APPLICATION OF CAx TECHNOLOGIES IN MODELLING AND SIMULATION OF CNC MACHINE TOOL AND PROCESSING COMPLEX PART

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***ABSTRACT**: This research presents the use of CAx technologies in the design of a Computer Numerically Controlled machine. The sub-assemblies and assemblies of the Computer Numerically Controlled machine are designed by using CAD (Computer Aided Design) software. Then the CNC machine virtual assembled model is presented. The model is loaded into other integrated CAD/CAM/CAE software and a NC code for a complex part (impeller) is generated. The next stage shows simulation of complex part (impeller) processing on a virtual Computer Numerically Controlled machine. By using CAE (Computer Aided Engineering) module of the integrated software, a static analysis of the loaded complex part (impeller) has been performed and its deformations and stress have been estimated for different materials and different rotation speeds. Based on the performed analyzes and simulations, a recommendation is given from which material the complex part (impeller) should be manufactured in order to meet the technical criteria and the costs for the used material and manufacturing to be as low as possible.*

***KEYWORDS**: Computer Aided Design (CAD), Computer Aided Manufacturing (CAM), Computer Aided Engineering (CAE), CAx technologies, CNC machine*

1 INTRODUCTION

In order to survive the great competition on the market, companies must launch new products with better quality and lower cost in a shorter time.

Today in order to reduce the time and cost of development and production, intensively are used CAx technologies: Computer Aided Design (CAD), Computer Aided Manufacturing (CAM), Computer Aided Engineering (CAE), Computer Aided Process Planning (CAPP), etc.).

The all above mentioned technologies contain the term CA-Computer Aided which contributes to the unification of all Computer Aided technologies with one word CAx, where "x" is a substitution for any of the technologies (Rao, 2010; Dankwort et al., 2004).

The companies that not use these technologies can not survive on the market. Today the products that are found on the market are optimized in terms of the number of used components, as well as the quantity and type of material used, which contributes to reducing the costs and increasing the quality. It is a direct result of the application of CAx technologies.

2 CAD - COMPUTER AIDED DESIGN

Computer Aided Design (CAD) involves activities that lead to the development, analysis, or modification of certain parts or products. The evolution of Computer Aided Design is largely related to computer graphics. CAD covers much more than computer graphics. Interactive computer graphics is an essential technological basis for the Computer-Aided Design. Modern CAD systems are based on interactive computer graphics. Computer interactive graphics represents a user-oriented system in which a computer is used to create, transform, and display data in the form of images or symbols. The designer, in fact the user of the computer modeling system, enters data and commands into the computer software in order to obtain the geometric model. The graphic image is created with basic geometric elements - points, lines, circles, etc., which can be modified according to the designer's needs, enlarged or reduced, moved to another location on the screen, rotated, etc. (Mercer, 2004; Groover & Zimmers, 2003).

Interactive computer graphics is one component of a Computer Aided Design system. The other component is the designer. Interactive computer graphics is a tool used by the designer in order to solve a specific design problem. Actually it increases the power of the designer.

There are several basic reasons to implement a Computer-Aided Design system (Haideri, 2015; Alavala, 2008):

1. Increase the productivity of the designer. The CAD system is used to assist the designer in visualizing the product and its components. It is also used to reduce the time required for analysis, synthesis and documentation of the finished product design. This enables lower design costs and completion of project in shorter time.

2. Improving the quality of the design. The CAD system enables the performance of detailed engineering analyzes and consideration of a large number of design alternatives. Design errors are also reduced, due to the high accuracy of the system. These factors lead to better design.

3. Improving communication. The use of the CAD system provides engineering drawings with higher quality, greater standardization in technical drawings, better technical documentation, fewer drawing errors and greater readability.

4. Creating a production database. The database is created during the production of the parts and subassemblies of which the product is composed. From the database we can generate a list of necessary types of materials for manufacturing the components, calculation of the required quantities of materials, production costs, etc.

