Study on advanced machining conception on numerically controlled milling machines for air-craft complex component parts

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***Abstract*—**The main purpose of the paper is to achieve an optimization of processing technology for a complex frame whose geometric configuration allowed the group technology approach and increasing the speed of batch processing by optimizing the total length of tool paths. Industrial requirements of concurrent engineering, standard product data models and an integrated manufacturing environment motivated the research work and its conclusions showed that the interaction between different types of models could provide a description of the products, how they should be manufactured and what manufacturing resources should be used. The machining process with advanced NC programs (SURFCAM Velocity 4.0) of a wing frame made of aluminum alloy for an air-craft represents the subject of this work. The frame is a representative part for a grouped technology, viewed in a computer integrated manufacturing system according the flexible manufacturing system principles. The manufacturing conception of the part was developed taking into account the dynamic, static and thermal transitory loads of the frame and optimizing the total length of tool paths with SURFCAM Velocity 4.0 program. The paper offers an interdisciplinary approach of the construction and technology design for important parts, which suppose supplementary safety measures and, implicitly, supplementary quality assurance measures.

***Keywords*—** frame, manufacturing, simulation, tool path

I. Introduction

INDUSTRIAL engineering methods are outdated today by computers, robots, programmable controllers, numerical controls etc. Market economy, with its rigors and demands, makes necessary now more than ever, the transition from quantity to quality, and focus should be on approaching of the peak areas of science, of advanced technology and efficient management methods. After the appearance of CNC machine tools, developments were mainly marked by the rapid development of computing techniques, processing centers, group technology, sensors, techniques of geometric modeling and graphical data processing, simulation, CAD/CAM systems, diagnosis systems and techniques, high-level programming languages, artificial intelligence.

First, complex parts like air-craft wing frames were manufactured on universal machine-tools, involving a major manufacturing preparation and serious problems in assuring the quality of the product. Later, likewise parts were manufactured on 2&1/2 axes NC machine-tools, where the generation of complex surfaces needed to let a stock for the final operation of adjusting the boundaries in order to eliminate the milling traces [1].

Today, the processing on NC machine-tools with 5 axes lead to [2]:

- refining the quality of execution especially by eliminating human intervention;
- process repeatability and part interchangeability acquiring;
- reduced time for the conception of the manufacturing preparation;
- reduced rate of scrap;
- machining of complex parts with technological difficulties such as thin walls, considerable depths etc.;
- increased flexibility of the manufacturing;
- elimination of adjustment operations and improved quality of the obtained surfaces.

Competitiveness may be improved if the concept of computer integrated manufacturing (CIM) is implemented because avoiding any unnecessary activities which add no value to the product will simplify the enterprise activity and reconsidering the flows in the company will reduce manufacturing time, indirect costs for transport and store. Independent subsystems like conception, planning, manufacturing, inspection and maintenance will be unified through automation and integration by CIM. One of the major subsystems of the CIM is the subsystem CAE - Computer Aided Engineering use electronic means of calculation and programming environments in order to optimize the engineering results. CAE deals with the analysis and evaluation of projects using computer-assisted techniques to calculate operational, functional and manufacturing parameters of the product.

In the design process, CAE finds its place among the stages of synthesis, analysis and evaluation and also has a well established place in the concept of simultaneous engineering. Based on information provided by CAE the product design is iterated during the first steps of the design process until the optimum solution is found. Nowadays the trend is to pass from the description of phenomena during materials cutting to their prediction. So, modeling and simulation of processing and developing of practical recommendation cutting parameters selection in integrated

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manufacturing became the subject of the most of current researchers work. The process plan parameters meaning fixture layout design, operation sequence, selected tool path strategies and the values of cutting variables had to be chosen before the machining start [3].

Improving NC machining efficiency and machining accuracy by proposing tool selection criteria is approached in [4]. The characteristics, such as path-interval, step length and tool wear were discussed and established models to provide the reliable criteria of tool selection. Tools geometry model for efficiency evaluation in order to demonstrate a qualitative and quantitative analysis was established by differential geometry. The analyzed parameters such as efficiency, scallop height for different machined surfaces were deduced by utilizing computer modeling to provide reliable selection principles of flat end cutter and disc cutter with a concave end in order to improve NC machining. Propeller blade was taken as an example to verify the proposed models of machining parameters. The comparison of surface intersecting curve (scallop height) between flat end cutter and disc cutter with a concave end were computed. A small tilting angle was applied to an initial tool orientation in the tool-center plane to provide equal curvature radius for the normal intersecting line for tool curvature surface and cutter contact point and to clarify the comparison between flat end cutter and disc cutter with a concave end (Fig.1).

