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THE MANUFACTURE OF BALL BEARINGS: BACKGROUND, PROCESS, AND FUTURE

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ABSTRACT

The aim of this paper is to explore the manufacture of ball bearings at a moderately-detailed level. In addition to the manufacturing processes themselves, an introduction to bearings in general, a brief history of bearings, advantages, disadvantages, and alternatives to the processes outlined, and the future of and innovations in ball bearing technology will be discussed, in order to provide additional context and relevant information to the reader. Some details, processes, and other relevant information are omitted due to the breadth of the topic and length constraints, but the author hopes the treatment is sufficient to grant the reader an intermediate-level understanding of ball bearings and their manufacturing process.

Keywords: bearing, ball bearing, manufacturing

1. INTRODUCTION

SKF, the largest bearing manufacturer in the world, states prominently at the bottom of every page on their website that "whenever there is movement, SKF's products may be used" [1]. Indeed, bearings are a ubiquitous mechanical component in our modern society, and are critical to the functioning of countless machines and devices that improve our quality of life.

1.1 Types of Bearings

As the name somewhat implies, the purpose of a bearing is to "bear" or support a rotating structure while minimizing friction. There are many different types of bearings with different properties, applications, and price points. Several of the most common bearing types are shown in Fig. 1. The first distinction must be made between **rolling bearings** and **plain bearings**. The rolling bearing describes a group of bearing types that employ rolling elements that separate the two surfaces that are being rotated relative to one another. This is in contrast to the plain bearing (also known as the slide bearing, journal bearing, or friction bearing), in which the two surfaces simply slide relative to one another without any rolling elements in between them [2,3]. This bearing type, while light, cost-effective, and having a high load-capacity, is very inefficient and wears easily due to the direct rubbing of the two surfaces against each other.

Within the overarching category of (rolling) bearings there are still more distinctions to be made between bearing types. The foremost rolling bearing type is the **ball bearing**, which uses small, smooth spheres that roll between the two surfaces. The other main rolling bearing type is the **roller bearing,** which utilizes small cylinders instead of spheres as the rolling elements. The increased contact area but also increased friction from using cylinders instead of balls means that roller bearings are more suited to applications involving higher radial (perpendicular to the axis of rotation) loads and lower speeds than ball bearings. Due to the relative ease of manufacturing cylinders compared to spheres, they also tend to be cheaper [4].

There are also bearings that are neither plain nor rolling bearings, such as **fluid** or **magnet bearings**. These bearings use fluids and magnetic fields, respectively, to separate the two surfaces, and can achieve very low coefficients of friction and very little wear over time, though at a significant premium in cost [5].

Figure 1. Types of bearings [6]

Another way to distinguish bearings is by the type of loads that they support. The ball bearing pictured in Fig. 1 is designed to primarily support radial loads, such as the downward loads imparted by the weight of a vehicle onto its wheels. **Thrust bearings**, on the other hand, are designed to support primarily axial loads (e.g. for the rotation in a Lazy Susan), and they can also come in both spherical and cylindrical rolling element variants. Other, more expensive bearings, such as tapered roller bearings, are designed to support both radial and axial loads. For the most part, however, when most people think of "bearing" they think of the radial-load-supporting ball bearing. It is the most commonly used bearing type due to its excellent balance between cost (and hence manufacturability) and performance (low friction, good operational lifetime). As such, it will be the focus of this paper.

1.2 Components of Ball Bearings

Ball bearings consist of the outer and inner rings (races), the cage (retainer), and the balls themselves. Seals that prevent lubricant from leaking out and dust or debris from coming in are optional. An exploded view of the standard ball bearing is shown in Fig. 2.

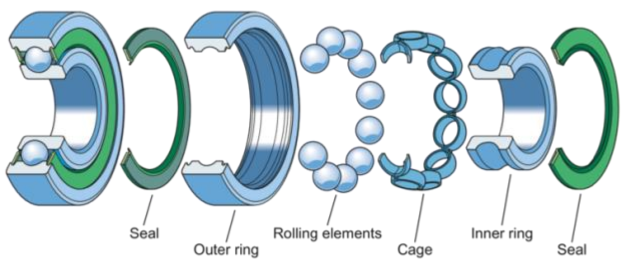

Figure 2. Components of ball bearing [1]

Today, some of the largest bearing manufacturers in the world are SKF (Sweden), Schaeffler/FAG (Germany), Timken (USA), and NSK (Japan) [7].

