DEVELOPMENT OF THE CONCEPTUAL DESIGN OF AN AEROSTATIC POROUS BEARING USING TRIZ (INVENTIVE DESIGN METHODOLOGY)

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Abstract. *This work presents a methodology based on TRIZ for conceptual design of porous aerostatic bearings applied to high speed air bearing spindle, as found in dicing technology machines. The trend towards miniaturization has increased the demand of microcomponents. The use of TRIZ during the conceptual design allows one to identify, faster and systematically, similar constructive solutions, directing the search of creative approaches for the technical problem. In this context it is proposed a design methodology focused on conceptual design to aerostatic ceramic porous bearings. The contradiction matrix technique, considering the main prefixed design parameters, indicated that the constructive solution using porous material (ceramic) in bearings lubricated with air film are more adequate for high speed ultra-precision machines. The concept of component was validated through the construction of a physical prototype. Experiments have been conducted to verify the maximum load applied to radial porous aerostatic bearings, considering the load capacity of the ceramic porous material developed. The ceramic porous bearings were manufactured with internal diameter and width of 11 mm, coupled inside steel bushes. The set was assembled on a shaft with length of 200 mm subjected to high rotating speed up to 10.000 rpm.*

Keywords*: TRIZ; creative process; porous ceramic; aerostatic bearings.*

1. INTRODUCTION

The present tendency of miniaturization of the equipments and devices is accelerating the development of microcomponents applied to different areas of the human knowledge. The manufacturing of machines and components as dicing, small bearings, micro-milling, and capillary structures are technological examples of the demand in the nanotechnology area. New options of material and technology of mechanical components are essentials to the design of ultra precision machines, specifically dicing machines.

The performance of an ultra precision machine tool depends on the static and dynamic behavior of the mechanical subsystems that compose it. Among them, the bearing-shaft pair is fundamental to the quality of the manufacturing process. Such important parameters, as precise control of rotation, the repeatability of movements, and the machine load capacity, strongly depend on the bearing-shaft pair characteristics (Balestrero, 1997). According to Cheng and Rowe (1995), the selection of the type of bearing basically depends of the type of application and the demands of operational parameters (load capacity, stiffness, high speed, low friction, repeatability of movements and resistance to high temperatures).

Considering these design characteristics the lubricated air bearings have some important advantages when compared to other kinds of bearings such as the oil-lubricated and rolling bearings. These advantages include low heat generation, high precision of motion and practically no contamination (Hamrock, 2004). Externally pressurized air bearings held characteristics of low noise, friction reduction and low heat generation, load capacity and stiffness sufficient for applications that require high precision in high speeds (Powell, 1970). Due to the low viscosity of the air, externally pressurized air bearings tend to be unstable. The choice of restriction type in the air feeding can reduce this problem and define the operation range and load capacity of the bearing.

An alternative design construction to improve the stability of the air film and to increase the bearing stiffness is the use of metallic porous material, e.g. graphite or non metallic materials, e.g. structural ceramic. This design solution presents some additional advantages, such as low manufacturing cost, low material density, low wear due to abrasion, high dimensional stability, high chemical inertia, and tend to result in bearings with equal, or even higher, stiffness than those built with pockets or inherent orifices (Nicoletti and Silveira, 2007). Another important property of the ceramic material is the machinability, where no ductile deformation and porous re-covering occurs, because of the open porous characteristics. A study about static behavior was made by Nicoletti and Silveira (2007), through modified Reynolds equation whereas considered the Darcy´s equation of porous media applied to air journal bearings.

The objective of this work is the development of conceptual design of the aerostatic ceramic porous bearings based on TRIZ methodology. These bearings can be applied to spindle of the dicing machines which can be used for manufacturing of micro components and slicing of biomaterial samples.

1.1 TRIZ METHODOLOGY (The Theory of Inventor's Problem Solving)

The creative process is the ability to solve problems with competence and originality. The ideas and its "products" must be originals, adaptable (to design function) and completely development capable. The creative thinking (or divergent thinking) is more adequate to search new solutions, in opposition to convergent thinking, that looks for a well-known solution. According to Back *et al.* (2008) the TRIZ, Russian acronym for the *Teorija Rezhenija Izobretatel´skisch Zadach,* is a design methodology or a philosophy that looks for an ideal solution to a problem inside of the knowledge area that allows its systematic and progressive evaluation.

The research on the TRIZ, or systematic innovation, starts considering the hypothesis that there are inventive universal principles that form a base for innovative solutions and these principles could be identified and codified, thus one can have a systematic approach. In 1946, Altshuller proposed the TRIZ methodology with focus in the systematic study of the technical problem, or hard TRIZ; due to high amount of effort demanded by the intuitive methods that, sometimes, did not supply viable solutions. Altshuller found this systematic approach through high survey of the patents' number to determine a sort of solutions for problems that leads to inventions. An inventive solution is the one that solves a technical contradiction, e.g. to increase the strength of a material and to reduce its weight, or to solve a physical contradiction. A technical contradiction is an inverse dependence between parameters or characteristics of a machine or technology and the physical contradiction is an opposition in physical requirements of an object. Some engineering parameters such as load capacity, weight, cost and material can generate conflicting situations.

