# IMPROVED BEARING ALLOY—
# A CONTRIBUTION TOWARD ENVIRONMENTAL PROTECTION

**by**
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## ABSTRACT

There are differences between European and US bearing metals. This paper shows the mechanism for improving the properties of bearing alloys and the environmental problems that have arisen so far in this connection. Since 1994, a new generation of bearing alloy has been on the European market, further improved, but no longer harmful to the environment. Although this is a material with a high load-bearing capacity, its plastic deformation (creeping) could be greatly reduced, so that bearing lifetime can be enhanced or its load-bearing capacity can be increased. The technology was accepted well in the marketplace and is successfully used in a wide range of European industries, e.g., for rolling-mill bearings, gears, generators, turbines, and ship propulsion. This paper compares this improved alloy with the US standard ASTM B 23-2. The advantages realized are clearly shown. Practical examples are presented, and an outlook to further improving the load-bearing capacity of bearings is given.

## INTRODUCTION

The bearing metal most widely used in the US is the alloy according to standard ASTM B23-2. In Europe, there are comparable standard alloys. In order to compare the data of European alloys with those of American alloys, one must first of all convert the unit of measurement from N/mm$^2$ to psi, taking into account, however, that measuring methods and measuring points are defined differently. The ultimate strength in compression, for example, is measured in the US at an upsetting deformation of 25 percent, and in Europe, of 50 percent. The yield point is determined in the US at an extension of 0.125 percent, and in Europe, at 0.2 percent. But even after a corresponding conversion of the values, there are still some considerable differences between European and US bearing metals. In Europe, there is a series of special alloys possessing improved technical properties, in comparison with the standard alloys. In the following, the conditions leading to improved properties of bearing metals, as well as the disadvantages that may at the same time arise, will be explained. Finally, a further improvement will be introduced; it combines the positive properties of all former bearing materials, avoiding the disadvantages.

## KNOWN MEASURES OF IMPROVEMENT

There are three measures leading to an improvement of the properties of the material. First of all, the lead impurities have to be minimized. Then, the composition of the basic alloy consisting of tin, antimony, and copper has to be optimized. Finally, additional alloying elements have to be used.

### *Reduction of Lead Impurities*

There are tin-based standard bearing metals existing with lead content up to 3 percent. Even for standard bearing metals where lead is not an alloying element, lead impurity of 0.35 percent is accepted. Lead contained in bearing metals based on tin always constitutes an impurity deteriorating the technical properties of the materials, in particular under higher loads and temperatures. This has several reasons. For example, lead tends to precipitate on SbSn crystals, enveloping them, so to speak, and weakening in this way the compound of the crystallization microstructure. Lead forms a eutectic with antimony and tin, which has a melting point of 361°F. If the alloy contains cadmium, a eutectic with a melting point as low as 293°F is formed. Taking into consideration that bearing metals begin to melt at a temperature of 433°F to 466°F, it is clear that the drastic reduction of the melting point through the presence of lead reduces the technical load-bearing capacity to about the same degree. As the operating temperature in a bearing may reach 284°F, a lead impurity of 0.35 percent, which is usual for standard alloys, entails a risk. Furthermore, it is found again and again in practice that the lead is not homogeneously distributed in the alloy, but that spots with higher lead concentrations occur, where the problems described above arise, forming weak points where cracks and damage originate. These experiences show that a considerable improvement of the quality is already reached by a drastic reduction of lead impurities alone. Therefore, for high-quality bearing alloys, the author accepts only a maximum lead impurity of 0.06 percent.

### *Composition of the Basic Alloy*

The basic alloy always consists of the alloying elements tin, antimony, and copper. After the decision in favor of a lead-free alloy has been made, varying the contents of antimony and copper can additionally influence the technical properties. Each additional percent of antimony or copper increases the compressive yield strength by about 500 psi. This general statement must, however, not induce one to increase these contents at will. The ASTM B23-2 standard alloy has a content of antimony of 7.5 percent and a content of copper of 3.5 percent. When increasing the content of antimony, the solubility limit of antimony in tin is exceeded as soon as 8 percent is reached. Cubic SbSn crystals will then form. This does not limit the above statement about the increase of the compressive yield strength, but the cubic SbSn crystals may lead to restrictions in the dynamic impact load of the material. No indications are made regarding the quality of the dynamic impact load capacity of ASTM alloys. But according to the rules of materials science, it is logical that a larger number of sharp-edged crystal corners in an alloy will increase the potential for crack starters, unless the ductility of the matrix is increased at the same time. Furthermore, the quantities of antimony and copper cannot be increased at will, because an excessive accumulation of crystals in the matrix also entails a change of the microstructure and, consequently, the risk of a change of properties. With high concentrations of antimony, for example, a multiple agglutination of the SbSn crystals is observed. Furthermore, problems might occur when the material is processed in the foundry. With too high concentrations of copper, for example, copper precipitations might form on the surface of the steel backing. They constitute a hard intermediate layer, which does not possess sufficient toughness and leads to binding defects. For all these reasons, a limitation of antimony to 12 percent and of copper to 6 percent has proved appropriate.