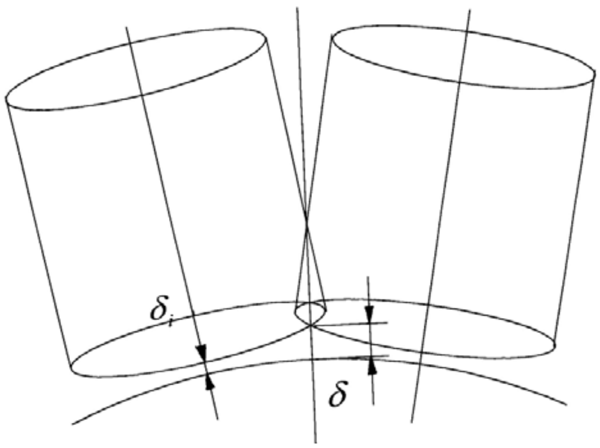

Fig. 1 the features of NC machining on the convex elliptical region using flat end cutter [4]

The milling process simulation in a transient 3D virtual environment allowed the prediction of the part thin wall deflections and elastic–plastic deformations during machining. It also permitted the prediction of the work piece non-linear behavior during machining due to its changing geometry, the fixture-work piece flexible contacts and the inelastic properties of the material. Using the finite elements method analysis of the developed model, the effects of initial residual stress residing inside the raw stock upon part deformation may be modeled. Also the model of the integrated analytical machining load given by the cutting force components and average shear plane temperature may be determined. Improving the reliability of stability prediction methods is a challenge in research now for given machines and processes.

Starting from the identification of the constitutive and damage laws of the material, a numerical model was built in [5], where it was emphasized that the formation of the chip had involved the intrinsic behavior of the material. A 2D FE model for face milling of AISI 4340 was detailed taking into account dynamic effects, thermo-mechanical coupling, constitutive damage law and contact with friction. The machining simulation proved the importance of having a material damage model as a mechanism for generating new free surfaces. Johnson–Cook plasticity and damage models were capable of simulating chip formation. The yield stress was taken as a function of the strain, the strain rate and the temperature in order to reflect realistic behavior in face milling. Johnson-Cook work material model was used for elastic plastic work deformations. Process simulation needs a material separation criterion (chip criterion) and thus The Johnson-Cook damage constitutive law adopted in model presented here allowed defining advanced simulations of tool's penetration in workpiece and chip formation. Plane strain condition was used throughout this study. The work piece was discretized with a mesh composed of CPE4RT elements, and local fine mesh was given along the moving path of the cutting edge because of very high gradients of solutions in this area, such as temperature, stress, etc. The cutting insert was modeled as a rigid body. The chip formation process was treated as a Lagrangian problem. Every boundary segment of workpiece was defined as a Lagrangian boundary region. Stresses and chip formation and cutting force were shown at different stages of the cutting process. The calculated cutting force were compared with experimental data and found to be in good agreement, validating, therefore, the proposed FE model. Fig. 2 shows the initial geometry, mesh and assembly of the workpiece and the cutting insert.

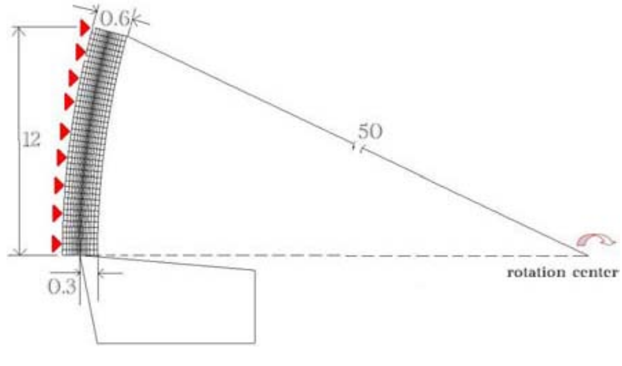

Fig. 2 initial geometry, mesh and assembly of the tool and the workpiece in chip formation analysis [5]

And the prediction of stability for metal cutting operations usually involves a process and a structure model. It was observed that stability limits may be increased in machining using different cutting strategies so that the machining time may be minimized in order to maximize the productivity by avoiding chatter. Or using a cutting pattern selected by considering the geometry, boundary and cutting conditions, the stability limits may be increased and the machining time may be reduced significantly [6]. The geometrical and topological information of the work piece's virtual model had to be examined in order to perform optimal high speed milling operations, before applying the suitable machining strategies of high speed cutting.

It was found that the initial stresses embedded within the raw material seemed to have an effect on the final part deformation. In fact, the stress distribution and magnitude, measured using a neutron diffraction method, seemed to be related to the size of the deformation error [7]. The study focused on the longitudinal deformation, which was found to be significant compared to the other directions. The sampling size should be enlarged, in order to plot a complete 3D cartography for the stress distribution, and validate the conclusion. Regarding the residual stresses measured on the machined parts, they were also found related to the final part deformations.

The residual stress induced by metal cutting is a complex problem in machining engineering because it involves the machine property, the stability and intensity of fixture system, the state of blank, and the reaction between workpiece and working environment.