2. HISTORY OF THE BALL BEARING

Historians speculate that the invention of the rolling bearing predates the invention of the wheel rotating on a plain bearing. It is theorized that the Ancient Egyptians used rolling bearings in the form of wooden logs to transport massive stone blocks, such as those used to make the pyramids, although this is simply speculation [2].

The earliest confirmed use of rolling bearings was a wooden ball bearing supporting a rotating table from the remains of the Roman Nemi ships in Lake Nemi, Italy, dated to 40 BC.

Around the year 1500, Leonardo da Vinci sketched the first known design of a wooden ball bearing (Fig. 3), which he intended to incorporate into his design for a rudimentary helicopter, the aerial screw.

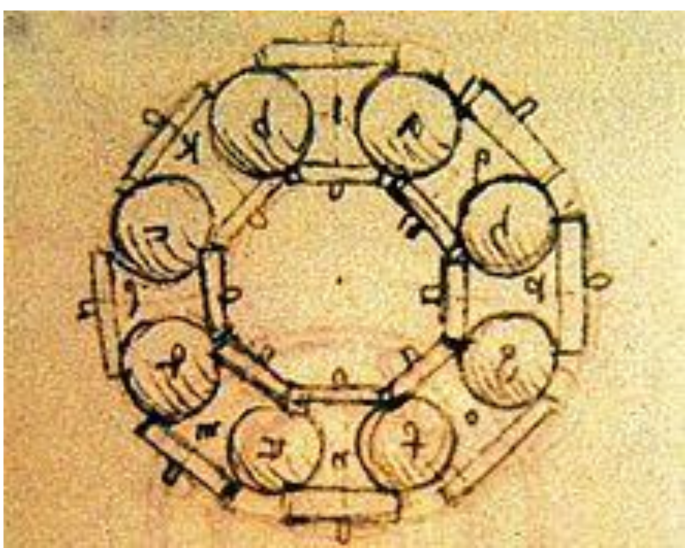

Figure 3. Leonardi da Vinci's ball bearing sketch [2]

In order to reduce friction caused by the balls rubbing against each other, the idea of "caging" or "capturing" the balls around the interior of the bearing was described by Galileo in the 17th century.

The first practical caged-roller bearing was invented by watchmaker John Harrison in the mid 1740s. At first it was only used for a very limited oscillating motion, but it was later applied to a timekeeping device employing true rotational movement.

Philip Vaughan, a British inventor and ironmaster, came up with the first modern ball-bearing design, with the balls running along a groove in the axle assembly. He was awarded a patent for the design in 1794.

The first patent for a radial-style ball bearing was awarded in 1869 to French bicycle mechanic Jules Suriray, who used the design to win the world's first bicycle road race.

In 1883, Friedrich Fischer, founder of FAG, developed an approach using milling and grinding to produce balls of equal size and exact roundness suitable for mass production.

The modern, self-aligning ball bearing is attributed to Sven Wingqvist, cofounder of SKF. He was awarded a patent for his design in 1907.

Henry Timken, an American visionary and inventor, patented the tapered roller bearing in 1898, and soon formed a company to produce his innovation.

German engineer Richard Stribeck's extensive research on ball bearing steels led to the adoption of AISI 52100 steel as the most common material used in ball bearing manufacture.

During World War 2, SKF had a monopoly on ball bearing manufacture in Europe, and supplied the majority of Germany's ball bearings. If not for SKF's supply of bearings, the war would've likely turned out very differently [8], which demonstrates the importance of precision bearings to modern machinery.

3. MATERIAL SELECTION

Before the manufacture of a ball bearing itself can begin, the materials used must be selected. A suitable material for both the rings and the balls is one that has high hardness (low rolling resistance) and strength, resistance to cracking (good fatigue life), resistance to corrosion, resistance to abrasion, and a low cost. Additional desirable properties, although not absolutely necessary, are a very low coefficient of friction, resistance to extreme temperatures, and a light weight.

3.1 Steels

The material that strikes an optimal balance between these requirements is **AISI 52100**. 52100 is a chrome steel (1% C and 1.5% Cr) [9], meaning it contains chromium unlike carbon steel, but has much less of it compared to stainless steel. This means the material has decent corrosion resistance, while still maintaining most of the excellent strength, hardness, and fatigue life of carbon steel [5,10,11]. Its cost to produce is relatively low, and it can be heat-treated. Although 52100 is more resistant to corrosion than carbon steel, bearings made of this material still require surface treatments of rust inhibitor or oil to prevent oxidation.

