Development of Polymeric Matrix Composite to Replace Grey Cast Iron in Precision CNC Machinery Structures

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Abstract: The structure of CNC machines must withstand the machining loads and have adequate rigidity to ensure the dimensional accuracy of the product. Gray cast iron is the material normally used in the bases of these machines because it has a relatively low cost, is easy to manufacture, has high compressive strength, and has a high vibration damping capacity. The objective of this work was to develop a rock particle reinforced polymer matrix composite with mechanical properties suitable for the design of precision CNC machining machine structures. Different resin and rock types were analyzed and 3 limestone particulate reinforced composites with 13%, 16% and 23% by weight of epoxy matrix phase were developed, and determinate their mechanical properties through compression tests ABNT NBR 5739/2018 standard. With the obtained values, tests were performed in a finite element software to evaluate the use of the material in the structure of the aircraft aircraft wing CNC machine. The results showed that the best mechanical properties were observed in the composite samples containing 16% epoxy, which by FEM test showed an increase in structural stiffness and a 25% reduction in the maximum deformation resulting from the application of machining loads.

Keywords: Polymer matrix composites, Limestone, Rocks, Compression testing, Face milling Machine, Aircraft wings, Finite element simulation, Material selection.

INTRODUCTION

According to Norton (2013) [1], engineering design can be defined as: “The process of applying various scientific techniques and principles in order to define a device, method or system in sufficient detail to allow its implementation”. The structure of a machine must be made taking into consideration dimensional, finishing and geometrical tolerances, such as flatness, parallelism and perpendicularity that meet the design requirements [2]. In the design of the machine tool structure the stiffness requirement is much more important than the load capacity requirement, because the stresses generated during machining and their consequent deformations are generally well below the allowable limits for various materials [3].

Rigidity is not just about how much the machine tool as a whole will deform under static loads such as workpiece weight, machining loads. This point is also characterized by how much the machine will deform when subjected to vibrations under the action of inertial forces, and dynamic loads [4].

According to Koenigsberger (2016) [5], the power capacity and the desired performance quality of the machine determine the static and dynamic stiffness requirements of its structure. However, the design cannot be based purely on structural considerations, but must also be aesthetically satisfactory, ergonomic and economically competitive.

The accuracy of the machining machine is affected by the positioning accuracy between the cutting tool and the part to be machined and the relative structural deformations between them [6].

The most commonly used material for making structures is gray cast iron. Even though low carbon rolled steel is a better material to withstand tensile, compressive, torsional and shear loads due to its higher modulus of elasticity compared to the cast iron, it has a high vibration damping capability, self-lubricating characteristics, and relatively low cost [2]. Although many processes aiming at improvements in the development of cast irons with properties more suitable for different applications have been researched [6], these materials have some advantages, which justify their wide use still today, an alternative for this application is the use of composite materials, which are artificially made materials, in combination with a naturally formed one, where the present phases are chemically different and separated by a distinct interface [7]. The properties of composite materials are a function of the properties of the constituent phases, their relative quantities and the geometry of the

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dispersed phase. The distribution and interaction of these two phases determine the final properties of the compound structure [7]. Particle-reinforced composites, which are the main object of study of this work, are formed by the matrix and the dispersed phase, which is in the form of particles. In this sense, much research has been carried out with the aim of recycling different types of materials to be used as a reinforcement phase in the development of new composites [8-10].

The matrix phase can be made from metals, polymers or ceramics. Metals and polymers are generally used in the matrix, since some ductility is desirable. The matrix is responsible for several functions, such as interconnecting the dispersed phase, acting as a means of transmitting and distributing external stresses, and protecting the dispersed phase against surface damage, as a result of mechanical abrasion or chemical reactions with the environment [11]. Among the polymer matrices, there are epoxy-based thermosets, which will be used in this work. A thermoset is a material that cures after the addition of an appropriate hardening agent, through an exothermic process [12].

Composite materials have a significantly higher inherent complexity compared to traditional isotropic materials (metallic materials). These materials have well-defined, repeatable and predictable properties from classic manufacturing processes such as casting and rolling. On the other hand, composites have their properties influenced by many factors and variables. These characteristics make the mathematical modeling of the mechanical behavior of composites more difficult and laborious, but also allow the freedom to adjust the manufacture of composite material to give it the properties that are appropriate to its needs, thus meeting a possible specific design requirement [13].