Workpieces with large aluminum alloy structure are used widely in modern aviation products because of the light density, high ability of bear weight, the property of resisting decay and meeting the whole requirement. It is important to improve machining precision by controlling and minimizing the deformation widely existing in milling. The residual stress is the main physical reason responsible for machining deformation inducing.

The distribution law of the residual stress in the finished surface during milling process was analyzed and computed using elastic and plastic finite element techniques in [8], where the effect of tool impact and material removal on residual stress was considered simultaneously. It was proposed the "stress wave effect" in order to explain the results of the simulation. The stress wave effect helped to interpret the physical phenomena of machining, reflecting the residual stress distribution characteristic. The interpretation given by the paper is important for the research of the machining deformation in order to eliminate it.

Thin-walled parts require a lot of material to be machined and a lot of tool paths when high speed machining is used. For parts with complex configuration and thin walls, the high-speed milling operations are often limited by the so-called regenerative effect that causes poor surface finish [9]. The strong relationship between surface roughness and vibration during machining was proved by simulation and experiments investigating surface roughness evolution and the stability of the process.

And the conclusion was that relation between the vibration amplitude and the surface roughness was too complex to give predictive values. High speed cutting aspects in the computer-aided manufacturing system, like optimal technology and strategy suggestion, machining safety requirements and process stability of different strategies leaded to a significantly reduced programming time to produce high speed cutting appropriate tool paths [10].

Obtaining the required accuracy and roughness for finished parts from the stage of finishing process and eliminating the adjust operations for removing traces tools were the technological criteria adopted by the authors of this paper for an advanced machining conception of a complex frame, component of an air-craft assembly. According to the geometric criterion, the optimum is achieved by minimizing the total length of tool paths.

This is achieved by using SURFCAM Velocity 4.0 software, a programming environment which allows the modeling of surfaces machining on NC machine tools, with the possibility of tools path generation and their post-processing. It provides the possibility of generating the trajectories of the cutting tool for multi-surfaces through Z-level roughing and Z-level finishing operations.

II. Part Manufacturing Conception

This papers aims to present the manufacturing conception development for the frame represented in Fig. 3, made of duralumin, respecting the principles of CIM, adapted to a flexible manufacturing system. The frame is a component part of an air-craft wing.

Duralumin is a largely used material in the aerospace industry and produced as a raw material from different manufacturing processes, e.g., forging, molding, rolling and extruding. All these operations and also the heat treatment for improved mechanical properties induce residual stresses within the material. The distribution and magnitude of the stresses through the depth is depending on the machining conditions for a given material, like speed, feed, depth of cut, cutting tool geometry, tool path strategies, etc.

The part configuration involves the task known as pocket machining. There are two main types, of milling strategy in pocket machining: direction-parallel milling and contour-parallel milling. Direction-parallel milling uses line segments parallel to each other as cutter path elements. The beginning and the end of each line segment arc determined by the contour of the pocket. In contour-parallel milling, the offset contour segments are used as cutter path elements.

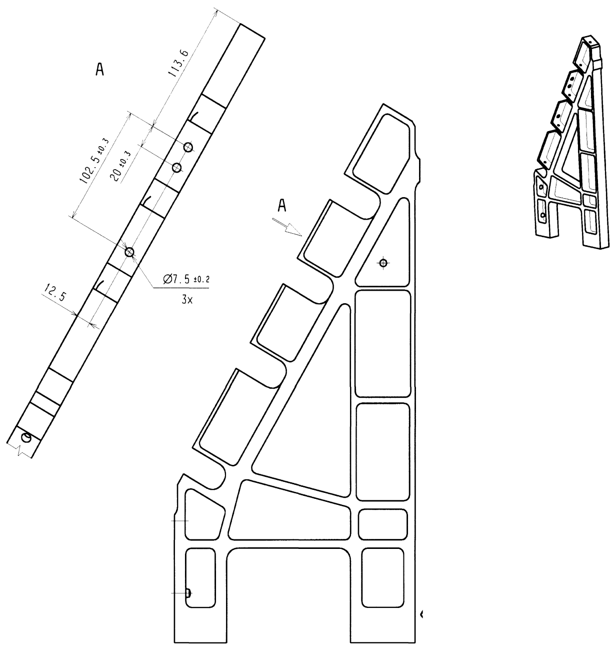

Fig. 3 part configuration

This means that the pocket area is milled in a spiral-like fashion, cutting along curves equidistant from the contour.

For more complicated pockets with islands, the latter method results in a significantly shorter tool path length and a better surface quality because of uniform cutting. Many papers describing contour-parallel tool path generation are based on the method of successively shrinking the outer contour. This task is executed in three steps: offsetting each contour element, closing gaps between the offset elements, and eliminating self-intersections of the offset elements.