In this paper, the SolidWorks software package was used for real and accurate design of a Computer Numerically Controlled milling machine. The all CNC machine components were designed and optimized separately and later assembled. Machine optimization is needed to detect sub-assembly faults, especially on slip surfaces. When the optimization was done and the bugs were corrected, the next step was to set boundary values on the moving surfaces/objects, such as the workpiece, main spindle, slides, etc.

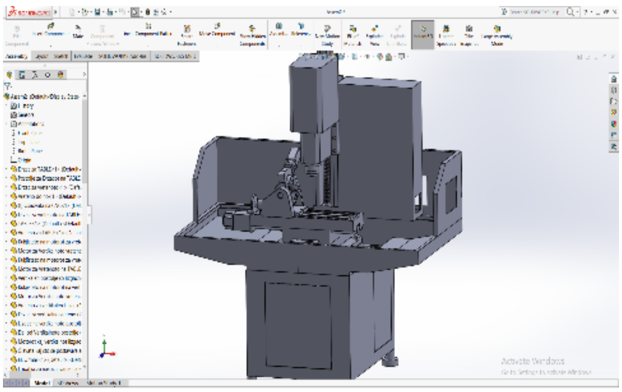

Fig. 1 Assembly of CNC machine

Fig. 2 A rendered view of the CNC machine assembly

After the Computer Numerically Controlled milling machine is fully designed and assembled (Figure 1), a rendered view of the machine is presented (Figure 2).

3 CAM – COMPUTER AIDED MANUFACTURING

CAM (Computer Aided Manufacturing) can be defined as application of computer technology in the process of production, using Computer Numerical Controlled machines (CNC machines) and software applications, nearly in all steps in the production process (Elanchezhain et al., 2007; Eickenberg, 2005).

CAM is usually closely connected with CAD, because the end product of CAD in the design process (3D model, technical documentation, various standard files, etc.) is an input parameter in the process of Computer Aided Manufacturing (Lee, 1999; Grewal & Sareen, 2007).

The general benefits the companies obtain from the implementation of CAM technology in the production process, are:

- higher productivity;
- higher flexibility in the production process;
- higher quality and repeatability;
- less influence of the operators on the product quality;
- elimination of technological errors during the equipment programming;
- less scrap.

This section demonstrates the use of an integrated CAD/CAM software in generation of NC code and simulation of processing the complex part (impeller) on a virtual Computer Numerically Controlled machine. The complex part (impeller) is shown in Figure 3.

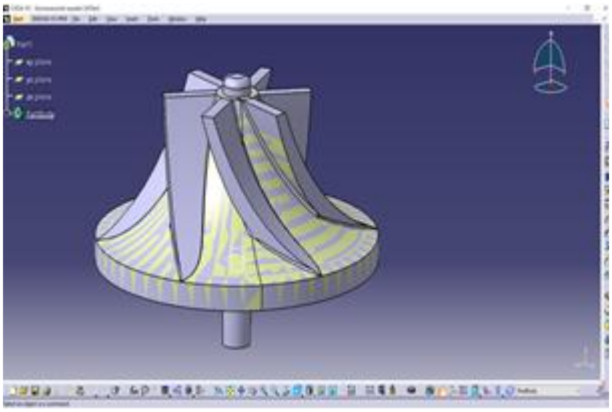

Fig. 3 Model of complex part (impeller) presented in integrated CAD/CAM software

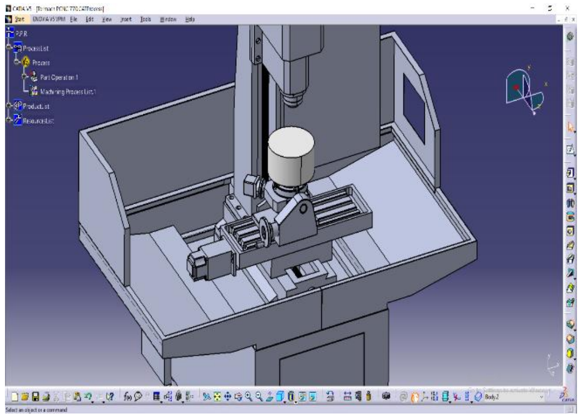

Fig. 4 Raw material piece attached on the Computer Numerically Controlled machine working table