The other common bearing material is **stainless steel**. Stainless steel has less strength and hardness than chrome steel, especially since it cannot be heat-treated due to its lower carbon content (~0.1%) [12], but it has superior corrosion resistance. It is commonly used in marine, food, and medical applications.

The last steel commonly used is **AISI 440C** martensitic stainless steel. 440C has a similar carbon content to 52100 (~1%), but a much higher chromium content (17% compared to ~1.5%) [13], giving it a corrosion resistance better than 52100 though worse than stainless, which also contains a high amount of nickel. Its high carbon content means it is heat-treatable, giving properties close to 52100. It has a load capacity around 20% lower than 52100, can operate at higher temperatures, and is generally more expensive. It is primarily used by US bearing manufacturers [5].

3.2 Ceramics and Plastics

Another type of bearing material is **ceramics** such as silicon nitride (Si_3Ni_4) and zirconia (ZrO_2) [14]. Compared to steel, ceramics are harder, have better corrosion resistance, lower coefficients of friction, are lighter weight, and can operate at higher temperatures. As such, they are often used in applications involving high speeds and/or exposure to extreme temperatures and harsh environments. They also have the added benefit of being insulative and non-magnetic, making them suitable for applications involving strong magnetic fields (e.g. inside an MRI machine). Their downside is an increased cost and brittleness. In practice fully-ceramic bearings are rare – **hybrid bearings** consisting of steel rings and ceramic rolling elements are more common as they take advantage of the low rolling resistance, light weight, and corrosion resistance the ceramic balls offer while not compromising the strength and toughness of the overall structure.

In cases where great corrosion resistance and light weight are desired, and required load capacity is not high, **Nylon** or other engineering plastics are an excellent choice. Lastly, the contacting surfaces can be coated with a self-lubricating **PTFE** (Teflon) or **graphite** liner to provide consistent, controlled friction and durability [5,15].

4. MANUFACTURING PROCESS

The process of producing ball bearings can be split into the processes to produce the inner and outer rings, the balls, and the cage. The process for the cage will not be discussed in this paper due to length constraints. The processes for the rings and balls are summarized in Fig. 4. There are multiple variants of the processes, especially when materials other than AISI 52100 are used, so the most common (as judged by the author) ones are presented in this section, while alternative processes are presented in the next section.

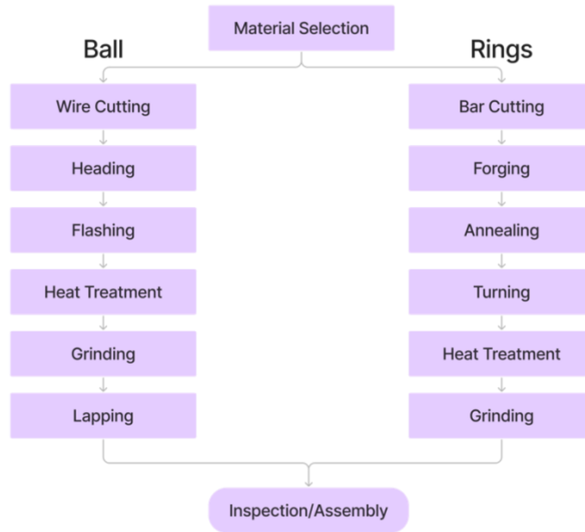

Figure 4. Manufacturing steps for rings and balls [10,11,16–18]

4.1 Inner and Outer Rings

1. The first step in the production of the inner and outer rings is **bar cutting.** Solid cylindrical or rectangular bars of the chosen material are cut into smaller pieces by a flame cutter (Fig. 5) or saw, depending on the bar's size.

Figure 5. Flame cutting of bar stock for large bearing rings [16]

2. The next step is **forging**. The cut pieces are hammered and/or pressed at high temperature and pressure into shapes that progressively resemble the desired annular shape. The inner and outer diameters are smaller and larger than the desired final diameters, respectively, in order to leave material to be taken away by finishing operations. Forging has the added benefit of strengthening the material through work hardening, though this effect is diminished at the high temperatures needed to plastically deform steel.