In the TRIZ there are 39 engineering parameters defined, obtained from patents researched by Altshuller (Carvalho and Back, 2001). The engineering solutions are classified in modifications and improvements. These parameters are shown in Table 1(a). The referred parameters were identified and describes through of repetition in many knowledge areas to solution of engineering problems. Altshuller concluded that there are laws of technical system evolution, according which solutions found can be generalized, and the more creative inventions were the ones that have solved some kind of technical or physical contradiction. The TRIZ methodology is based on following elements:

- *The Ideal Final Result and Ideality* that is a conception where the systems (technical or not) evolve, in the sense of increasing the main functions or usefulness and to reduce useless and harmful;
- *Contradiction,* which is the knowledge that the evolution of the technical systems leads to the solution of the contradiction composed in the system;
- *Resources,* which means that the problem is solved with the own problem, by a reconfiguration of the elements of the problem itself;
- *Systematic* – is the idea which is possible to look at a context involving time, space and interactions,
- *Functionality:* that consists in modeling of the real elements from problematical situation and the solutions in the level more abstract for the functions.

Altshuller found a pattern, according which the solutions described in the patents were obtained using certain principles to resolve the contradictions or conflicts between engineering parameters, these principles were put together and named 40 Principles of Invention or Method of Inventive Problems (MIP) (presented in the Figure 1(b)). The MIP is the method of TRIZ more applied to conceptual design and its inventive principles are heuristically obtained from generalization or classification of solutions repeatedly used in the creation, development and improvement of the technical systems of different areas based on patents. The fastest way to use the inventive problems technique consists in the analysis of each principle to try to apply it in the improvement of the technical system.

Table 1(a) – Engineering parameters (TRIZ) Altschuller, 1969 *apud* Back *et al*. 2008).

Number	Engineering parameters	Number	Engineering parameters
1	Weight of moving object	21	Power
2	Weight of stationary	22	Loss of Energy
3	Length of moving object	23	Loss of substance
4	Length of stationary	24	Loss of Information
5	Area of moving object	25	Loss of Time
6	Área of stationary	26	Quantity of substance
7	Volume of moving object	27	Reliability
8	Volume of stationary	28	Measurement accuracy
9	Speed	29	Manufacturing precison
10	Force (intensive)	30	Object-affected harmful
11	Stress or pressure	31	Object-generated harmful
12	Shape	32	Ease of manufacture
13	Stability of object	33	Ease of operation
14	Strength	34	Mantenability
15	Durability of moving object	35	Adaptability or versatility
16	Durability of non moving object	36	Device complexity
17	Temperature	37	Difficulty of detecting
18	Ilumination intensity	38	Automation level
19	Use of energy by moving	39	Productivity
20	Use of energy by stationary		

Table 1(b) – Inventive Principles (Altshuller, 1969).

1. Segmentation	2. Taking out
3. Local quality	4. Asymmetry
5. Merging	6. Universality
7. Anti-weight	8. Nested "doll"
9. Preliminary anti-action	10. Preliminary action
11. Beforehand cushioning	12. Equipotentiality
13. 'The other way round'	14. Spheroidality - Curvature
15. Dynamics	16. Partial or excessive actions
17. Another dimension	18. Mechanical vibrations
19. Periodic action	20. Continuity of useful action
21. Skipping	22. "Turn Lemons into Lemonade"
23. Feedback	24. "Intermediary"
25. Self-service	26. Copying
27. Cheap short-living objects	28. Mechanics substitution
29. Pneumatics and hydraulics	30. Flexible shells and thin films
31. Porous materials	32. Color changes
33. Homogeneity	34. Discarding and recovering
35. Parameter changes	36. Phase transitions
37. Thermal expansion	38. Strong oxidants
39. Inert atmosphere	40. Composite materials

According to Slocum, *et al*. (2009), the basic techniques used in the TRIZ are: contradiction matrix, the Ideal Final Result (IFR), Resources, ARIZ algorithm and Substance-Field Analysis that represent procedures to search for solutions presented by Figure 1.