Table 1. Mechanical properties of the different materials for the complex part (impeller)

Material	3.1 Young's modulus [N/m²]	Poisson's ratio	Density [Kg/m³]	Thermal expansion [K]	Yield strength [N/m²]	Average Price [US $/kg]
Titanium alloy Ti-6Al-4V	1,14 e+011	0.34	4460	9,5 e-006	8.8 e+008	21
Aluminum alloy Al 6061-T6	7 e+010	0.346	2710	2,36e-005	2.76 e+008	2.2
Plastic Polybutylene Terephthalate	3 e+009	0.4	1400	10.8 e-005	1.075 e+008	1.2

All parts, sub-assemblies and assemblies of the Computer Numerically Controlled machine are designed in the SolidWorks software package and saved in IGES format. The IGES format enables their loading into integrated CAD/CAM software and creation of an assembly in which restrictions of the movement of the assembly components can be set.

All machine parts are imported through the interface of the integrated CAD/CAM software and saved in the appropriate format. After the completion of the procedure for all machine parts, the parts are merged in sub-assemblies and at the end in final assembly. The raw material piece attached on the Computer Numerically Controlled machine working table is shown in Figure 4.

An integrated CAD/CAM software package was used to generate a trajectory for processing a specific complex part (impeller). The CAD/CAM software operates on following principle: 1.defining the processing method of the CAD model of the working part, 2. selection of tool moving patterns, and 3.generation of an automatic tool movement trajectory (NC code) adapted to the machine control unit.

Today there are many different integrated CAD/CAM software packages, such as: CATIA,

PTC Creo (Pro/Engineer), Solidworks CAM, Fusion 360, Siemens NX (Unigraphics), etc.

4 CAE - COMPUTER AIDED ENGINEERING

Computer Aided Engineering (CAE) is a technology that uses computer systems for model analysis through numerical simulations. The result is the simulation of behavior of the model under the given conditions, with the possibility of its optimization and redesign. The oldest and most common method for computer aided analysis is the Finite Element Method (FEM). This method allows the determination of Von Mises stress, deformations, heat distribution, fluid flow and other engineering problems. With CAE software systems we can perf

orm analyzes of static, frequency, dynamic and thermal behavior of the given model, as well as structural optimization in order to achieve a certain functionality (Charles, 1984; Raphael & Smith, 2013).

In the CAE software systems first step is identifying the geometry and defining the material from which the model is built. The relevance of the obtained results depends on the choice of the selected mesh density and the type of finite elements. It is made interactively, before the start of generating the mesh. Generating a mesh is usually time consuming process. It consumes most of the time in the whole analysis. The generation of the mesh is followed by the numerical analysis of the CAE software system, where matrices are automatically generated. They determine the behavior of each individual element.

Combining these matrices into matrix equations and solving them results in calculation of different parameters in the defined nodes of the finite elements (Hetem, 2000; Chang, 2016). The obtained results are presented by the CAE software system as a graphical representation of the model in different colors, where each color represents a certain parameter value. The resulting graphical representation can be deformation, Von-Mises stress, temperature distribution, deformation rate, etc. (Zienkiewicz, 1977; Rieg et al,, 2014).

In this paper, the complex part (impeller) tests are performed using three different materials: titanium alloy (Ti-6Al-4V), aluminum alloy (Al 6061-T6) and polymer plastic material (Polybutylene Terephthalate). Mechanical properties of the materials are shown in Table 1.

The results of the performed tests on the model of the complex part (impeller) are presented graphically and in tabular form. The tests are performed for three different materials (titanium alloy, aluminum alloy, plastic) and three different rotational speeds (6000 [rpm], 4000 [rpm] and 2000 [rpm]).

