TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 67, Issue Special IV, August, 2024

PRELOAD TESTING SYSTEM FOR ANGULAR CONTACT BALL BEARINGS USING SHAPE MEMORY ALLOY MODULES

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Abstract: *The preloading of bearings, particularly in industrial machinery, is critical for ensuring reliable operation and preventing premature failure. While established methods exist for maintaining proper preload, this paper presents a variation of constant pressure preload systems. This approach is suitable for situations where traditional methods are costly to implement initially or incur high operational expenses during maintenance. The proposed solution involves employing disc-shaped springs made from shape memory alloys (SMAs), tailored to specific applications. SMAs regain their original shape when subjected to specific stimuli, often involving temperature changes. The stiffness of the disc springs progressively increases with rising temperatures, providing additional preload. In this study, a preload is achieved for a pair of angular contact ball bearings in a test setup, followed by the integration of SMA disc springs into the system. As the system operates and reaches a certain temperature, the preload increases, ensuring effective operation at the desired speed. A dedicated apparatus was developed to observe the behavior of SMA disc springs, determining the friction torque and bearing preloads required for this alternative constant pressure preload method.*

Key words: *Angular contact ball bearings; shape memory alloys; ball bearings; preloading system; active preload; experimental testing.*

1. INTRODUCTION

Rolling element bearings are frequently used in a wide spectrum of applications ranging from the most common house hold appliances all the way to the highly complex devices and machinery [1]. Rolling element bearings come in many shapes and sizes and are designed to cover the needs of various applications that require low friction and high-speed rotation capabilities, smooth running and reduced vibrations, specific loads and torques and reliability among others.

Ball bearings are a category of rolling element bearings that use steel or ceramic balls as the rolling elements. According to the material that they are made of there are steel, ceramic and hybrid ball bearings available. Steel ball bearings are made from special bearing steel grades (both raceways or inner and outer rings as well as the rolling elements and pressed steel sheet, brass or PTFE cages).

Ceramic ball bearings are made completely out of ceramic materials that display good wear resistance properties and can be operated at speeds that are 1.2 – 1.5 times higher than steel bearings. Hybrid ball bearings use the steel raceways from the regular bearings and replace the rolling elements with ceramic ones. Angular contact ball beatings (Fig. 1.) are a type of ball bearings that are designed to bear axial loads in both directions with a high load capacity while having a limited radial load support capability. The research on angular contact ball bearings has increased in the past two decades due to demand for high reliability and higher supported speeds needed to overcome new design challenges. The main feature of this type of bearings is the ability to support an increased axial load with the increase of the contact angle when mounted in face-to-face or back-to-back configurations.

The contact angle ranges between 15° and 40° depending on the manufacturer and product range.

The two main methods of applying preload to bearings, are position preload and constant pressure preload – which is further expanded upon in this paper [2]. Houpert [3] proposed a novel analytical method for ball and roller bearings, considering five relative race displacements to calculate bearing loads and tilting moments. It enables easy analysis of complex systems involving bearings, shafts, and housings. Additionally, it provides analytical expressions for load distribution and can be integrated into nonlinear Finite Element Analysis (FEA) software, enhancing its capabilities. Paleu et al. [4] developed a test rig able to reach 120,000 rpm and to monitor friction torque and temperature in high-speed bearings. Modern data acquisition and virtual instruments track friction torque during tests on all-steel and hybrid ball bearings under high-speed and light load conditions with oil-mist lubrication. Gupta [5] proposed a quasi-static model for angular contact bearings by incorporating contact mechanics, bearing kinematics, and friction behavior in ball-race contacts. This enhanced model improves predictions of traction behavior and heat generation, comparable to dynamic analyses. It serves as a design tool for optimizing thermal dissipation in ball-race contacts, supported by standalone software for practical application. Cretu et al. [6] proposed a vector method to solve quasi-dynamic equilibrium in a tapered roller bearing, incorporating centrifugal forces and roller gyroscopic moments. Primary solutions are then utilized for dynamic analysis, considering lubrication regimes and sliding traction forces. Olaru et al. [7] analyzed a high-speed 7206 C ball-bearing with mist lubrication, the film thickness and lubricant parameter λ for starvation and thermal effects. The lubricant parameter serves as a safety criterion, correlating friction losses, temperature, and limit speeds. A new speed limit concept based on λ was developed by the authors. Nelias et al. [8] developed a new model that predicts power losses in high-speed gearbox ball bearings, considering cage action and lubricant film thickness. It calculates forces using lubricant properties and treats cage and ball kinematics as unknowns. Power losses are determined by friction forces and sliding speeds among bearing elements. The model shows that total power loss is mainly affected by rotational speed and oil flow, with the cage playing a significant role. Bujoreanu et al. [9] emphasized that the brake effect on the bearing's cage can lead to abnormal operation and premature failure, developing a simplified analytical kinematics model based on power loss equilibrium, correlated with a scuffing model. This aids in estimating scuffing risk for angular contact ball bearings, assisting designers and users. Tudose et al. [10] proposed a new system approach, contrasting with prior methods by considering both known loads and bearing deformations. It balances loads and moments transmitted to bearings with those from elastic rolling element deformations. The paper showcases its application in bearing life calculations and optimal design arrangements.