Also, polymer granite absorbs up to 8 times the vibration relative to gray cast iron, improving the resulting roughness in the machining process and also extending the life of the cutting tool used [14, 15].

Various types of fillers including metal powders, ceramics, carbons, and minerals have been explored as promising additives. Calcium carbonate, or calcite, derived from natural sources like chalk, limestone, and marble, is widely utilized across industries due to its affordability, stability, and ease of processing, imparting desirable properties such as white coloration [16]. Studies performed on polymer cementitious composite made of epoxy resin coating modified with aggregate and cementitious substrate found that the preparation process of the samples could have significantly affected the strength results and therefore, the obtained strength results are different when manually or mechanically vibrated [17].

The objective of this present study is to analyze the behavior of a rock particle reinforced polymer matrix composite material as an alternative for use in precision CNC machine structures in place of the traditionally used materials. Samples were made in order to verify from mechanical and computational tests the influence of epoxy resin variation on the recipe in favor of the reduction of the deformation of the structure of a CNC machine for aircraft wing machining, developed by Tecnodrill company [18].

MATERIALS

The properties of the developed materials were determined by compression tests and the use of the mixture rule. Below are described the materials and methods used.

An ARALDITE GY 260 BR epoxy resin and hardener ARADUR 2963 BR, both from the manufacturer HUNTSMAN, were used as matrix. For the reinforcement phase, limestone particles of different particle size were used.

Three different recipes were made, with 13% of the weight of the matrix composite (epoxy resin + hardener), one with 16% and the other with 23%, and in all cases the same amounts and proportions of particulate distribution were maintained. Table **1** shows

Table 1: Recipes Used of the Developed Composite Materials

Limestone Sizes [mm]	Mass [g]		
	Recipe 13%	**Recipe 16%**	**Recipe 23%**
0.5 and smaller	250	250	250
0.05 to 0.1	150	150	150
1	350	350	350
3 to 4	250	250	250
Epoxy Resin	150	200	300

the recipes made with their proper proportions of each phase and constituent.

METHODS

Three recipes were made by varying the percentage of epoxy resin, and on the samples of each of them were performed compression tests to determine the Young's modulus, yield strength, and based on the rule of mixtures, were obtained the other properties Poisson's ratio and density, and the shear modulus was obtained by calculation. Based on these results, the best recipe was selected to be applied in the analysis of a CNC machine structure, through a finite element software to obtain the responses of the metal structure filled with the composite material compared to one made only from welded steel.

After defining the recipes, the resin and other materials were mixed and filled into cylindrical PVC pipe forms. The samples were left for seven days before being tested for compression. In Figure **1** are shown the samples outside the PVC forms.

Figure 1: Samples prepared for the compression tests.

The samples were made to be tested according to ABNT NBR 5739/2018. The tests were performed on an EMIC model DL 20000 universal testing machine, which has a maximum load capacity of 200 kN. According to the standard the test was performed with constant loading of approximately 0.45 MPa/s, applied continuously and without shocks, at room temperature of 22ºC. The software used for data collection was TESC version 3.04. Table **2** shows the characteristics of 16% epoxy samples, which obtained the best mechanical properties.

According to ABNT NBR 5739/2018, the H/D ratio in the samples may vary between 2.02 and 1.94, and if this does not occur, a correction factor should be applied to the maximum breaking force of the test. In the tested samples, the correction factor was applied according to the norm on the already corrected rupture forces listed in the table.

To determine the density, the specific weight of the matrix was first calculated using the rule of mixtures, taking into account the specific weights of each part of the epoxy, resin and hardener, as found in the manufacturer's datasheet, being 2/3 resin and 1/3 hardener. Having already calculated the specific weight of the matrix, the same concept was applied to the composite, using the specific weight of the particulate, found in the CES software database, and the percentages of each phase, matrix and reinforcement of the composite. The properties required for the finite element method (FEM) test are the yield stresses obtained directly from the compression tests. The modulus of elasticity that was obtained from Eq. 1, where E is the modulus of elasticity, σ is the normal stress and ε is the deformation [7]. Poisson's ratio and composite density were determined by the mixture rule [4,5], presented in Eq. 2, where P_c is the property of the composite, P_p and P_m are the properties of the

Table 2: Sample Characteristics (16% epoxy)