The tests performed on the model of the complex part (impeller) made of titanium (Ti-6Al-4V) at 6000 [rpm] are shown in the following figures: Figure 5 (Von-Mises stress at 6000 [rpm]), Figure 6 (Translational displacement at 6000 [rpm]), Figure 7 (Deformed mesh at 6000 [rpm]) and Figure 8 (Principal stress at 6000 [rpm]).

Table 2. Results of the tested complex part (impeller) for different materials at the 6000 [rpm]

Analysis	Static Analysis		
Rotation Speed	6000 [rpm]		
	Von-Mises stress [N/m^2]	Translational displacement [mm]	Principal stress [N/m^2]
Titanium alloy Ti-6Al-4V	1.07 e+007	0,00202	1.35 e+007
Aluminum alloy Al 6061-T6	6.57 e+006	0,00232	8.35 e+006
Plastic Polybutylene Terephthalate	3.75 e+006	0.025	4.99 e+006

The complex part (impeller) made from aluminum alloy and plastic was also tested. The results are shown in Table 2.

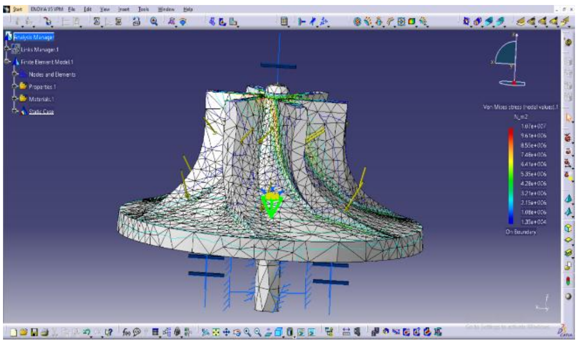

Fig. 5 Von-mises stress (Titanium alooy Ti-6Al-4V at 6000 [rpm])

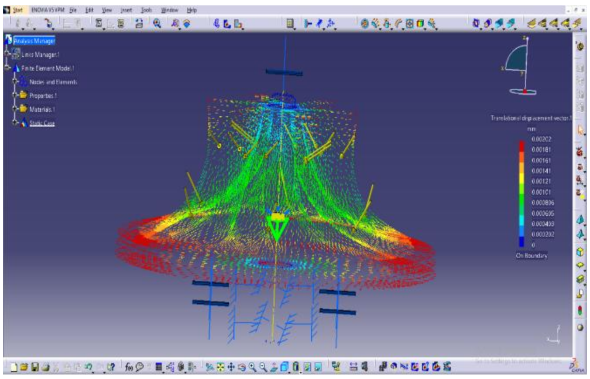

Fig. 6 Translational displacement (Titanium alloy Ti-6Al-4V at 6000 [rpm])

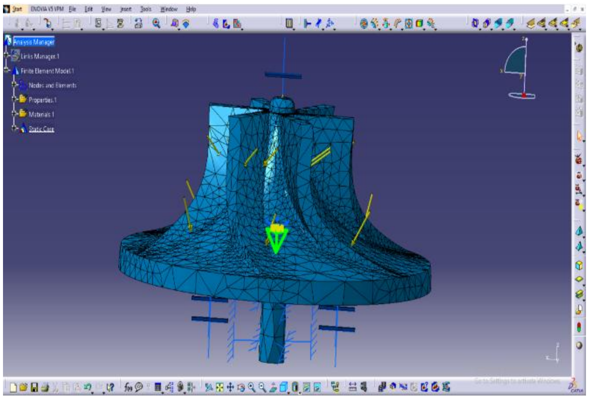

Fig. 7 Deformed mesh (Titanium alloy Ti-6Al-4V at 6000 [rpm])

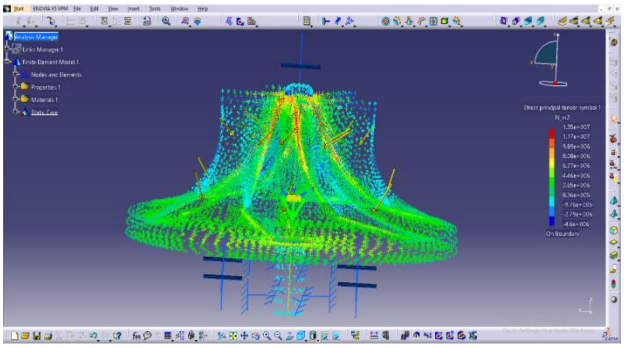

Fig. 8 Principal stress (Titanium alloy Ti-6Al-4V at 6000 [rpm])