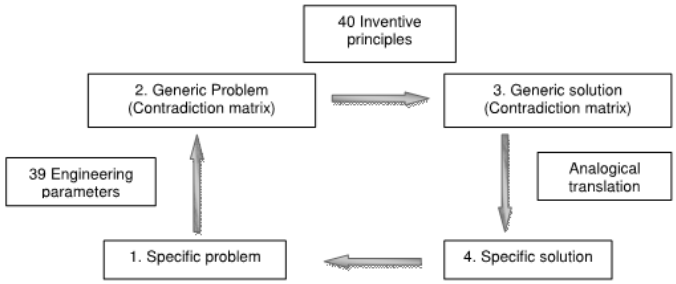


Figure 1 – TRIZ Flowchart (from Slocum *et al*. 2009)

2. DEVELOPMENT OF A CONCEPTUAL DESIGN OF AIR BEARINGS APPLIED TO SPINDLE OF ULTRAPRECISION MACHINES USING TRIZ METHODOLOGY

2.1 Problem definition

The problem is concentrated in the high requirement of the performance parameters of an ultra precision machine, that is directly related to functional basic characteristics such as: precision, stiffness, repeatability of movements, load capacity; that are related to static and dynamic stability of its components.

In machining process for components with small width, as found in dicing saw, the vibrations must be minimize in order to obtain an accurate cutting. Thus, it is possible to identify problems related to tribology field. Tribology can be defined as a science that includes the understanding of the interaction between surfaces with relative movement, as well as the practices related to mechanical components.

The bearings are machine elements that support the shaft, restricting its movement and reducing the friction between the contact surfaces, in this case a shaft with journal and fixation elements is used. The speed can be increase until 40,000 RPM according to the spindle drive, tool and material cutting speed and by limitations of the rotation of the bearings. The friction between the fixed and mobile elements of the pair shaft-bearings are restricted by spindle speed. If the speed overshoots 60,000 RPM, excessive heat is generated by friction that can lead to the catastrophic failure of the system. If the system (tribological pair shaft-bearings) can be optimized, new reliable operation range can be reached, contributing to increase quality in the production.

2.1.1 Ideality

Ideality is an ideal solution to a system. The local ideality or ideal final result is the description of a status after the solution of a specific problem based on the needs of the customer and not necessarily the technical restrictions to implement the solution (Demarqui, 2005). The "Ideal Final Result", defined initially in TRIZ, represents a perfect result where it is possible to obtain all useful functions without aggregating any negative effect. This condition represents a technical system with weight zero and null volume. Furthermore the system does not demand additional costs; does not use any type of energy nor produce pollution.

In the real condition, these concepts guide the search of the solution, specifically in the start process of the inventive problem solution when the solutions obtained by this technique are evaluated. The bearing, which is a part (subsystem) of the spindle system, as element of union between mobile part (shaft) and fixture surface (journal) must performance its functions to support the shaft (absorbing inherent forces generate during the process), to avoid the high friction between the surfaces and to limit other movements with minimum energy dissipation. In order to make the real technical system near to the Ideal Final Result it should be indicated to remove or to minimize the harmful function represented by friction and heat generated in the subsystem (reducing the energy consumption) maintaining the useful functions. This condition can be reached producing a bearing with material or technology with low friction coefficient.

2.1.2 Present contradiction of the system

The Michael's dictionary defines contradiction as "incoherence between current and previous affirmations, opposition between two proposals, from which one excludes necessarily to another one". For methodology TRIZ: a contradiction is a conflict between two requirements mutually exclusive, considering same characteristics of an element in the system.

The use of an inventive approach implies in a problem that do not suggest any way known of solution and involves one or more contradictions. Thus, if there is no contradiction, the problem has no inventive approach and it cannot be solved by TRIZ methodology. From the classic physics it is possible to define friction as natural force acting parallel to surfaces in contact and between then. In opposition there is the force that tends to put the parts in relative movement.

The lubricants are substances that interpose between surfaces in relative movement, forming a film. This film avoids or minimizes the wear, substituting the dry friction by viscous friction. The viscous friction occurs between the layers of the lubricating fluid (phenomenon in microscopic scale). The mechanical energy consumed to win the viscous friction inside the film (oil, air or magnetic) warms the system resulting in heating (energy loss or consumption) that should be managed guarantying that fundamental characteristics are maintained during the operation condition. The Figure 2 presents a dicing machine that uses the air bearings in the spindle.

The main problem is to avoid the wear between the surfaces. The wear can be defined as a cumulative undesirable alteration on the initial dimensions, resulted from a gradual removal of discrete particles from the surfaces in contact due to mechanical abrasion. For the displacement occurs between two surfaces in contact it is necessary to apply force enough to win the friction resistance and for the continuity of the displacement (slip) the force must be maintained, applying energy to the system. This energy is distributed in the system as elastic deformation, wear particles formation, emission of acoustics energy and heat (in the interface of the surfaces in contact, increasing the temperature above of the ambient temperature).