CP nº	H (mm)	D (mm)	H/D	Factor	Area (mm²)	x2-x1 (mm)	F1 (N)	F2 (N)
1	38.21	27.53	1.39	0.95	595.25	0.259	297.63	9078.36
2	38.13	27.66	1.38	0.95	600.89	0.541	300.45	8673.24
3	38.65	27.76	1.39	0.95	605.24	0.218	302.62	8868.66
4	37.45	27.94	1.34	0.94	613.12	0.266	306.56	8731.53
5	39.54	27.75	1.42	0.95	604.81	0.237	302.40	9475.51
6	39.17	27.80	1.41	0.95	606.99	0.333	303.49	8549.39
7	39.14	27.87	1.40	0.95	610.05	0.233	305.02	9405.23
8	39.53	27.58	1.43	0.96	597.42	0.287	298.71	10009.58
9	40.01	27.83	1.44	0.96	608.30	0.176	304.15	8254.67
10	37.24	27.61	1.35	0.95	598.72	0.166	299.36	8548.04

particulate and the matrix, respectively, as well as V_p and V_m are the volumetric fractions of particulate and matrix. Already the shear stress was obtained from the properties presented above and is calculated by Eq. 3 [4], where G is the shear modulus and v is the Poisson's ratio.

$$E = \frac{\sigma}{\varepsilon} \tag{1}$$

$$P_c = P_p V_p + P_m V_m \tag{2}$$

$$G = \frac{E}{2\,(1+\nu)} \tag{3}$$

FINITE ELEMENT METHOD (FEM)

After determining the yield stress, rupture stress, modulus of elasticity, shear modulus and Poisson's ratio of the composite materials being studied, which are properties necessary to characterize the material in the modeling software, a finite element testing was performed on the structure of an aircraft wing milling machine, where stress and strain results were compared between a welded ASTM A36 structure filled with 16% epoxy composite and another ASTM A36 welded structure only. The software used was Inventor 2015 Pro, the steel properties were taken from the literature [9], and as boundary conditions, the structures were considered fixed at their support points, and the loading was done by distributing the machining loads, previously established, on the machine linear guides. Figure **2** shows the machine that is being developed by the company and on which the analyses will be performed. The equipment consists of a CNC milling machine for facing the wing surface that is mounted in contact with the aircraft fuselage. This machine was chosen for analysis due to its development stage and the opportunity to verify the benefits of using this polymeric granite composite, and to verify some advantages that the recipe, already used in other machines by the company, presents.

On the other hand, it is already known that this possible improvement adds weight and cost to the structure. The analyses were performed on a more simplified set than that shown in Figure **2**, since for the software to perform the calculations, the modeling cannot contain gaps between the parts, generating errors when generating the mesh, for example. Therefore, only the carriages and welded structures, the linear guides, the skates and the composite in the structures were considered in the simulation set.