### *Additional Alloying Elements*

In Europe, it is usual to improve the technical properties of bearing metals by adding further alloying elements, in particular arsenic, nickel, and cadmium. All materials, including bearing metals, which came into being decades ago, were developed empirically. Finally, they were good and stood the test. With that, the purpose was fulfilled. The reasons why the materials were so good were not extensively explored, partly because it was not yet possible at that time, but also because it was not necessary. So the author began constitution research work to find out the interaction of the different elements. If this is known, it is possible to specifically extend the system and to improve the material. The effects of the common additional elements arsenic, nickel, and cadmium were examined, with the following results:

#### *Arsenic*

Small shares of arsenic are found in the SbSn phase, whereas considerable quantities are within the matrix. Arsenic is used as a nucleating agent for refining the SbSn crystals.

#### *Nickel*

Nickel can be detected exclusively in the $Cu_6Sn_5$ crystals. As the entire nickel used is to be found exclusively there, any positive or negative influence of this element on the properties of the material as a whole can be excluded, in particular the assumed improvement of the gliding properties. This effect of nickel is known from bronzes, but, even there, only in case of a share of several percent. The only possible effect of the nickel—which due to its low quantity would be very slight—consists in a kind of mixed-crystal hardening of the $Cu_6Sn_5$ crystals.

#### *Cadmium*

Cadmium is used for hardening the matrix. It enormously increases the compressive strength of the bearing metal. Cadmium was detected at about equal shares both in the Sn matrix and in the SbSn crystals. The solubility of cadmium in the present alloy amounts to approximately 1.2 percent, i.e., it corresponds to the quantity used. Only about half of it is available for the desired matrix-hardening effect.

## DISADVANTAGES OF ADDITIONAL ALLOYING ELEMENTS

In general, all these additional elements have one common disadvantage. The awareness of the environment is growing, and it is increasingly discussed that these elements are ecologically harmful and should be forbidden. This development is particularly marked in the case of cadmium. As cadmium is, however, the very element to enormously improve the compressive strength of the bearing metal, it was very important to find an equivalent substitution.

## CONSIDERATIONS ON THE SUBSTITUTION OF THE ELEMENTS CADMIUM, NICKEL, ARSENIC

The results of the alloy analyses performed show clearly that the low quantities of nickel do not have the desired effect of improving the gliding properties. For this reason, nickel can be excluded from the alloy altogether. The crystal refining can be achieved, for example, with silver instead of arsenic. For the substitution to be found for the element cadmium, the following criteria apply:

- The element must be soluble in the tin matrix to achieve a mixed-crystal hardening.
- The element must not form any eutectics with a low melting point with tin.
- The element should not form any additional compositions with the other alloy constituents.
- The element must not have a detrimental influence on the mechanical properties.
- The element must be toxicologically harmless.
- The element and the production of the alloy must not be too expensive.
- The alloy should be recyclable in the simplest possible way.

The following elements are soluble in the tin matrix (Table 1):

- *Arsenic* is soluble, but toxic, like cadmium, and should also be substituted. As mentioned before, the decision was made to substitute it with silver.
- *Gold* brings excellent technical improvements for bearing metals, but is far too expensive.
- *Bismuth* forms eutectics with tin with a low melting point and is, therefore, not usable.
- *Gallium* possesses a high reactivity, and its handling is critical.
- *Mercury* is toxic and, therefore, unsuitable.
- *Lead* has detrimental properties and is, furthermore, ecologically questionable.
- *Thallium* is toxic.
- *Indium* is in principle suitable as a substitute for cadmium, but it is expected to be classified as toxic.
- *Zinc* seems to be suitable.