The reliability of the bearings and the machinery they are used in is influenced by several factors like the installation procedure, lubrication, operating temperature, loads, level of vibrations etc. In the case of angular contact ball beatings, preload plays an important role in ensuring a high reliability of the bearings. When using angular contact bearings in high precision applications, e.g., in machine tools, an optimum preload or a negative operating clearance is required for the smooth running of the spindles at high speeds by reducing as much as possible the internal clearance of the bearings.

Preload also plays a key role in reducing costs of operating industrial machinery as it extends the lifespan of the bearings from a maintenance standpoint. If the proper preload is ensured, the machines can run longer, thus reducing downtimes and maintenance costs for unplanned interventions [11].

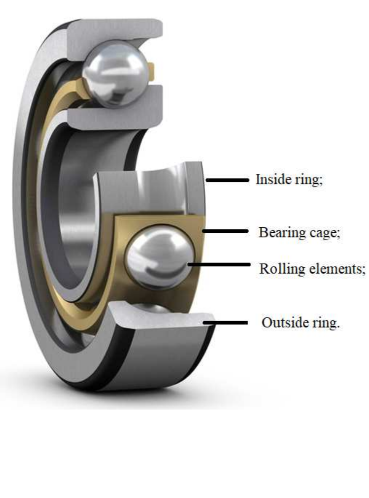

Fig. 1. Generic SKF Angular contact ball bearing [11].

2. SHAPE MEMORY ALLOY MODULES

Shape memory alloys have been around for a few decades and the research performed in this field opens up new uses for this kind of materials. Several types of shape memory alloys have been developed. They are being tested and improved in order to be used in new applications and in order to reduce the manufacturing costs to make them more accessible. Initially, these alloys were expensive to fabricate and hard to form into a specific shape because their properties were not entirely known and understood. Over the years, as more and more researchers began working with such materials, the progress in this field made it possible to obtain new types of shape memory alloys with better characteristics and more economical ways to manufacture them. The older Ti-Ni based shape memory alloys (commercially known as Nitinol) were improved and a new Fe-Mn-Si class of alloys were developed. These new alloys are less expensive than the Ti-Ni based ones, have higher strain recovery rates and are more accessible in terms of processing and machining into the desired shapes and sizes. Usually, these alloys are made into the shape of cylinders, strings, sheet metal, meshes, rods etc.

Shape memory alloys are used in the aircraft and automotive industry, in robotics, in the medical industry, civil engineering, HVAC systems, electronics etc.

Generally, shape memory alloys display the property to regain their initial shape when exposed to specific stimulants, often involving heat. This property is called shape memory effect or SME. Electricity is another method of triggering a response from particular shape memory alloys by applying a certain current and varying its value to obtain different degrees of deformation and recovery.

The shape memory alloy with the following designation: Fe-28Mn-6Si-5Cr presented in this paper, was processed into disc shaped springs - called *modules* (Fig. 2.), in order to test the possibility of using this type of alloy as an elastic element for the constant pressure preload method of preloading ball bearings [12, 13].

