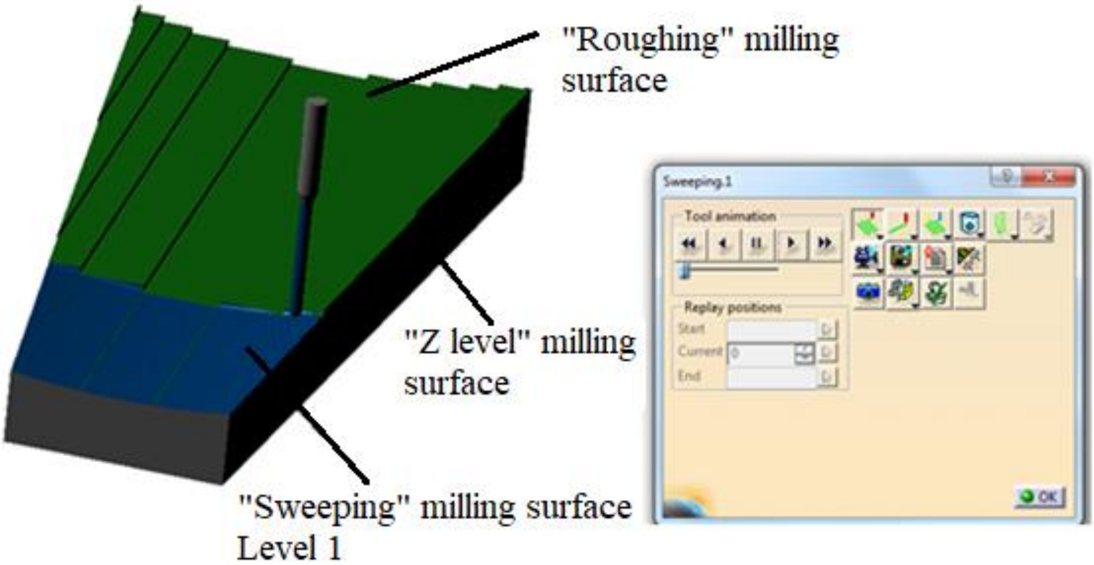

Figure 16. Screenshot during the "Sweeping" Operation Level 1 in the video simulation.

Figure 17. Screenshot during the "Sweeping" Operation Level 2 in the video simulation.

Figure 18 shows the Remaining Material Analysis of the upper die available within the simulation, where the deviation was 0.1mm and acceptable for the design and manufacturing requirements of the sails die.

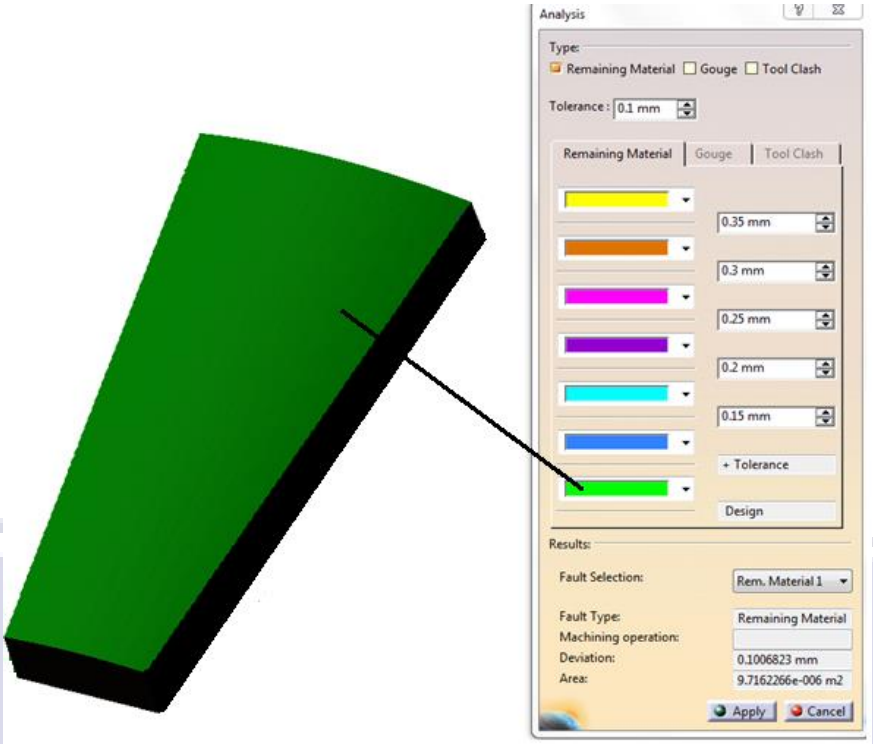

Figure 18. Machining analysis of upper part.