The execution tolerances of the main dimensions were 0+0.02 mm in order to assemble the frame with the other parts and made the superior assembly. Given the wide range of dimensions of this frame-type used to configure the wing, the approach of the part manufacturing conception was suitable for grouped technology. The surface quality was very important for processing, too.

The part was manufactured on a NC machine center with 3 axes. The processing technology conception was developed based on the necessity of geometrically and technologically optimization. Obtaining the required accuracy and roughness for finished parts from the stage of finishing process, eliminating the adjust operations for removing traces tools represented the technological criterion adopted for technologically optimization.

The force and heat of milling induce residual stress which is mainly in the finished layers of the workpiece as a result of the tool’s action during milling. The residual stress determines tension in the exterior layers and compressive stress in the interior layers. The dimension and performance of the workpiece are negatively influenced by the existing of residual stress.

Minimizing the total length of tool paths represented the criterion adopted for geometrically optimization.

The productivity of contour-map machining is closely related to the tool-path patterns used for machining each cutting layer. Traditionally, the tool-path patterns for contour-map rough milling are determined manually based on an engineer's manufacturing experience and the suggested values provided by machining handbooks, so the generation of a tool-path pattern is difficult and time-consuming. It was noted that the frequency of plunge and retract and traversing motions are the major factors that influence the efficiency of a tool-path pattern.

Using SURFCAM Velocity 4.0 program there were achieved both criteria. This dedicated program offers available facilities for modeling the manufacturing of the surfaces on NC machine tools, with the possibility of tools path generation in order to post-process them, i.e. to transform the tool paths in machine-code and to develop the machining program. So, there were generated the tool paths for pockets machining as shown in Fig. 4, detailed in Fig. 5, and then the tool paths for exterior contour machining according to Fig. 6.

In order to manufacture the part with the geometrical configuration as shown in Fig. 3, the following steps were accomplished:

- The 3D model part generation started from the part drawing using a programming environment for 3D geometric modeling like SolidWorks, ProEngineer, Catia etc.;

- Using the finite element analysis in COSMOSM program and performing static, dynamic and heat transfer analysis on the imported 3D model, the critical sections were determined. The geometrical and shape optimization aimed to considerably reduce the width of the walls (approx. 20%) and save a lot of material in order to reduce the frame weight (a permanent necessity for the air-craft parts).

- Then the 3D model was imported in SURFCAM Velocity 4.0 in order to perform the NC programs;

- The tools paths were obtained for each operation using SURFCAM Velocity 4.0. The determined configuration of the critical sections was considered and the appearance of supplementary mechanical stress during the process was avoided as much as possible [11].

The distortion of machined components is a major concern in the manufacture of structural aerospace components. The distribution of machining-induced stresses can affect a component’s ability to withstand severe loading conditions, as well as causing dimensional and geometrical deviations. It can also lead to high rejection rates and quality-related problems during component assembly. It is therefore essential to understand the mechanism which determines parts distortion; this could result both from existing residual stresses in workpieces or induced by the machining process.