Fig. 2. Fe-28Mn-6Si-5Cr shape memory alloy modules;

The modules were crafted using the high-pressure torsion (HPT) method in order to achieve better shape recovery and mechanical performance required for the use in a constant pressure preload system and the testing device. Fe-Mn-Si shape memory alloy modules were developed for self-adaptive axial preload control in angular contact bearings. Processed by high-speed high-pressure torsion (HS-HPT), these modules exhibit shape memory effect, high tensile stress, and fatigue resistance. They are tested for feasibility and functionality, showing potential as temperature-responsive compression displacement systems. All the aspects regarding the behavior of the SMA springs are presented in [14].

3. PRELOAD TESTING DEVICE

In order to test the aforementioned shape memory alloy modules, a special testing device was designed and manufactured (Fig. 3.).

The device uses a pair of 7206 CTAP4 angular contact ball bearings (9) mounted on an internally cone shaped part (8) that is attached to a spindle (11) and placed inside of a steel cylinder (6) that acts as a housing. The cylinder is encased, both ends having custom covers installed (5 and 10) in order to allow the device to be mounted on a machine spindle that is being driven by a flat belt transmission. The device is locked with the help of, six studs (3) placed on the circumference of the device and equally distanced apart, secured with fasteners (doubled nuts and washers) (4). The part labeled (1) is used to apply the initial preload force to the modules package.

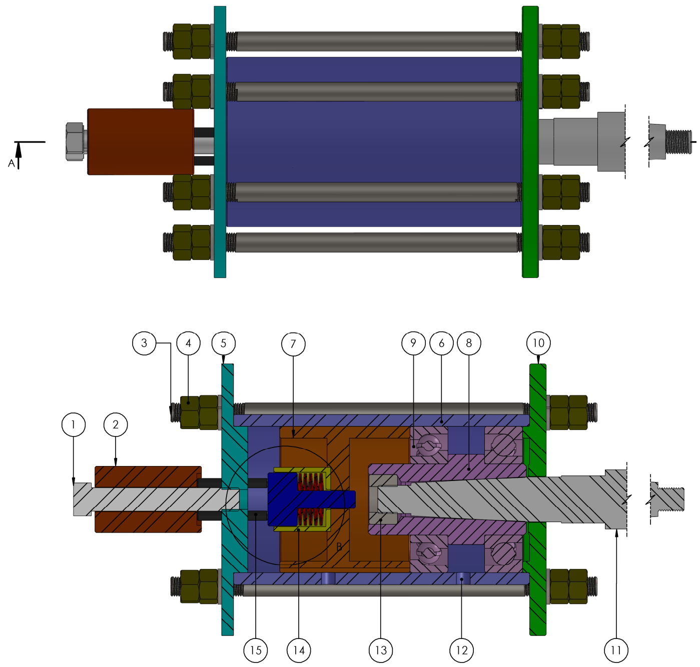

Fig. 3. Angular contact ball bearings testing device -top and section view - bottom;

Part no. (2) is a compression load cell that is employed to measure the preload values and to determine the changes in preload when the modules are activated. The part labeled (7) is used to transfer the induced forces to the bearings outside rings to apply the preload.

The threaded hole (12) is used for mounting a temperature sensor to monitor the internal temperature and of the device and that of the ball bearings.

The assembly shown in the detailed view B contains the shape memory alloy modules which are presented in a close--up view (B), in the next figure.

The testing device is secured to a high precision grinding spindle (11 and 13) manufactured by Terom Iasi, in Romania. The grinding spindle itself is mounted on a custom fully adjustable support that allows the belt transmission to be properly tensioned. The spindle is being ran by a two staged flat belt transmission connected to an electric motor. The electric motor is controlled using a three-phased electric motor controller that can be programmed. The test rig also includes control systems for oil mist lubrication, compressed air controls, a cooling solution for the transmission components, a general power supply cabinet with power controls and indicators for the different components as well as several fail-safe devices.

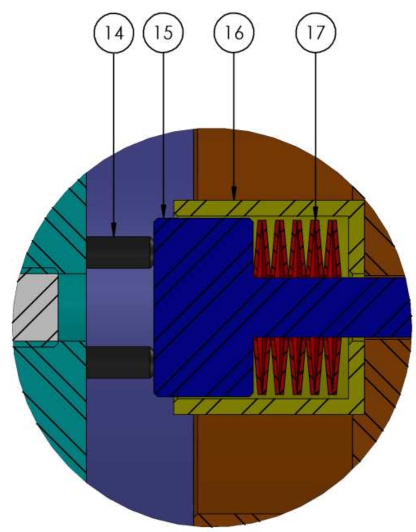

Fig. 4. Detailed view of the modules package;

In Fig. 4. a stack of five pairs of the shape memory alloy modules (17) is shown installed in a case (16) that drives the part numbered (6) in Fig. 3. to apply preload to the angular contact ball bearings. The stack of modules is centered by a piston like part (15) that is being pressed by three rods (14) enabling the preload to be transferred to the modules and further to the ball bearings [9].