The results also can be presented in different document formats. The document file contains all the necessary data about the model, such as type of used finite elements and material, definition of boundary conditions and loads, numerical values of the results, etc. This enables the report of the conducted analysis to be easily understood. The results of the tested materials, in addition to the graphical representation, are also present in a tabular format for easier perception and comparison.

From the obtained results it can be seen that the Von-Mises stress for the model of the complex part (impeller) made of titanium alloy (Ti-6Al-4V) is the highest, then follows model made of aluminum alloy (Al 6061-T6), while the model made of plastic (Polybutylene Terephthalate) has the lowest value. If we analyze the deformations that occur in the complex part (impeller) made from these different materials, it can be noticed that titanium alloy (Ti-6Al-4V) and aluminum alloy (Al 6061-T6) have similar displacements. Titanium alloy (Ti-6Al-4V) is the strongest material among these three materials. The obtained results for Von-Mises stress is the highest for the model of the complex part (impeller) made of titanium alloy (Ti-6Al-4V).

The complex part (impeller) made of plastic (Polybutylene Terephthalate) has a Von-Mises stress 1.75 times lower than the impeller made of aluminum alloy (Al 6061-T6), and at the same time has the largest displacements, at rotational speed 6000 [rpm]. However, the complex part (impeller) made of plastic (Polybutylene Terephthalate) satisfies the testing because the obtained Von Mises stress is 3.75 e+006 [N/m^2], which is below the limit of the yield strength of plastic material (Polybutylene Terephthalate) which is 1.075 e+008 [N/m^2] (Table 1).

In order to perform the comparative analysis, the same tests of the complex part (impeller) model were performed, but with lower rotational speed.

The tests performed on the model of the impeller made of titanium alloy (Ti-6Al-4V) at 4000 [rpm] are shown in the following figures: Figure 9 (Von-Mises stress at 4000 [rpm]), Figure 10 (Translational displacement at 4000 [rpm]), Figure 11 (Deformed mesh at 4000 [rpm]) and Figure 12 (Principal stress at 4000 [rpm]). The complex part (impeller) was also tested for other materials, aluminum and plastic. The results from the analysis of the all tested materials at 4000 [rpm] are given in Table 3.

Table 3. Results of the tested complex part (impeller) for different materials at 4000 [rpm]

Analysis	**Static Analysis**		
Rotation Speed	**4000 [rpm]**		
	Von-Mises stress [N/m^2]	Translational displacement [mm]	Principal stress [N/m^2]
Titanium alloy Ti-6Al-4V	4.75 e+006	0.000939	6.01 e+006
Aluminum alloy Al 6061-T6	2.92 e+006	0.00102	3.71 e+006
Plastic Polybutylene Terephthalate	1.67 e+006	0.0162	2.22 e+006

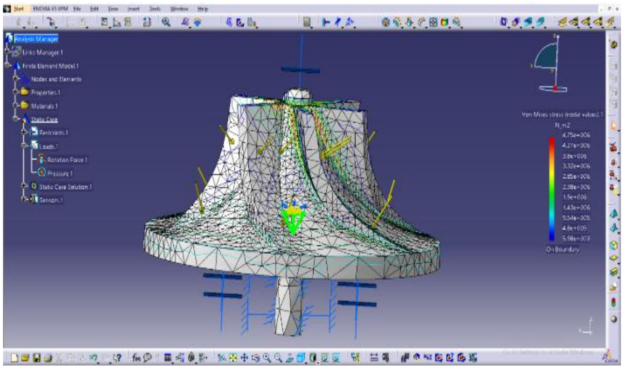

Fig. 9 Von Mises stress (Titanium alloy Ti-6Al-4V at 4000 [rpm])