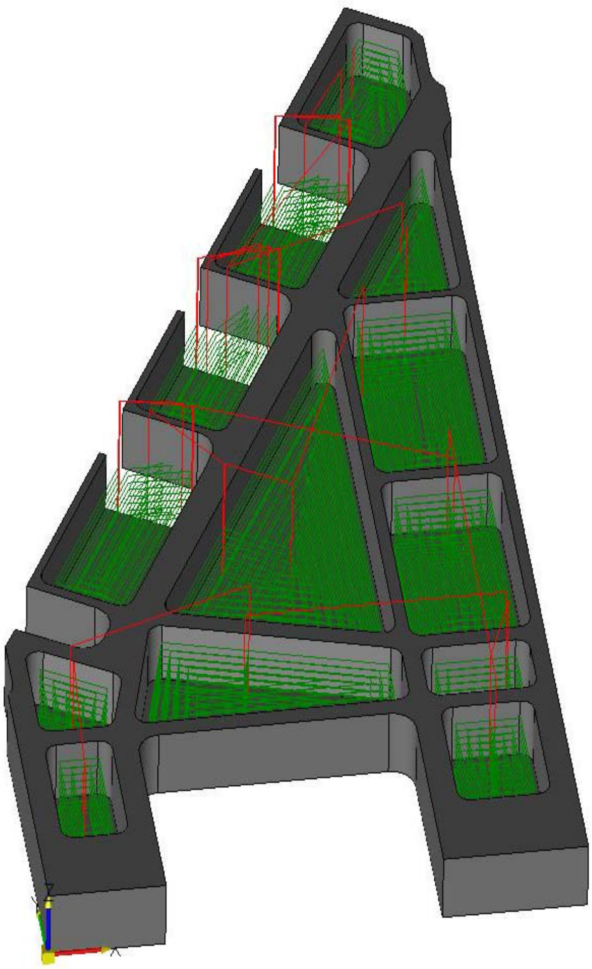

Fig. 4 tool paths generation for interior pockets machining

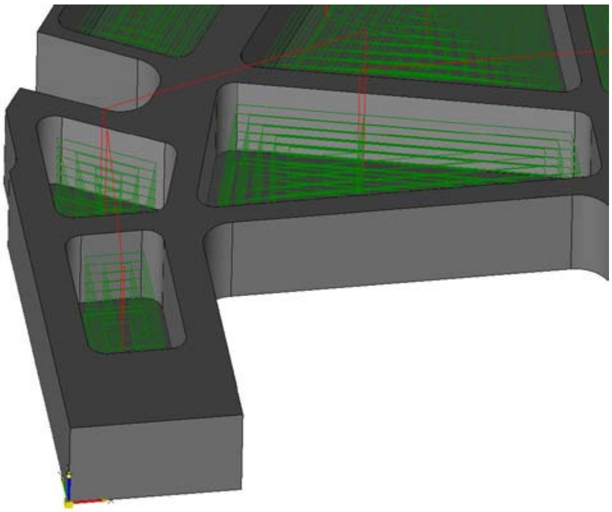

Fig. 5 tool paths generation for interior pockets machining (detail)

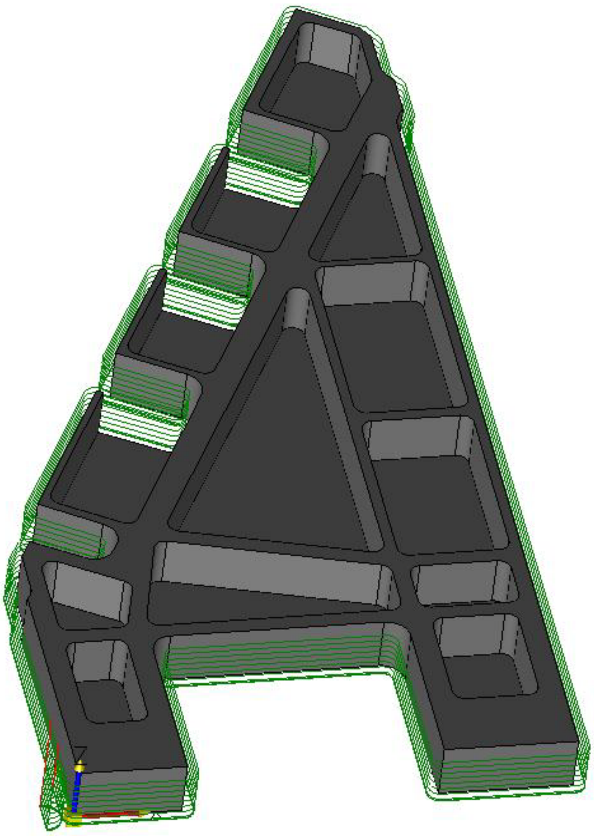

Fig. 6 tool paths generation for exterior pockets machining

The distribution, signs, and magnitudes of the residual stresses may be at the origin of the deformations measured, which indicates that residual stresses embedded within the raw material are partly responsible for the distortion of the parts following their machining. The tool path is stored in a file including the position of the tool and the orientation of the tool axis defined in a workpiece coordinate system. A NC-postprocessor converts the machine independent data file into a machine specific NC-program [12]. After the post-processing programs development the part was machined on the NC milling machine.