The present contradiction in the system can be defined as a technical contradiction. The contradiction in this case study is "if the speed of shaft increase, the production increase, but the friction generated between surfaces in contact rise the temperature too", generating heat and wear of surfaces in contact. The problem can be reorganized and be declared as: "The speed and production should be increased, but the friction and its consequences (heat and wear) must be restricted."

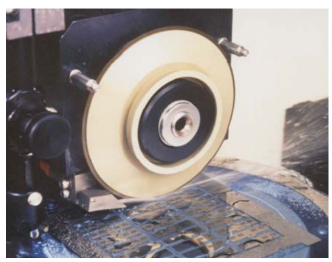


Figure 2 – Dicing Saw (GSI – Westwind, 2008)

The pair shaft-bearing is a fundamental component in the design of high speed spindle. However, it is very difficult to choose and/or concept an adequate bearing. There are different physical mechanisms that lead to different geometries for bearings offering advantages and disadvantages depending on the application. There are properties that must be considered in the choice process of bearing during the design development and operation conditions such as: maximum speed, applied load, accuracy in the movements, stiffness, type of lubrification as well as manufacturing, cost, impact on environment, maintenance program.

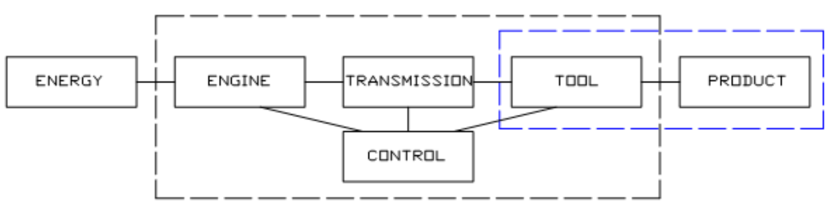


Figure 3 – Minimum structure for technical system.

In general, the technical systems are developed to performance one essential useful function and other desirable ones. These functions can be defined as a principal positive function and secondary positive functions. The principal function determines the purpose of the system. Other functions of the system are the secondary useful functions which add value to the system without changing the functionality of the principal function as showed by Figure 3.

There are also the undesired functions (negatives) which are called negative functions, which can be an obstacle to the system development. The negative functions reduce the efficiency level of the positive functions of the system or lead to other undesirable negative effects in the system or sub-systems. According to this, a technical system is defined as a set of elementary functions performed in a specific sequence. The functional modeling helps in the description of the possible methods to represent and to improve an elementary function, defining elementary actions in the operational zone or system frontier.

A bearing can be represented as a set of elementary functions, for example: 1. "to support shaft" (as much in the radial direction as in the axial one); 2. "to facilitate the rotation movement" (reducing the friction); 3. "to restrict other movements, performed in a specific sequence"; 4. "to sustain operational conditions" (continuous movement). Thus, the "bearing-shaft system" can be represented, according to TRIZ, through basic elements: a) a tool that performs the principal function, in this case the bearing; b) an element or component related with the tool, in this case the shaft and c) environment represented by the frontier by which the tool and object are related. The Figure 4 shows the mean components of the bearing.

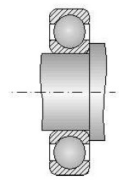


Figure 4 – Example of a bearing: Ball bearing

2.2 Algorithm for Solution of Inventive Problems (ARIZ)

There are some techniques to eliminated the contradiction formulated using the TRIZ methodology, such as: 40 inventive problems, contradiction matrix, Substance-Field Analysis an ARIZ, that can be used together. The ARIZ has changed since 1956, with 10 different updates of the algorithm. Based on the recent version, there are 9 steps (around 40 procedures to solve the problem). In this work there were considered the following steps:

A. Problem analysis;
B. Model analysis of the problem;
C. Ideal Final Result and determination of the physical contradiction;
D. Mobilization and resources utilization;
E. Knowledge base use;
F. Change or re-formulation of the problem;
G. Method of analysis that solves the contradictions;
H. Used of solutions obtained;
I. Analysis of steps to lead to the solutions.

The initial engineering problem was changed in a model using operators: a technical contradiction between two elements and the function of "X" element that must be solved. Then, this problem model is developed in the direction of Ideal Final Result.

2.2.1 Problem analysis

The main objective of this first step is to make clear the situation of the inventive problem by constructing an Innovative Situation Questioner (ISQ). The ISQ consists of a set of questions that gather all the necessary information about problem and is an integrated tool of the ARIZ (Algorithm of Inventive Problem Solving) a procedural method of the TRIZ.

The ARIZ helps to define the problem through of survey of a high numbers of information support which is supplied by a knowledge base, that includes a system of standards for the solution of inventive problems; engineering effects (physical, chemical, biological, mathematical and particularly geometric); techniques for the elimination of contradictions (inventive principles) and methods for the application of resources of nature and technology. The ISQ is composed by questions set to assist in the definition of the status of the problem from the new point of view. The questions are not necessarily orientated for engineering but are selected and listed considering innovative thinking from others human knowledge areas.