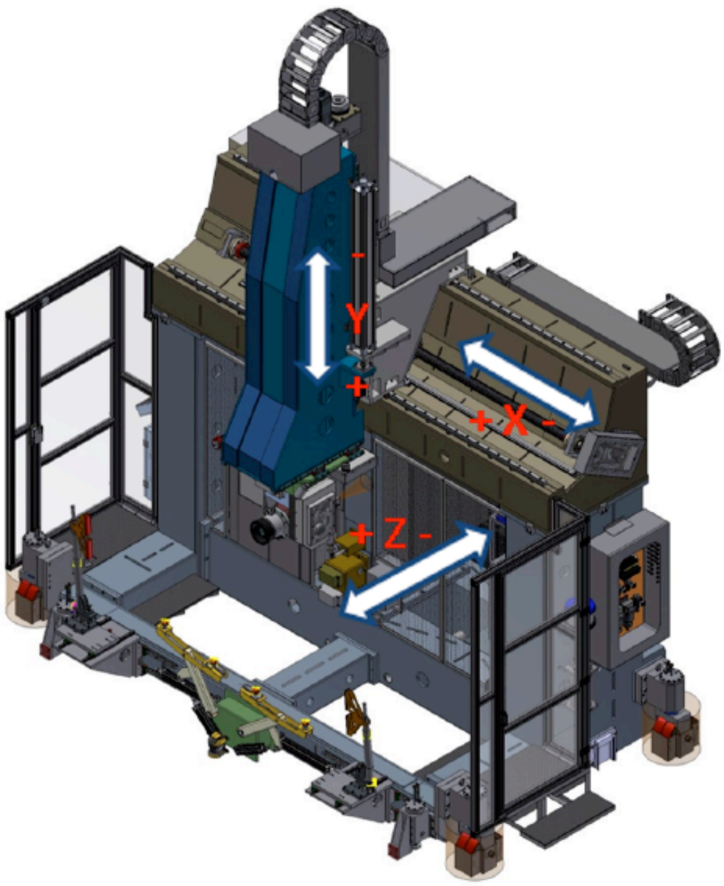

Figure 2: WingMill Facing Machine.
Source: Tecnodrill (2018)

RESULTS

The results were presented initially by checking the properties of the fabricated materials, choosing the best type of composite and applying the finite element method. According to the recipes analyzed, the material that presented the best mechanical properties was the composite with 16% epoxy resin, as can be seen in Table **3**.

Table 3: Property Comparison of the Developed Composite Materials

Epoxy [%]	E [GPa]	σ [MPa]
13	1.58	31.20
16	2.25	49.54
23	2.01	45.80

Among the evaluated properties, the Poisson's ratio and the density were determined from Eq.2, selecting the variables according to the characteristic to be obtained, and the matrix and reinforcement phase data extracted from the Cambridge Engineering Selector software database. Table **4** shows the properties obtained for the 16% epoxy sample, which were used for FEM calculations.

Table 4: Composite Properties Obtained for the 16% Epoxy Sample

Property	Value
Yield Strength	49.54 [MPa]
Young Modulus	2.25 [GPa]
Shear Module	0.87 [GPa]
Poisson's ratio	0.30
Density	2.36 [g/cm³]

As can be seen in Table 4 above, there is a value of 0.87GPa for the shear modulus of the material studied. This can be compared to a similar composite generated in the CES software, as seen in Figure 3 below.

Figure **3** above shows the graph that relates the compression stress to the shear modulus. A line was drawn approximately from where the shear modulus result of 0.87GPa, obtained by equation (6), is located. It can therefore be said that the result obtained is consistent, as it is close to others contained in the literature.

NUMERICAL SIMULATION

The results of the numerical simulations by FEM will be presented comparatively between the ASTM A36 steel only structure and the ASTM A36 steel structure filled with the composite material.

Based on Figure **4** the maximum deformation point of the structure can be verified, it is also the region where the cutting tool is mounted. The maximum stresses resulting from the ASTM A36 steel structure test were 26.42 MPa, while for the composite case it was 23.88 MPa, it is noteworthy that this maximum stress happened at a specific point of the structure, and for the most part the tension was lower.

As for the deformation in relation to the machining loads, the composite structure obtained a maximum deformation of 0.064 mm, and steel-only structure in this same situation it presented 0.086 mm, which represents a 25% reduction in the maximum deformation over machining loads. Table **5** shows the compiled results of the FEM tests.

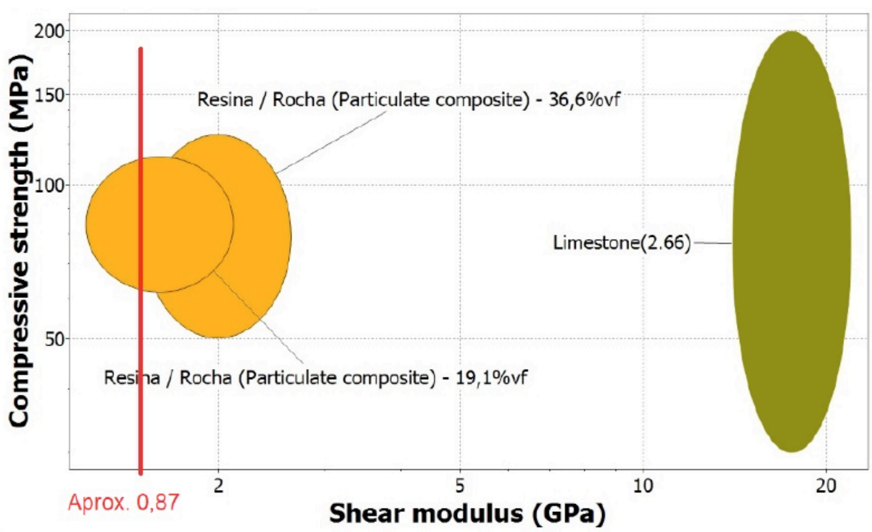

Figure 3: CES Shear Modulus Graph.
Source: Adapted from CES 2015 (2018).