3. Next the forged pieces are **annealed** to get rid of any internal residual stresses to prepare the material for machining.
4. The pieces then undergo various **turning** operations to trim them down to close to their final dimensions, achieve concentricity, improve surface finish, and also carve out the concave features on the outer and inner surfaces of the inner and outer rings, respectively, where the balls will sit.
5. In the **heat treatment** step, the rings are heated and cooled to various temperatures to improve their hardness, strength, and fatigue life. It generally consists of three basic operations: heating to a high temperature, quenching to a low temperature, and tempering at a medium-low temperature. Oil instead of water is used for quenching to prevent cracking.
6. The inner and outer surfaces of the rings then undergo **grinding** (Fig. 6) to achieve the final desired dimensions and geometry and to further improve surface finish.

Figure 6. Inner diameter grinding [19]

4.2 Balls

The process for making the balls of a ball bearing are similar to the process for making the rings, although they demonstrate some key differences, including a requirement for higher dimensional tolerances. Figure 7 illustrates the six steps of the process.

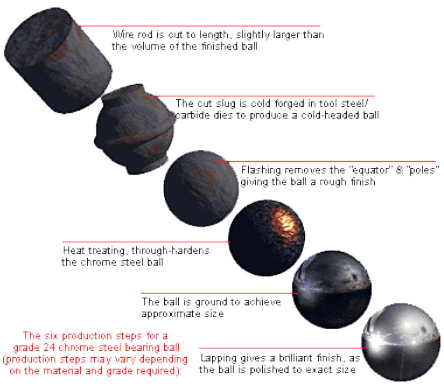

Figure 7. Steps in ball bearing manufacture [19]

1. The first step in the manufacture of the balls is **wire cutting**. In this step, wire of the chosen material is cut into pieces with volume slightly larger than that of the finished ball.
2. The pieces are then pressed into a die to form rough spheres (slugs) during the **heading** step (Fig. 8). Hot-heading or cold-heading can be performed, depending on the material and the size of the slugs. Cold-heading offers the benefit of work hardening, though requires a stronger press.

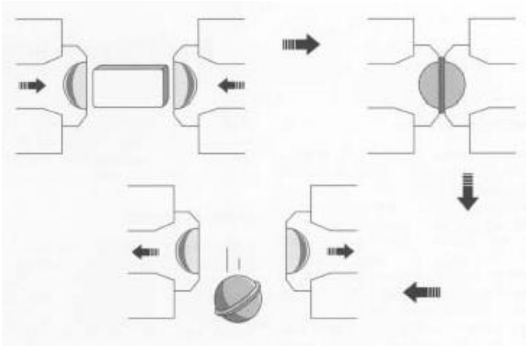

Figure 8. Heading process [20]

3. During **flashing**, burrs and rough edges of the spheres are removed by passing the balls through two grooved metal sheets – one fixed and one rotating.
4. Just as for the rings, the balls are **heat treated** to improve properties. In the case of AISI 52100, they are heated to 810 C, quenched to 60 C, and tempered at 170 C [17]. Annealing as an individual step is not needed due to the lack of a turning process.
5. In the **grinding** step, the dimensions, geometry, and surface finish of the balls are further refined through a process similar to the one used in flashing.
6. In **lapping**, tiny surface imperfections are removed to produce extremely tight tolerances, refined geometry, and a mirror finish (Fig. 9). It involves the use of an abrasive slurry or paste along with a rotating lap or workpiece.

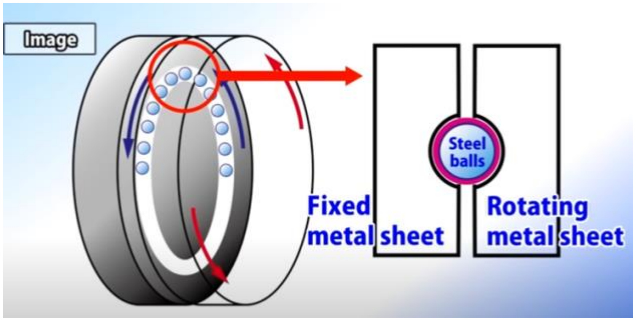

Figure 9. Lapping process for bearing balls [17]

4.3 Final Steps

Depending on the material used, both the rings and balls may undergo an optional **demagnetization** step to rid them of any magnetic interactions that could impede smooth motion [21].

After the rings and balls have completed manufacture, **washing, inspection,** and **assembly** are left.