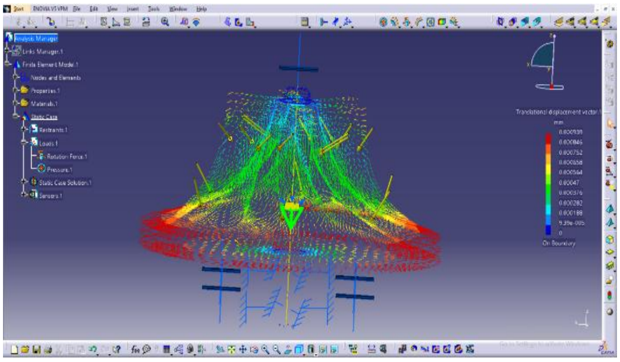

Fig. 10 Translational displacement (Titanium alloy Ti-6Al-4V at 4000 [rpm]

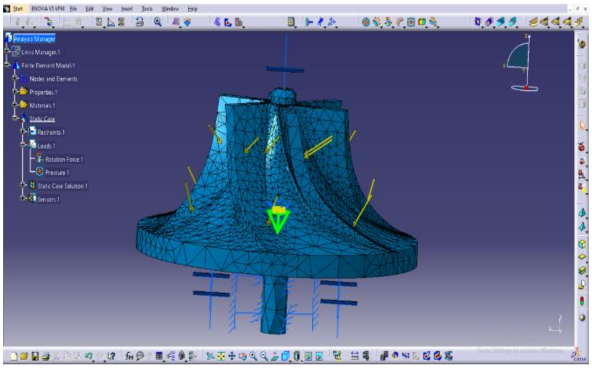

Fig. 11 Deformed mesh (Titanium alloy Ti-6Al-4V at 4000 [rpm])

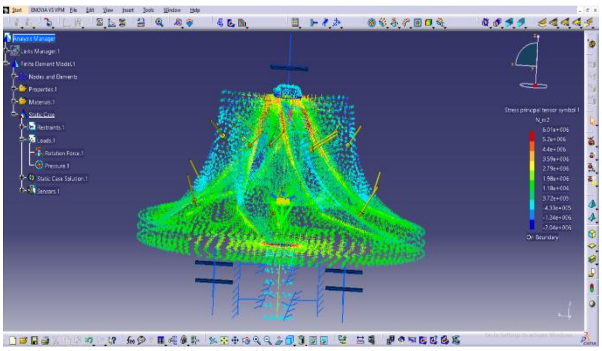

Fig. 12 Principal stress (Titanium alloy Ti-6Al-4V at 4000 [rpm])

From the obtained results again it can be seen that the Von-Mises stress for the model of the complex part (impeller) made of titanium alloy (Ti-6Al-4V) is the highest, then follows model made of aluminum alloy (Al 6061-T6), while the model made of plastic (Polybutylene Terephthalate) has the lowest value.

If we analyze the deformations that occur in the complex part (impeller) made from these different materials, it can be noticed that again that titanium alloy (Ti-6Al-4V) and aluminum alloy (Al 6061-T6) have similar displacements. Obviously titanium alloy (Ti-6Al-4V) is the strongest material among these three materials. The obtained results for Von Mises stress is again the highest for the model of the complex part (impeller) made of titanium alloy (Ti-6Al-4V).

Again he complex part (impeller) made of plastic (Polybutylene Terephthalate) has a Von-Mises stress 1.75 times lower than the impeller made of aluminum alloy (Al 6061-T6), and at the same time has the largest displacements, at rotational speed 4000 [rpm]. However, the complex part (impeller) made of plastic (Polybutylene Terephthalate) agagin satisfies the testing because the obtained Von-Mises stress is 1.67 e+006 [N/m^2], which is again below the limit of the yield strength of plastic material (Polybutylene Terephthalate) which is 1.075 e+008 [N/m^2] (Table 1).

The same tests on the model of the complex part (impeller) were performed once more, for new rotational speed of 2000 [rpm].