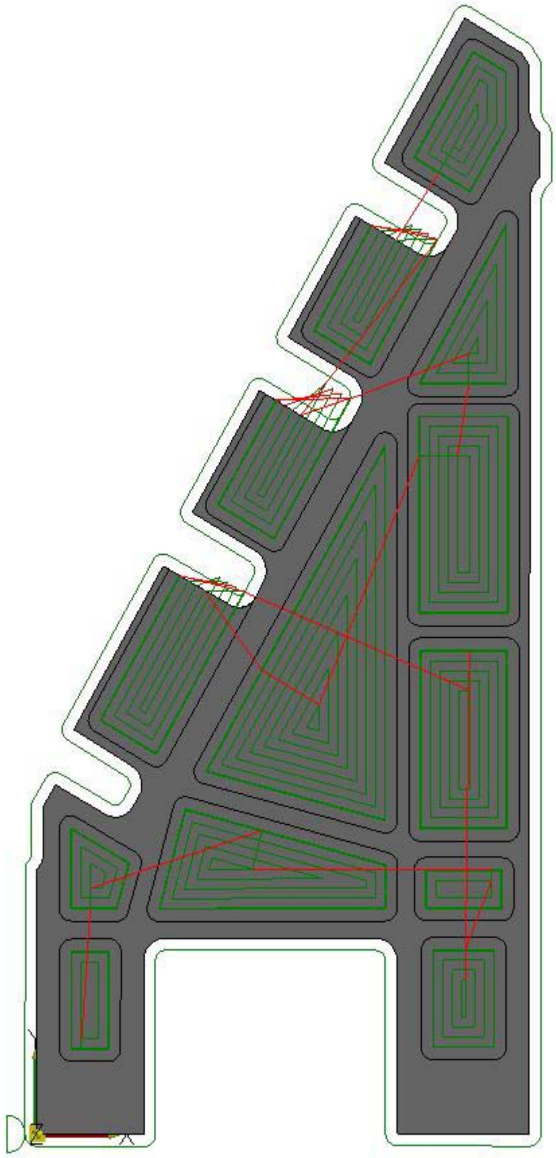

Fig. 7 the assembly of tool paths generated for pockets and exterior contour machining

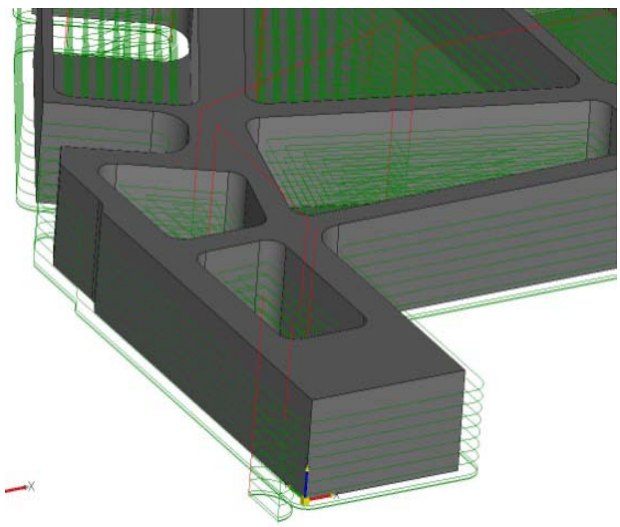

Fig. 8 the assembly of tool paths generated for exterior contour machining (detail)

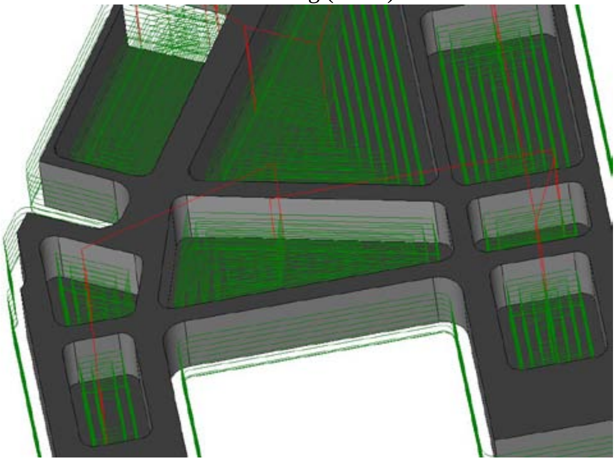

Fig. 9 the assembly of tool paths generated for pockets machining (detail)

III. Simulation and Optimization of Computer Programs

CAD / CAM (computer-aided design / computer-aided manufacturing) systems and solid-modeling techniques have been introduced to handle the geometric complexities generally encountered in the machining processes modeling.

Better accuracy, higher productivity, and the need for sustained operation represent the major demands of today machining industries. Meeting those needs may only be achieved through control of the cutting process.

Basically, there are two approaches. The first approach uses on-line adaptive controllers, but it fails to deal with process transients characterized by sudden jumps in force magnitude, and relies heavily on sensing devices. The second approach tackles the issue through geometric and physical modeling of the cutting operation. The geometric simulation must accurately compute the required geometric information (i.e. cutter-part intersection geometry).

The physical simulation is basically a process model that relies on the geometric data to determine the instantaneous cutting forces, torques and deflections. Consequently, in order to implement a simulation of the actual machining process, the first step is to extract accurate cutter-part immersion geometry.

Machining process simulation systems may be used to verify NC (numerically controlled) programs as well as to optimize the machining phase of the manufacturing. These systems contribute towards improving the reliability and efficiency of the process as well as the quality of the final product.

SURFCAM Verify module generated tool paths which were checked allowing a real time view of the model processing, starting from the semi-finished part chosen by the user. So, the user may obtain a quick look of the process of material removing and the processing errors may be detected.

For the considered frame, there were simulated on computer all the processing operations, respecting the established order by the technological route [13]. The machining simulation of the frame presented above is shown in Fig. 10 for the pockets milling and in Fig. 11 for the exterior contour milling.

In Fig. 12 it is exposed the simulation of the finishing milling getting the final configuration of the considered frame. The main goal was to obtain the correct geometry and required surface quality, to eliminate unwanted interferences, material missing from surfaces and edges. After computer simulation analysis, the tools paths were restored for obtaining the optimal joining of all processing operations.