In order to prevent the modules from slipping into each other interfering with the results, spacers/ washers were added between the modules Fig. 5.

Fig. 5. The modules package with the spacers used in the current experiment;

4. EXPERIMENTAL RESULTS AND DISCUSSION

In order to determine whether or not the ball bearings can benefit from the preload induced by the modules, several tests were carried out. According to the bearing manufacturers, angular-contact ball bearings are to be mounted with a certain preload depending on the size of the bearing, type of application, loads etc. This preload must also be taken into account when designing a preload system which must ensure that the preload is maintained through the lifespan of the bearings.

The tests were conducted at both low speeds and low torque and at low speeds and higher torque using grease as a lubricant. The obtained results showed that after a run-in period defendant on the rotation speeds, the preload increased due to the modules stiffening when the specific temperature was reached (Fig. 6, Fig. 7, Fig. 8). The operating temperature of the system increases according to the shaft's speed- the higher the speed the quicker the temperature rises. Once the modules become rigid achieving the proper preload, the temperature tends to stabilize ensuring the reliability of the system.

In order to predict the behavior of the angular contact ball bearings under the effects of the preload induced by the shape memory alloy modules a theoretical model was developed. In the case of a light preload, the first stage of the running-in period sees an increase of the friction torque until the contact points between the ball and raceways become uniform.

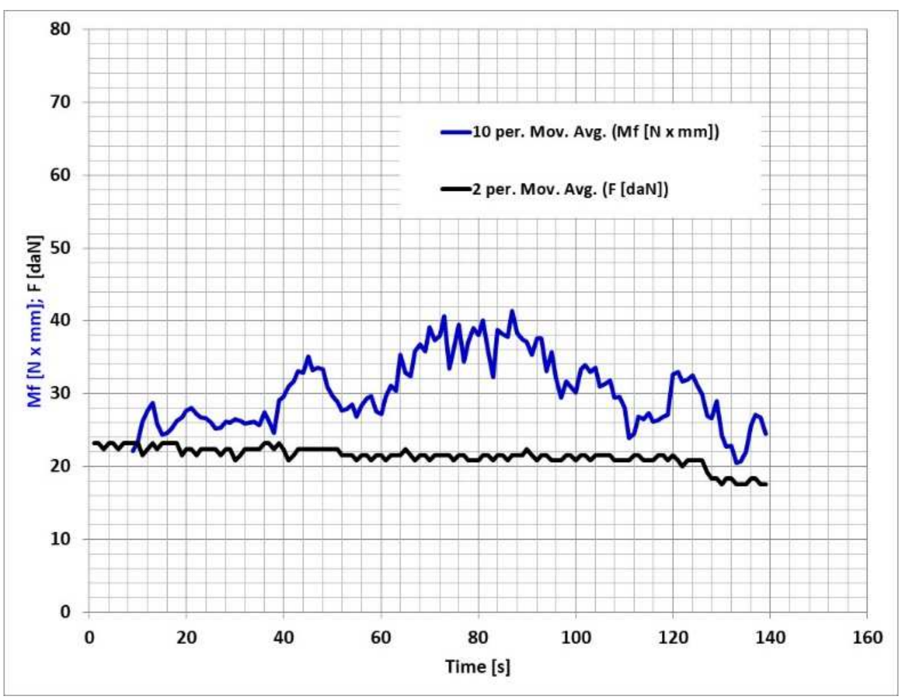

Fig. 6. Load and torque vs. time:
preload 224 N and speed 138 rpm;