A.1 Questioner of Innovation Situation (ISQ) (Developed by Kishinev School of TRIZ)

A.1.1 Information about system

i) System's name: Bearing;
ii) Principal useful function: to support the shaft facilitating the speed rotation (reducing the friction) and to limit others movements;

iii) Present or necessary structure of the system: the bearing is a component of the spindle as a machine element of joint between a mobile component (shaft) and a fixture component (journal). The bearing must supply the functions: to support the shaft (absorbing the inherent forces during the operation); to avoid or reduce significantly the friction between the shaft and journal and to limit movements, without dissipation of energy and using a small space;
iv) System functioning: machine element to support and lead the shaft having the characteristics to reduce the friction originated by relative movement of rotation between the fixture and mobile parts joint by it;
v) Environment of the system (environmental condition around system): the system interactions with air and its source of energy to operate that is a motor (power generation).

A.1.2 Substance resources

The substance resources in the present system are: shaft, journal, bearing, air, humidity, heat, lubricant, material of bearing and shaft, others material of the contact.

i) Field resources - the present field resources are: the mechanical field, which supports the shaft and avoids the other movements originated by the forces applied during the operation conditions and that creates the friction between surfaces; the thermal field, that is generated through friction and the gravitational field;
ii) Space resources: the space resource is the volume occupied by bearing system (inner and outer of bearing);
iii) Time resource: the time resource is the anterior and during of the operational process;
iv) Information resource: there is no information resource;
v) Functional resources: the functional resource is the mechanical function whose journal and bearing accomplish, which is to support the shaft, maintaining it rotating with minimum effort during the operation condition (in this case, machining process).

A.1.3 Information related to problem condition

i) Improvement necessary in the system related to the function that must be eliminated: the improvement necessary is the increase of the rotating speed of the shaft to increase the cutting speed to make the system more productive bringing high quality to the machined components. Other improvement to be achieved is the machining quality represented by the stiffness of the pair shaft-bearing.
ii) Mechanism that causes the system limitations: the limitation of the system is the rotating speed, demanded to work with fragile materials like the ones used in nanotechnology and biomaterials that need high rotating speed to guarantee structural quality of the machined component.
iii) Undesirable consequences of the limitation: the friction between the fixture surface (shaft) and the mobile one (journal) causes a degradation in the system (heat and wear);
iv) Description of the problem: previous studies were made where the main objective were to increase the rotating speed, to reduce the friction, to improve the accuracy of the movements of the machine and to extend the bearing useful life. There was a gradual development and use of technical specifications since sliding bearing applied for low velocities, Ball bearings applied widely in industrial applications, bearings lubricated with oil and air and magnetic bearings.
v) Other problems (secondary) to be solved: unknown until the moment.
vi) Other systems that have a similar limitation: other systems that have similar problem were not identified.

A.1.4 Alterations in the system

i) Allowed alterations in the system: the system must perform the designed functions using available technology.
ii) Limitations related to alterations in the system: the change in the system must be viable technologically without increasing the production costs.

A.1.5 Criteria to choice the solutions concepts

i) Technological characteristics desirable: the system must be of manufacturing complexity and assembly equal or easier than present system.
ii) Economic characteristics desirable: The system should show economic advantages making interesting the technology change.
iii) Initial chronogram: A development period must be established; in this case the initial results (prototype) must be obtained in a period of 12 months.
iv) Innovation level desirable: the system must operate in an interval of rotating speed greater than the present systems, offering high stiffness, better accuracy in the rotating motion and inferior cost when compared with commercial bearings.

v) Others: The system must fit in a small place.

A.1.6 Ideal Final Result

The system must have a simple manufacturing and assembly solution in relation to present bearings used in ultra-precision machines.

A.1.7 Description of the previous studies to solve of inventive problem

i) Previous study: Previous studies to improve the rotating speed of the bearings improved some aspects of bearings for application in the ultra precision machines, especially aerostatic bearings in which were changed the geometry of the orifices and pockets to improve the air distribution in the film. But the cost and reliability still limitations in this kind of the bearing.

A.1.8 Structure of the problem

In order to reduce the investigation area it is necessary to change an "initial situation" in a "specific problem". The initial situation is a situation where some undesirable characteristics or properties (harmful) are chosen. An initial situation can be changed in a specific problem introducing (or removing) some restrictions. The functional tree, showed in the Figure 5, establishes the relationship between the main and auxiliary functions of the system and classifies them in kinds of the problems.