During washing, ultrasonic waves wash off any dirt or oil stuck to the parts. During inspection, an automated machine checks the size and surface of the parts. An additional human inspection is also necessary to confirm the absence of any imperfections that weren't picked up by the machine. Scratches are discovered by the way light is reflected off the parts.

Finally the rings, balls, and retainer (process not covered here) are assembled via either manual or automated processes. In general, smaller bearings are more economical to produce via automated processes, whereas larger or more niche (low volume) bearings are more economical to produce by hand. Regardless of if the process is manual or automated, the balls are positioned such that they are equally spaced around the concavity between the inner and outer rings. They are then secured in place by the cage before all components are pressed together [22].

Before or after assembly, lubrication in the form of oil or grease, as well as rust inhibitor can be added. Oil has the lowest friction and highest load-capacity of the lubrication options, but is messy, can contaminate other components, and requires constant maintenance. As such, grease is often used for its lower maintenance, especially in high-torque, low-speed applications where the increased friction compared to oil is not as big of a drawback [10].

Seals can be used in order to prevent the oil/grease from leaking out and to prevent water, dust, or debris from leaking in.

5. ADVANTAGES, DISADVANTAGES, AND ALTERNATIVES TO THE PROCESS

As demonstrated in the history section of this paper, the modern ball bearing is a relatively old invention, and its manufacture has undergone many iterations and improvements over the years. As a result, the tools and methodologies to produce ball bearings are highly refined, but also difficult to change. Thus, an advantage of the process is that of economies of scale – high volume and low cost per part. A disadvantage is the difficulty/cost in adapting the process to suit different parameters. For example, the dies and tools used in the forging and flashing steps are very expensive and applicable to only a specific dimension/geometry. If a parameter, such as the diameter of the balls is to be changed, many tools, machines, and in the worst case, the entire process will have to be updated or replaced.

5.1 Advantages and Disadvantages

In terms of advantages and disadvantages specific to the process presented in this paper, an advantage is the excellent strength and fatigue life offered by the forging and heat treatment processes, while a corresponding disadvantage is the energy-intensiveness of the forging and heat treatment steps. An advantage of grinding is that it can achieve superior tolerances, geometry, and surface finish. A disadvantage is that it is a relatively expensive process [18].

5.2 Alternatives

The two disadvantages brought up above justify two potential alternative processes:

1. **Skip forging/annealing.** In this alternative for the ring making process, forging and annealing are skipped as the first two steps after bar cutting. Instead, turning is used both to rough and semi-finish the stock to the desired dimensions. As such, the stock must be a tube, not a bar, in order to give room for the boring operation. Such a process is outlined in Fig. 10. Much energy and tooling cost is saved and complexity reduced by this alternative, although it is likely less cost-effective for large-volume production due to the relatively slow nature of turning.

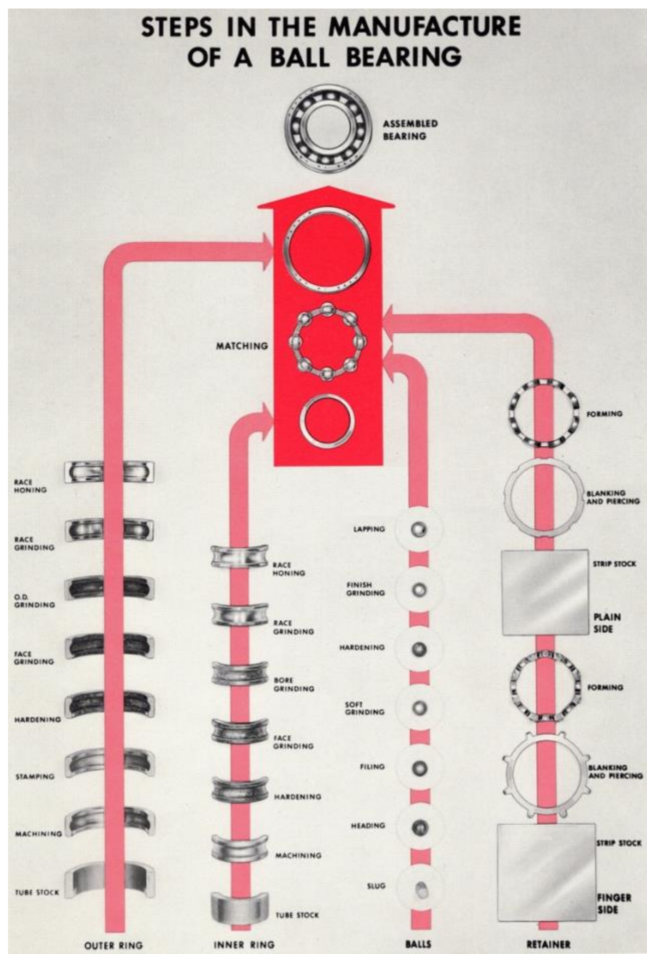

Figure 10. Ball bearing manufacturing with forging and annealing steps skipped [10]