The finishing cuts steps were set to be big enough without causing an overheating of the part and additional mechanical stress appearance. So, fine tuning of the machining process would provide more control over the quality of the product on a consistent basis [14].

From the stiffness point of view, different geometries require different manufacturing strategies. When the component shape is complex, many clamping configurations may be involved to prevent clamping stresses in thin walled parts. The machining conditions, material removal rate and cutting tools selection will also depend on the component shape, where more challenging cutting strategies and parameters may be required. The shape also influences the choice of manufacturing process for the raw material (casting, forging, extruding, rolling, etc.). This will lead to different stress distributions and part distortions.

Process planning of such parts is difficult due to the vast amount of paths to program and the low stiffness of the final part. The objective was to reduce the machining costs for producing “right first time” components avoiding hand-finishing processes and assuring part-to-part accuracy [15].

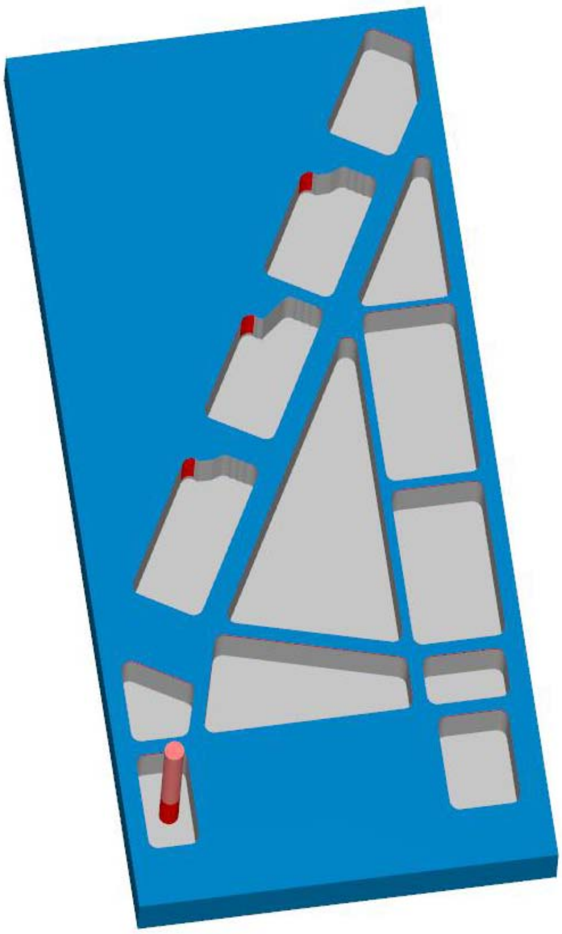

Fig. 10 Simulation of pockets machining

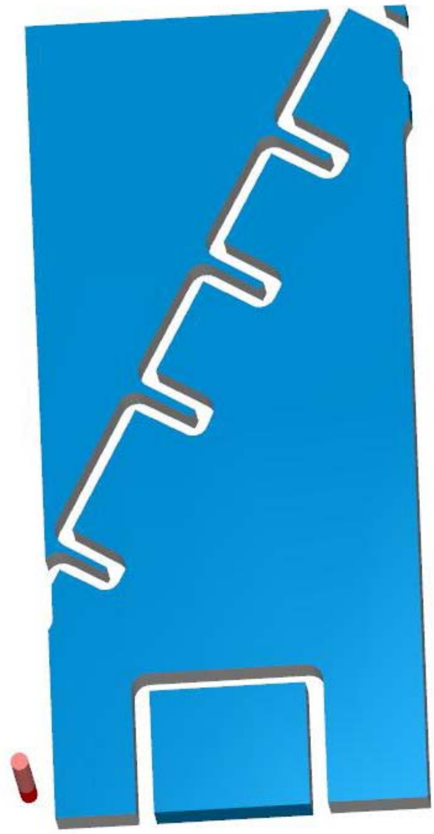

Fig. 11 simulation of exterior contour machining

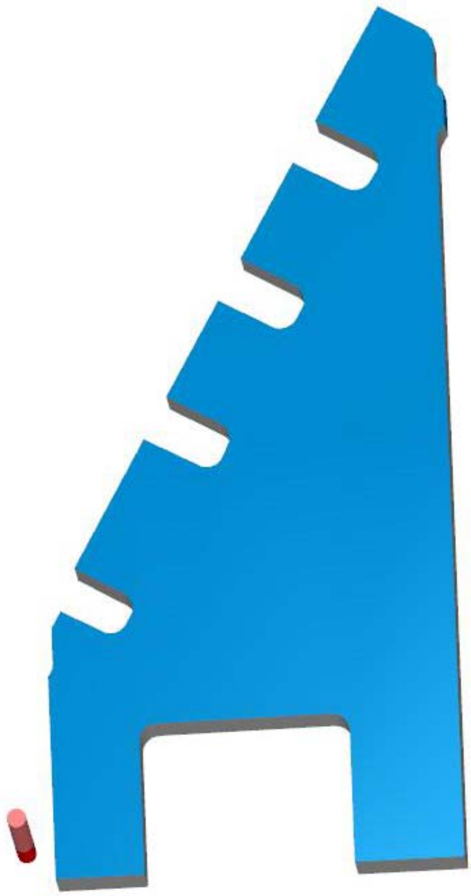

Fig. 12 simulation of exterior finishing milling

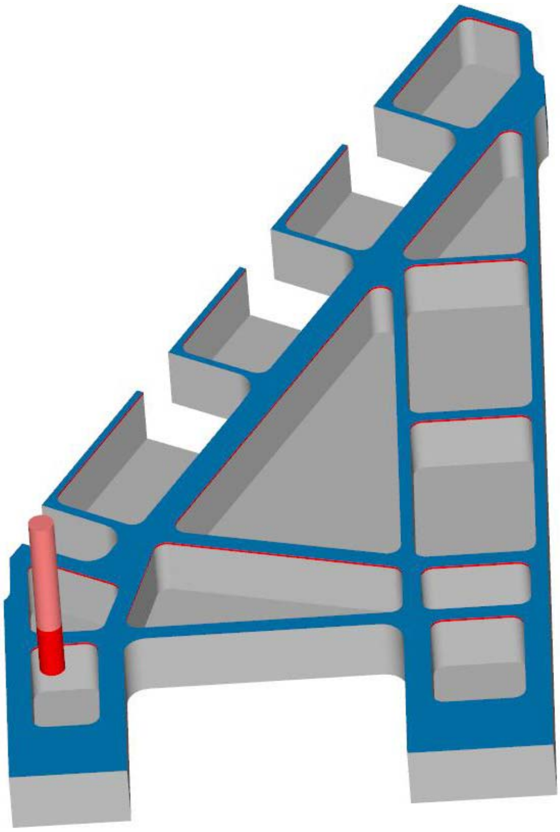

Fig. 13 simulation of the finishing milling in order to get the final configuration of the frame

All processing operations running on a given model were recorded by an operations manager (CN Operations Manager), where they were represented in the chronological order of their execution. This operations manager allowed the post-processing of the tool paths for the chosen NC machine-tool. (In machining simulation, the nominal cutting path is given in a form of NC code at selected sampling points.)

IV. Conclusion

It is known that the life of a structural part for aerospace use is typically a function of the interactions between the loading conditions in service, the existing component defects, as well as the existing residual stresses within the parts. The residual stresses may be considered as negligible or critical, depending on the particular case, may be beneficial or destructive for the component, depending on their type, distribution or magnitude. The machining processes used in manufacturing components always add residual stresses, resulting in a final distribution affecting the mechanical properties and producing dimensional and geometrical deviations for the part features.