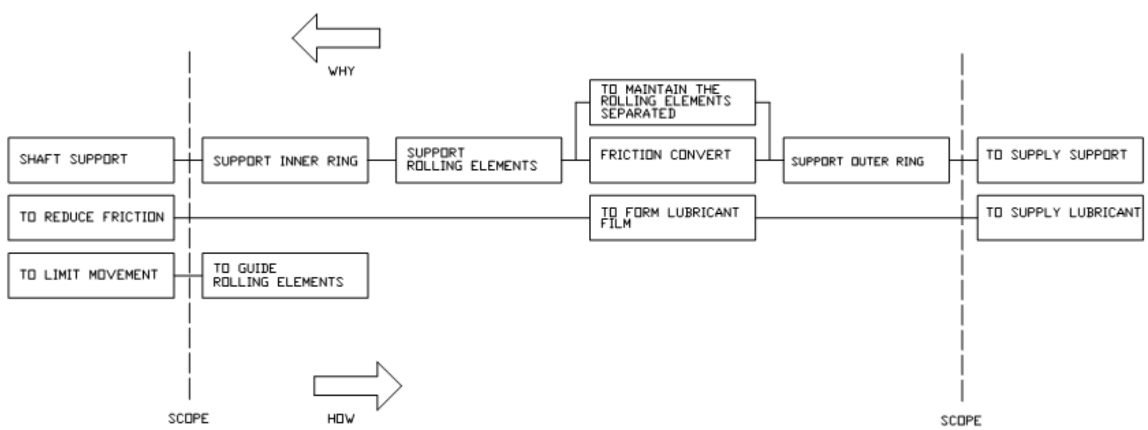


Figure 5 – Functional Tree of the "Bearing System".

Mini-problem in the system: the solution must improve the conditions of the elements that compose the original system without too much modification. According to definition "the function demanded must be obtained with minimal alterations in the present system". Then the solution should present ease implementation.

Mini-problem of the bearing: a technical system that supports the shaft, allowing its rotating speed (reducing the friction) and restricting motion that causes instability in the system. In the case of ball bearings, the elements are uniformly distributed through of a ball cage, confined between two rings, one fixed and other in motion.

Maxi-problem in the system: the solution found is not trivial, implying in maximum alterations in the system (only the function is maintained). According to definition "new concepts are exigent, but the design function remains the same in the system." Then the solution concepts are difficult to implement.

Maxi-problem of the bearing: a technical system that supports the shaft, allowing its the rotating speed (reducing or eliminating the friction) and restricting the motion that causes instability in the system, including an extension of the contact area around the shaft and the seat bearing. The system can have two lateral sides to limit axially the bearing.

A.1.9 Indicate the technical contradictions (TC-1 and TC-2)

TC-1: IF [increment the velocity] THEN [increment the production], BUT [increment the friction, wear and heat generation of the bearing].

TC-2: IF [the velocity decreases] THEN [the production decreases], BUT [the friction, wear and heat generation of the bearings decreases], situation do not allowed.

A.1.10 Identify the conflicting elements: represented by three elements:

a) A tool that performs the principal function: the bearing;
b) An object to be processed: the shaft;
c) Environment in which the tool and the object are inserted: interior of the spindle.

A.1.11 Selected analysis model

TC-1: IF [increment the velocity] THEN [increment the production], BUT [increment the friction, wear and heat generation].

A.1.12 Increase the conflict

If the velocity of the bearing is very low, so (-) the production will be reduced, but (+) the bearing will heat a little.

If the velocity of the shaft is very high, so (+) the production will be increased, but (-) the friction will be high.

A.1.13 Apply the standard tools to solve the conflict in the system

From the technical contradiction definition it is applied the Matrix of Contradiction.

2.3 Matrix of Contradiction

The 40 inventive principles and the matrix of contradiction are considered the accessible useful tools of the TRIZ. The matrix of contradiction contains 39 generic engineering parameters and 40 inventive principles to solve the contradictions, presented in the Table 1. The matrix of contradiction is a tool that allows a comparison from a specific problem in study at the present time with a generic problem that has been previously solved. This condition illustrates a form of storage of knowledge for solution of problems and provides the reuse of this knowledge in other situations.

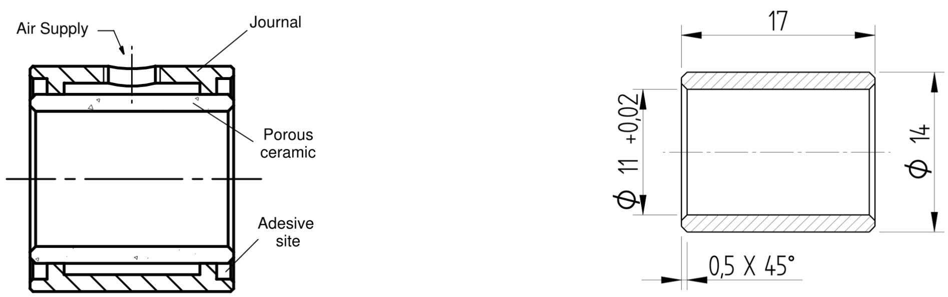
To use the matrix of contradictions it must be identified the contradictions techniques (TC-1) involved translate them into engineering parameters and then localize them in the matrix of contradictions. The inventive principles that produce greater potential of application (generally are chosen two to four principles), were used previously in the solution of similar contradictions.