7.2.4 CNC Machine Code Generation

After the success of the simulation process using Generating NC Code function in CATIA, the NC program for each part of the die in ISO format (G codes) is generated, followed by post-processing for the appropriate CNC machine and CNC control system. Using a memory card for transferring the NC programs to the 3-axis milling center control (FANUC OM model C).

7.2.5 Die Parts CNC machining

Figure 19 shows the "Z" level" operation to realize contour during machining one of the lower Sail die parts on the CNC machine, while

Figure 20 shows the "Roughing" and the "Sweeping" as finishing operations.

Figure 19. "Z-level" operation of lower Sail die.

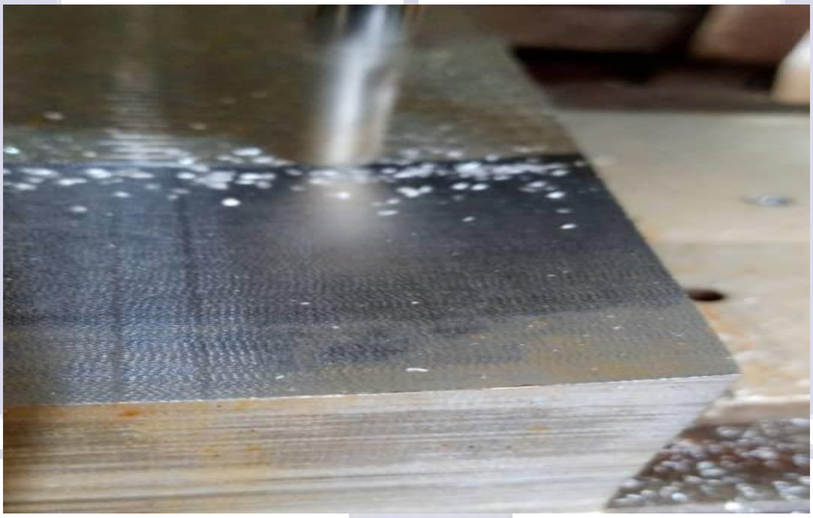

Figure 20. "Roughing" and "Sweeping" operations of lower Sail die.

7.2.6 The Die Testing

Once the die was correctly dimensioned and designed, the next step is to be tested. Making the first Sail sample was subjected to verification and testing.

Given the problems that the die involves, the designer must carry out these tests to increase his (her) experience and seek, in close collaboration with the workshop staff, a possible solution to these problems.

For future planning, all modifications made to the die must then be reproduced on the drawing to avoid losses due to repeated errors involving unnecessary expenses. The die was successfully manufactured and installed on the appropriate hydraulic press bending machine, as shown in
Figure 21.

The Sail prototypes were manufactured, and the needed die tuning was made.

Figure 21. Sails curving die installed on the bending machine during manufacturing the prototypes.

8 CONCLUDING REMARKS

Using digitized processes by a dimensional scanning system to perform RE and machining process simulation in a virtual environment within an integrated CAD/CAM system can reduce design time and avoid errors or modifications that increase costs and CNC machining processes time. From the content of this research paper, the following conclusions can be drawn

- The 3D CAD model of the Sail was obtained by applying various stages of RE; digitization of the physical Sail to getting the dimensional data by the laser scanning system; the processing of the measured data; and the CAD model construction.
- Deviation Analysis (available in the CATIA DSE workbench) was carried out to verify the 3D model of the windmill Sail. The design was good and adopted.
- Single-Operation die for curving the sails was designed based on the 3D Sail model using the CATIA Die Tooling Design.
- 3D model and Rough Stock of the die parts were prepared and transferred for both the lower and upper parts to the machine mode of CATIA advanced machining workbench.

- The appropriate planning and machining strategies are chosen to achieve the final geometric product shape, starting with the roughing operation to remove the metal quickly and giving a close form to the final product. Then achieving the contour using the Z-level finishing function in CATIA, and finally obtaining the required finishing of the die surface using a two-level sweeping operation.
- A CAM model was prepared for each part of the Sail die by applying the selected strategies, setting the machining parameters in the Advanced Machining workbench of CATIA software, and conducting machining & tool path simulations to ensure well performance during the real machining process on the CNC machine.
- NC program for each part of the die was generated, and the NC programs were transferred to the CNC machine.

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