2. **Hard turning or rolling instead of grinding**. Two alternatives to grinding to produce the final dimensions are **hard turning** and **rolling.** Hard turning is the turning of

hard, in this case heat-treated, materials. Precision hard turning can achieve surface finishes similar to grinding, at a significant reduction in cost and complexity [23]. Although rolling likely compromises on surface finish, it imparts compressive residual stresses that are lacking with grinding or hard turning. Since surface finish and compressive residual stresses are *both* aspects that improve bearing fatigue life, rolling has the potential to be an attractive option when all factors are considered [18].

6. FUTURE AND INNOVATIONS

As we have noted, ball bearings are employed in countless modern industries – from electronics to aerospace. As these industries grow, so too will the ball bearing industry. In 2023, the global ball bearing market was valued at USD 6.49 billion, and it is expected to grow to 12.15 billion by 2032. The Asia-Pacific region, with China and India in particular, have been responsible for the biggest growth of the industry in recent years, both in terms of supply and demand [24].

Although the traditional, low-cost ball bearing will continue to be a staple of modern engineering, new innovations in the ball bearing, driven by emerging technologies and evolving market demands, will increasingly be seen. Below a few notable ones are discussed.

6.1 Ceramics and Coatings

As introduced in the material selection section, full **ceramic** or **hybrid ceramic bearings** are becoming more popular due to their reduced friction, increased durability and resistance to extreme environments, and higher operational speeds (Fig. 11). Ceramic bearings are more difficult to manufacture and thus more costly, though advanced manufacturing techniques are driving the cost down. Self-lubricating bearings enabled by PTFE and graphite coatings are also improving the reliability and self-sufficiency of bearings, crucial in marine and extraterrestrial applications (e.g. Mars rovers) [25].

Figure 11. Hybrid bearings with silicon nitride rolling elements [26]

6.2 3D Printing

As with practically all modern manufacturing processes, the manufacture of ball bearings is experiencing disruption by **3D printing**. 3D printing technology has improved drastically over the last decade, with the ability to print engineering plastics, such as PEEK, nylon, acetal, carbon fiber, and Tullomer, a thermoplastic developed by Z-Polymers in Lowell, MA, claiming strengths as good as steel at a fraction of the weight [27,28]. 3D printing allows for the production of customized bearing designs tailored to specific applications. This capability leads to optimized performance and opens new possibilities in bearing design and manufacturing.

6.3 Smart Bearings

Another innovation in bearing technology that was only enabled in recent years through developments in networking, microelectronics, and precision sensors is **smart bearings** (Fig. 12). Smart bearings are bearings with embedded sensors that can relay real-time information about the bearing's operating state – including loads, vibrations, position/speed, temperature, and cycle count [29–31]. This innovation facilitates predictive maintenance, reducing downtime and enhancing operational efficiency. It also enables precise closed-loop control of shaft speed and torque, a gamechanger in cutting-edge automotive and aerospace applications (e.g. motor management) [32].

Figure 12. Smart bearing by SKF [32]

6.4 Environmentally-Friendly Bearings

Environmental concerns are likely to play a role in the future of the global bearing market. As consumers and governments become increasingly aware of the environmental impact of products and production processes, there will be a shift towards more energy-efficient and environmentally-friendly (carbon neutral) bearings utilizing sustainable materials and manufacturing processes.

7. CONCLUSION

The ball bearing is an integral component of modern machinery – wherever there is continuous rolling, there is a high chance a ball bearing is involved. Ball bearings are usually made from heat-treated chrome steel, and are machined and ground to extremely tight dimensional tolerances. Relatively new processes such as hard turning and rolling have the potential to improve upon traditional ones. Recent innovations in bearing technology and other fields have paved the way for bearings that are harder, stronger, lighter, smarter, more customizable, and more sustainable.

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