The technical contradiction is that: if speed rotating of the shaft increases, the friction between surfaces in contact increases, condition that generates heat and wear in the surfaces interface.

The parameters representative of the problem are: Speed (9); Stability of the object (13) for wear; Durability of the moving object (15); loss of energy (22) to energy dissipation; loss substance (23) for wear; quantity of substance (26) for wear and productivity (39). To solve the described problem is possible to combine the parameters more representative to solution. The feature that must be improvement related to parameter engineering of number 09 (Speed) and the feature that does not degrade is the number 13 (Stability of the object). The four inventive principles associated are: Segmentation (01); Mechanical Vibrations (28); and Homogeneity (33) and composite materials (40). A promising principle is the number 28, indicating the change of the mechanical system or change the mechanical system for a field system, which can be fluid film or magnetic or electric or electromagnetic force, in order system to reduce the friction between shaft and bearing. The problem can be described as: the feature that must be improvement is the number 15 (Durability of moving object) and the feature that had not degraded is the number 13 (Stability of the object). The three generic principles correspondents are: Local quality (03); Inversion (13) and changes in the parameters and/or and properties (35). The promising principle in this case is the number 35, which suggests change the state of the object that can be defined as change the hardness, the density and/or surface covering, or else to obtain a porous ceramic structure. From this study using TRIZ methodology were developed a set of samples with different with incorporation of pore-former agent (sucrose) with concentrations of 35 to 55% obtained with different times of milling. The estimation of the porosity and its respective permeability allow the obtaining of coefficients of viscous and inertial permeability of the material that is fundamental for the design and manufacturing of aerostatic bearings with porous surfaces as well as the homogeneous distributions of the pores in the alumina matrix. These characteristics were reached from of a sample with 55% of induced porosity and coefficient of viscous permeability (k_1) of the 6.81×10^{-12} m^2 and coefficient of inertial permeability (k_2) of the 1.2×10^{-4} m. The determination of the pore size and distribution were analyzed by Scanning Electron Microscope (SEM) and Mercury Porosimeter. The material has a media porosity round 26.26% and superficial area of the 2.304 m^2/g. The value obtained for k_1 contemplates the minimum values of the viscous coefficient permeability establishes in the review of literature (Silveira et al., 2006).

3. Bearing design and experimental test

It was designed aerostatic radial ceramic porous bearings to the shaft with diameter of 11mm. Each bearing is composed by bushes manufacturing with inoxidable steel (jacket) and a porous ceramic element (radial bearing). The two elements are assembled and adhered with epoxy resin. The Figure 6(a) showed the bearing design and the Figure 6 (b) is a technical design of the ceramic bushing whose 3 mm excesses are used for fixation in the assembly and its permeability is not considerable. The bearings were assembled on shaft of the 200 mm of the length. The Figure 7 (a) and (b) presents the prototype conceived to validate the TRIZ methodology and the porous material developed. The process to obtain the aerostatic porous bearing were: development and manufacturing of porous material, that was isostatic pressing on the radial format following of green machining to obtain the design dimensions and finally the bearing was sintered. The aerostatic bearing was supplied to the air pressure of the 8 kgf/cm$^{2.}$ The objective in this study is establishes the limit load that exceed the clearance of the 0.02mm, in the porous ceramic bushing.



a) Bearing design b) Ceramic bushe.

Figure 6 – Design of the aerostatic bearing with ceramic porous bushing.

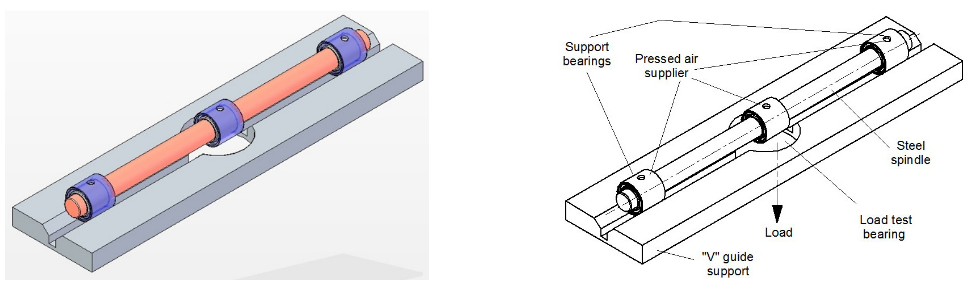


Figure 7 – Prototype obtained from TRIZ methodology.