The manufacturing conception of the wing frame was developed taking into account the dynamic, static and thermal transitory loads of the frame and optimizing the total length of tool paths with SURFCAM Velocity 4.0 program. The paper offers an interdisciplinary approach of the construction and technology design for important parts, which suppose supplementary safety measures.

The machining technology optimization was realized not only under geometric criterion, but also under technological criterion. According the geometric criterion, the optimum was obtained primarily by minimizing the total length of trajectories (curves) with which the whole area was covered, in terms of maximum accuracy providing from the geometric point of view and in terms of a calculation effort as lower as possible.

Determination of the final sequence of operations was based on minimizing the work-piece machining by minimizing the non-machining time between operations and the number of tool changes and the overall tool paths.

The maximization of the tool capacity of cutting was the main technological criterion considered. As a condition for general optimum, it was very important to establish the direction of machining trajectories so that to allow a comfortable manual finishing where it was necessary. This meant to give such a direction to the "rifles" which mark processing trajectories that could be conveniently attacked by the tool of the adjusting worker on a parallel direction to the direction of finishing.

Component parts with complex walls are frequently used for airplanes. Currently, simultaneously ensuring the machining accuracy and efficiency of thin-walled structures especially high performance parts still remains a challenge. Their machining requires special attention for not introducing additional tensions in the critical sections. In the studied case the mechanical stress in critical sections were determined by finite element analysis using previous experience of authors in optimizing and modeling the complex walls parts. Also, the finite element analysis and optimization saved 20% of material and provided small widths for walls where the model was not overloaded. Thus, interdisciplinary approach of the construction and technology design, of the execution and the control makes the parts with complex walls to require advanced technologies for processing.

A future research direction will concern the using of lightweight alloys as titanium alloys and others more resistant in mechanical terms for improving the processing technology of the parts with complex configuration and loads. The part thin wall deflections and elastic-plastic deformations during machining may be predicted by their milling process simulation in a transient 3D virtual environment, based on a comprehensive finite element analysis of the model.

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