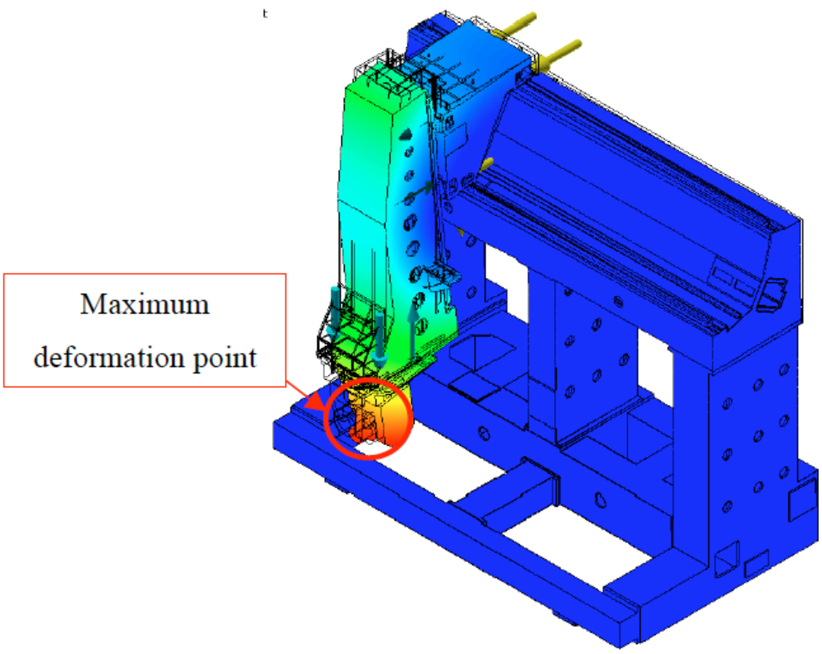

Figure 4: Maximum deformation point of the structure.

Table 5: Comparative Results FEA

Tests Developed	Without Composite	With Composite
Resulting tension [MPa]	26.42	23.88
Deformation [mm]	0.086	0.064

Regarding the weight of the machine, 8500 kg of composite material was added, which represents a 58% increase in the mass of the structure, which without the material was 14500 kg.

In order to obtain a financial overview, the cost of adding this material was calculated, considering (U$2.78) per kilogram of steel processed (raw material, welding, stress relief and blasting of parts), and (U$0.87) per kilogram of composite (raw material, mixing equipment rental, material processing and labor of the employees involved), based on previous projects. Adding the 8500 kg to the composite structure adds a cost of (U$7,500) to the project, which would be equivalent to adding 2600 kg of steel to the structure.

CONCLUSION

In this work were developed 3 types of epoxy particulate composites, with 13%, 16% and 23% of matrix phase, it was observed, through the tests and calculations to which the specimens were submitted, that the best mechanical characteristics were presented in the material with 16% of its weight consisting of epoxy.

Through the tests performed by the FEM, it was possible to see that the addition of the composite in the structure resulted in a 25% reduction in the maximum deformation generated by machining loads in relation to the structure without the composite.

Regarding the structure's manufacturing costs of the structure presented in this work, it is observed that although the addition of composite material initially represents an increase in the costs involved, on the other hand, the price of this material is lower than that of steel, since its manufacture is relatively simple, and can be performed by the company. Based on the idea that through the project the use of composite material is already foreseen, the steel consumption can be reduced, which would lead to a reduction in the overall manufacturing costs.

Thus, from the studies and tests performed on the epoxy particulate matrix composite, the results indicate that this material has excellent characteristics to be applied in machining machine structures. In addition to presenting an increase in the stiffness of the structure, proven by the reduction in deformation resulting in FEM tests. In addition, as can be seen from the literature, the material absorbs up to 8 times the vibration relative to gray cast iron, improving the resulting roughness in the machining process and also extending the life of the cutting tool used.

During the development of the work, it was observed that the final results can be improved by refining the composite fabrication processes, such as using a vibrating base at the material filling stage to reduce the air bubbles generated in the process, making the material more homogeneous.

CONFLICTS OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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