A weight was position in the middle bearing (Figure 8) to verify if the induced porosity was sufficient, in order to obtain the minimum porosity to form a stable air film and support the shaft. In the runs, there was an effective crossing of the air through the porous structure (alumina), with formation apparently uniform of the lubricant air film. Using a pressure air supply of the 6 kgf/cm^2, the system supported a static load of the 10 N, when there was contact between shaft and bearing.

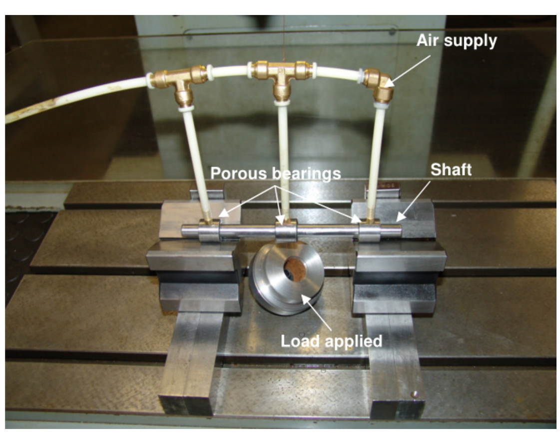


Figure 8 – Initial prototype using TRIZ methodology.

3. CONCLUSIONS

The development of the TRIZ methodology with the ARIZ lead systematically, through of joined between engineering parameters and inventive problems to a design solution focused for bearings applied to spindles. The methodology indicated that a change in the hardness, the density and/or surface covering can reduce of heat generation and friction maintaining or increase the speed rotating. Together with the previous studies about air bearings and structural ceramic the design solution was the development of the porous ceramic structure with physical characteristics to substitute metallic bearings where the supply air is made through of orifices and pockets or some applications with porous insert. The approach using porous ceramic to manufacturing of the air bearings in relation of porous metallic structure offers significant advantages such as: high stiffness and hardness of the ceramic material makes possible the grinding, without the strain and block of the micro porosity of the surface. The material developed will be improvement as well as the system of air supply to make more uniform the air distribution in the clearance. Finally, the permeability obtained with 55% of the pore former-agent was adequate and functional to manufacturing and operation of aerostatic bearings in this first prototype verifying a load capacity of the 10 N. These studies will continue with an improvement of the set up and its instrumentation to estimate the static and dynamic behavior comparing theoretical model previous developed to aerostatic porous bearing.

3. ACKNOWLEDGEMENTS

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4. REFERENCES

Back, N.; Ogliari, A.; Dias, A.; da Silva, J.C. “Projeto integrado de produtos”. Editora: Manole. 2008.

Balestrero, L.A.P., 1997, “A evaluation of aerostatic bearings for machine tools: study and dimensioning of a spindle shaft”, São Carlos: Univesidade de São Paulo, Escola de Engenharia de São Carlos, Departamento de Engenharia Mecãnica (D.Sc. thesis – in Portuguese). 1997.

Carvalho, M.A.C.; Bach, N., 2001, Uso de conceitos fundamentais de TRIZ e do MPI, no desenvolvimento de problemas. “3º. Congresso Brasileiro de Gestão de Desenvolvimento de Produto.” Florianopólis, SC, Brasil.

Cheng, K., Rowe., 1995. A Selection Strategy for the Design of Externally Pressurized Journal Bearings. “Tribology International”, Vol 28. No. 7, pp. 465-474.

Demarqui, E., 2005, TRIZ – “Theory to problem solution inventive applied to process planning in the automotive industry”. São Paulo: Universidade de São Paulo, Escola Politécnica, (M.Sc. dissertation – in Portuguese).

Hamrock, B.J., Schimid, S.R., Jacobson. B.O., 2004, “Fundamental of Fluid Film Lubrication”. McGraw Hill Co., New York, 750p.

Nicoletti, R.; Silveira, Z. C.; Purquerio, B.M., 2007, Dynamic characteristics of aerostatic ceramic porous bearings. “In: Proceedings of the XII International Symposium on Dynamic Problems of Mechanics (DINAME 2007)”. Ilha Bela, SP, Brazil.

Powell, J.W., 1970,”Design of aerostatic bearings.” The Machinery Publising CO. Ltd. 273p.

Silveira, Z.C; Purquerio, B.M.; Fortulan, C.A., 2006, Design, manufacturing and characterization of ceramic porous strutuctures applied to aerostatic bearings. “17o. CBECIMat, 17o. Congresso Brasileiro de Engenharia e Ciência dos Materiais.” Foz do Iguaçu, PR.

Slocum, M.S.; Domb, E.; Lunderg, C., 2005, Solution Dynamics as a function of resolution method (physical contradiction v. technical contradiction). “*The TRIZ Journal*” http://www.triz-journal.com/.

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