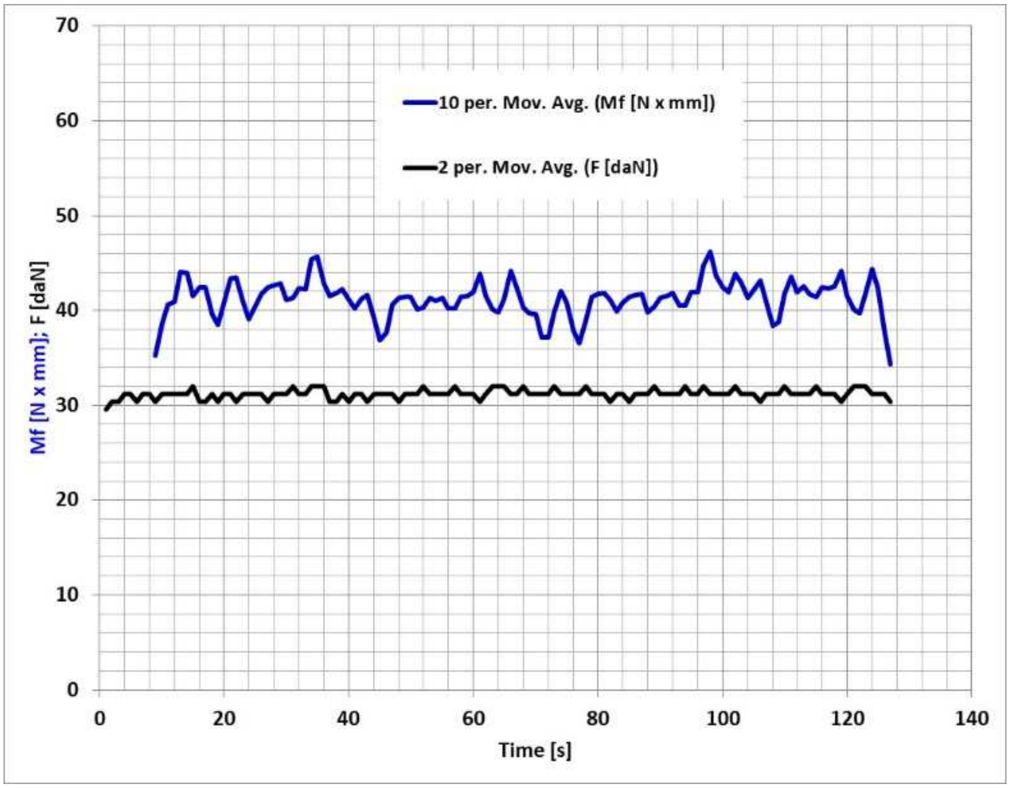

Fig. 7. Load and torque vs. time:
preload 320 N and speed 376 rpm;