The tests performed on the model of the complex part (impeller) made of titanium alloy (Ti-6Al-4V) at 2000 [rpm] are shown in the following figures: Figure 13 (Von-Mises stress at 2000 [rpm]), Figure 14 (Translational displacement at 2000 [rpm]), Figure 15 (Deformed mesh at 2000 [rpm]) and Figure 16 (Principal stress at 2000 [rpm]).

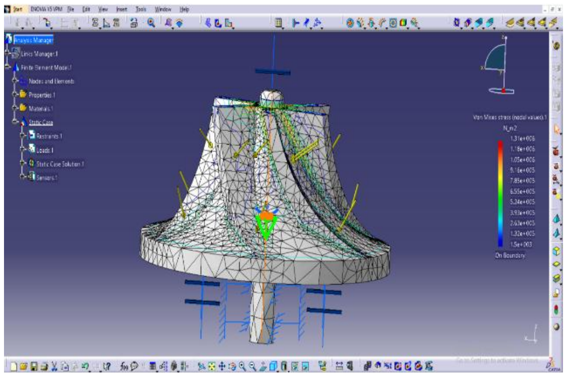

Fig. 13 Von Mises stress (Titanium alloy Ti-6Al-4V at 2000 [rpm])

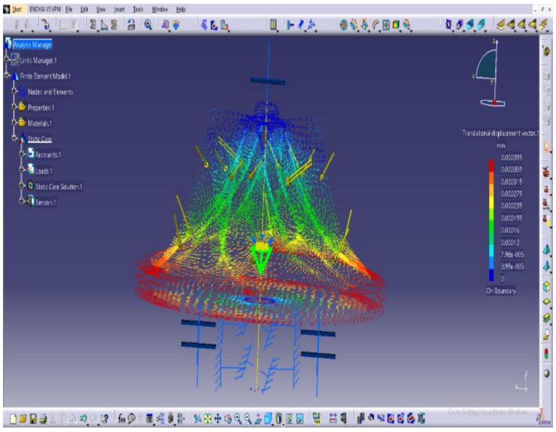

Fig. 14 Translational displacement (Titanium alloy Ti-6Al-4V at 2000 [rpm])

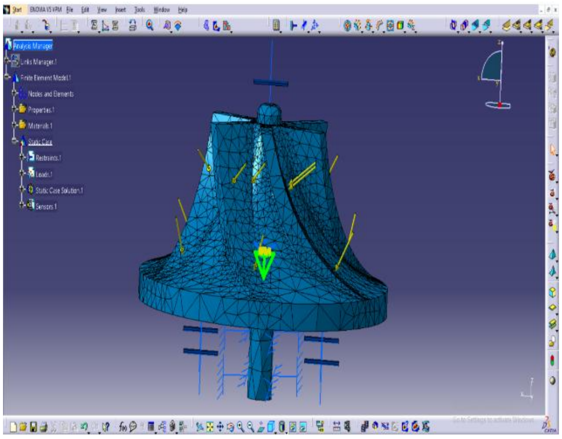

Fig. 15 Deformed mesh (Titanium alloy Ti-6Al-4V at 2000 [rpm])

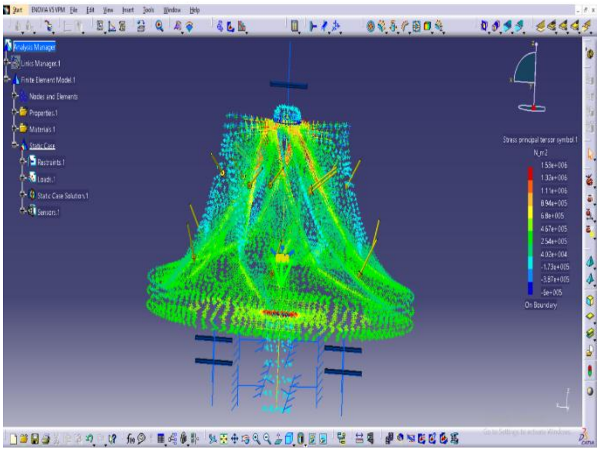

Fig. 16 Principal stress (Titanium alloy Ti-6Al-4V at 2000 [rpm])

The results from the analysis of complex part (impeller) model for different materials (titanium alloy, aluminum alloy, plastic) at 2000 [rpm] are given in Table 4.