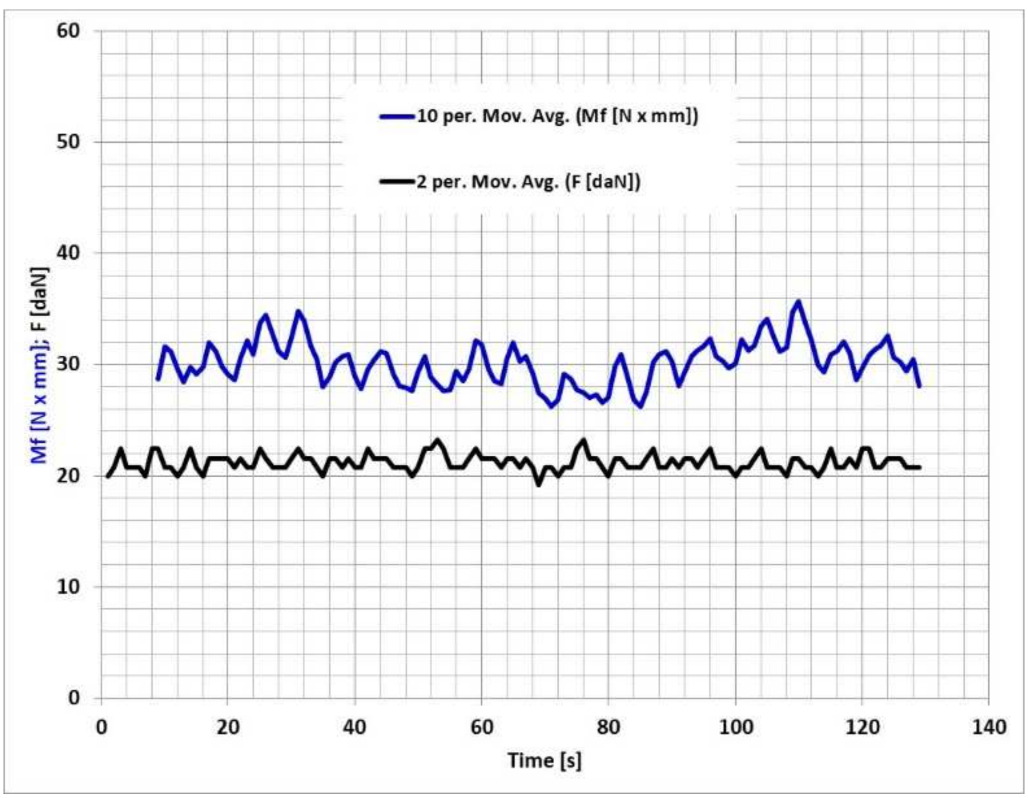

Fig. 8. Load and torque vs. time:
preload 224 N and speed 376 rpm;

5. CONCLUSIONS

When designing industrial machinery, achieving optimal preload for the bearings is crucial, considering factors such as operating temperatures, lubrication, and loads to ensure machine reliability. Adequate preloading mitigates potential bearing damages from high temperatures, skidding, or excessive loads, thus preventing premature machine failure.

Shape memory alloys (SMAs) present an innovative approach to constant pressure preload systems by leveraging their memory effect properties to induce optimal preload for bearings. Our paper proposes utilizing SMA modules to assess preload for angular contact ball bearings, offering promising results for broader application in industrial machinery.

Following initial tests, our device has been enhanced to accommodate research on ball bearing preloading, aiming to validate the feasibility of the proposed solution. According to the experimental results, the friction torque is accurately following the variation of the preload in time. The preload is maintained relatively constant.

Upon completion of our research, we anticipate that this system could be integrated into various machine tools and industrial equipment, enhancing machine reliability, reducing operating costs, and addressing increasingly demanding design challenges effectively.

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Sistem de testare a pretensionării rulmenților radiali-axiali cu bile utilizând module cu memoria formei

Rezumat: Pretensionarea rulmenților, în special a celor utilizați în echipamentele industriale, constituie un aspect critic în proiectarea mașinilor și echipamentelor industriale cu fiabilitate ridicată sau în timpul procesului de mentenanță având în vedere influența semnificativă a acesteia în prevenirea defectării premature a mașinilor. Deși existămetode consarate pentru asigurarea pretensionării adecvate a rulmenților, această lucrare prezintă o variantă a sistemelor de pretensionare cu presiune constantă. Acest sistem este propus pentru aplicațiile în care sistemele de pretensionare obișnuite sunt prohibitive în implementarea inițială din punct de vedere al costurilor sau implică anumite costuri operaționale ridicate pentru utilaje existente din perspectiva mentenanței.

Soluția propusă implică utilizarea în diferite configurații și moduri de aranjare a unor arcuri tip disc denumite „module” ce sunt confecționate dintr–un aliaj cu memoria formei și adaptate aplicației curente. Aliajele cu memoria formei au proprietatea de a reveni forma inițială atunci când sunt expuse la anumiți stimuli externi, în majoritatea cazurilor, aceștia fiind schimbările de temperatură. Arcurile tip disc se rigidizează progresiv odată cu creșterea temperaturilor de funcționare până la un anumit prag, oferind o pretensionare suplimentară.

În această lucrare, pretensionarea optimă este obținută prin aplicarea unei pretensionări inițiale calculată pentru un set de rulmenți radiali-axiali cu bile montați într-un dispozitiv de testare, ulterior încorporând în sistem, arcuri cu disc din aliaje cu memoria formei. Pe măsură ce sistemul atinge o anumită temperatură de funcționare, forța de pretensionare crește, asigurând o pretensionare adecvată pentru funcționarea eficientă a sistemului la turația dorită. A fost construit un dispozitiv dedicat pentru a observa comportamentul arcurilor tip disc confecționate din aliaje cu memoria formei determinând monentul de frecare și valorile forței de pretensionare necesare pentru metoda alternativă de pretensionare cu presiune constantă a rulmenților.

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