The conclusion is once again confirmed that the Von-Mises stress for the model of the complex part (impeller) made of titanium alloy (Ti-6Al-4V) is the highest, then again follows model made of aluminum alloy (Al 6061-T6), while the model made of plastic (Polybutylene Terephthalate) has the lowest value.

If we analyze the deformations that occur in the complex part (impeller) made from these different materials, it can be noticed that once again that titanium alloy (Ti-6Al-4V) and aluminum alloy (Al 6061-T6) have similar displacements. Obviously, as we conclude previously, titanium alloy (Ti-6Al-4V) is the strongest material among these three materials.

The obtained results for Von Mises stress is once again the highest for the model of the complex part (impeller) made of titanium alloy (Ti-6Al-4V).

Once again the complex part (impeller) made of plastic (Polybutylene Terephthalate) has a Von Mises stress 1.16 times lower than the impeller made of aluminum alloy (Al 6061-T6), and at the same time has the largest displacements, at rotational speed 2000 [rpm]. However, the complex part (impeller) made of plastic (Polybutylene Terephthalate) once again satisfies the testing because the obtained Von-Mises stress is 9.03 e+005 [N/m^2], which is once again below the limit of the yield strength of plastic material (Polybutylene Terephthalate) which is 1.075 e+008 [N/m^2] (Table 1).

From these analyzes we can conclude that depending on the purpose and operating conditions of the device (machine, construction) where the complex part (impeller) will be located, we will decide what material it will be made of (Table 5).

Table 4. Results of the tested complex part (impeller) for different materials at 2000 [rpm]

Analysis	Static Analysis		
Rotation Speed	2000 [rpm]		
	Von-Mises Stress [N/m^2]	Translational displacement [mm]	Principal stress [N/m^2]
Titanium alloy Ti-6Al-4V	1.31 e+006	0.000399	1.53 e+006
Aluminum alloy Al 6061-T6	1.05 e+006	0.000585	1.11 e+006
Plastic Polybutylene Terephthalate	9.03 e+005	0.0133	8.49 e+005

Table 5. Material for manufacturing the complex part (impeller) depending of the purpose

Device in which the complex part (impeller) is used	**Hairdryer**	**Central heating pump**	**Thermal turbine**
Selected material	Plastic Polybutylene Terephthalate	Aluminum alloy Al 6061-T6	Titanium alloy Ti-6Al-4V

5 CONCLUSION

This paper shows the application of CAx technologies, in a practical example of design of CNC machine tool (CAD), virtual processing of complex part (impeller) on virtual CNC machine (CAM) and complex part (impeller) static analyzes (deformations and stress) for different materials and different rotational speeds (CAE).

The use of Computer Aided Design (CAD) enables engineers to increase the productivity by focusing on innovation, product functionality and practicality, rather than focusing on routine activities in the design process. The preparation of the technical documentation is realized in a few simple steps, very fast and with great accuracy.

The application of Computer Aided Manufacturing (CAM) is the best possible solution for companies to achieve high productivity, flexibility in the production process, high quality and production of many different products at the same time. Computer technology today is implemented at every stage of production. The use of CAD technology for product modeling, together with the use of Computer Numerically Controlled machines and the corresponding CAM software solutions for work part programming, realize an integrated CAD/CAM system.

Computer Aided Engineering (CAE) allows engineers and designers to perform a variety of engineering analyzes (stress, deformation, temperature stress, etc.) without the need for a real physical model. The obtained results help engineers and designers in optimizing the construction of the product (shape, dimensions, material, price, etc.).

The use of CAx technologies in all stages of development and production of different products, are the key factor that allows high quality production, repeatability, cost reduction and time savings.

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