*Table 1. Elements Soluble in Tin.*

| Element | Chem. Symbol | Solubility in Sn, % | Remark |
|---|---|---|---|
| Arsenic | As | 20.0 | Toxic |
| Gold | Au | 0.3 | Far too expensive |
| Bismuth | Bi | 21.0 | Eutectics with Sn on low melting point |
| Gallium | Ga | 4.3 | High reactivity, handling is critical |
| Mercury | Hg | 1.0 | Toxic |
| Lead | Pb | 2.5 | Toxic, detrimental properties |
| Thallium | Tl | 0.6 | Toxic |
| Indium | In | 10.0 | (Toxic) |
| **Zinc** | **Zn** | **1.0** | **Suitable** |

### *Examinations with Zinc*

In the usual tin bearing metal, the zinc content is limited to less than 0.01 percent, as it had been assumed so far that zinc changes the microstructure. This general statement was questioned. A well-dosed admixture of zinc should not have a noticeable effect on the microstructure, the more so as it can be assumed that the element will be found both solved in the matrix and, due to its high solubility in copper, in the $Cu_6Sn_5$ crystals. Only in larger quantities, zinc could affect changes, most probably of the morphology of the crystals. Therefore, zinc seems to be a possible cadmium substitute and shall be examined in more detail as an alloy constituent. For an unambiguous assessment of the influence of certain elements and concentrations on microstructure and compression yield point, first of all alloys with the composition of the matrix phase, then alloys with different antimony and copper contents, and finally alloys with different contents of zinc were produced and their compression yield points measured. The addition of 1.2 percent of cadmium causes an increase of the compressive yield strength of approximately 2500 psi. Up to a concentration of approximately 0.7 percent, zinc causes an increase of the compressive yield strength of approximately 1800 psi. Up to the solubility limit of about 1 percent, the value remains constant. In the examinations, zinc showed, furthermore, a microstructure-refining effect, which becomes more marked with increasing content. The refining refers to both the SbSn precipitations and the $Cu_6Sn_5$ precipitations. Together with the mixed-crystal hardening, this has a positive effect on the mechanical properties. Above 1 percent of zinc, one notices, however, at the same time the tendency of a growing roundness of the corners and edges of the precipitations. At the same time, the compression yield point declines. Therefore, zinc fulfills to a very great extent the requirements imposed on an adequate cadmium substitute. It is soluble in the matrix and thus improves the latter's mechanical properties. Zinc contents of up to 1 percent do not change the microstructure. Zinc is relatively cheap.

### *Additional Microstructure Refining*

Although zinc has a microstructure-refining effect through which the mechanical properties can be influenced within certain limits through the number of precipitations, too high contents have a negative effect on the morphology of the precipitations and are, therefore, disadvantageous to the mechanical properties. It is useful to limit the zinc content and to use another element for further refining the microstructure. Such a microstructure-refining element should, if possible, not form any further intermetallic phases and have a nucleating effect on the $Cu_6Sn_5$ precipitations, as they in turn have the known nucleating effect for the SbSn precipitations. Exactly these characteristics were already found in former examinations performed with silver. Variations of the silver content of the basic alloy examined in the present case show that the optimum is reached with an admixture of 0.1 percent. Up to this concentration, the yield strength increases by approximately 500 psi, it remains constant up to 0.15 percent and, with higher concentrations, decreases. At the same time, with a silver concentration of more than 0.1 percent, no increase of crystal refining is observed.

## THE OPTIMIZED MATERIAL

The examinations carried out up to now reveal that cadmium increases the compressive yield strength by about 2500 psi, and the alternative with zinc and silver by 1800 + 500 = 2300 psi, so that an equivalent substitute seems to have been found already. A further improvement of the compressive strength was achieved by optimizing the contents of antimony and copper, as described above. Thus, the composition of the optimized bearing metal was SnSb12Cu6Zn0.6Ag0.1 (Figure 1).

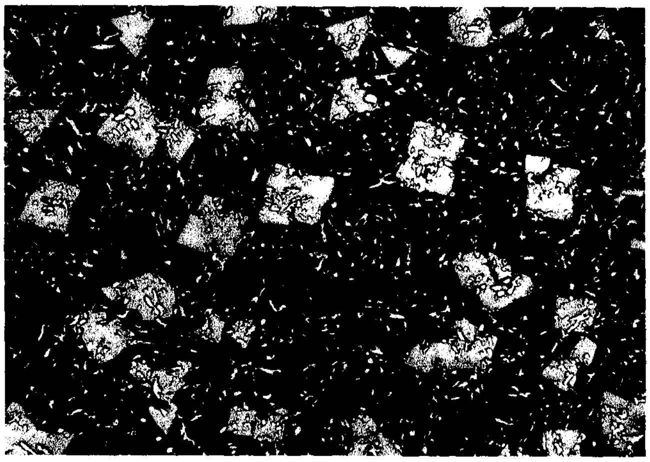


*Figure 1. Microstructure of Improved Bearing Alloy, 100:1, Etched.*

### *Physical Data*

As the basic alloy consists, as before, of the well-proven elements tin, antimony, and copper in the proven proportion of ingredients, the physical properties are in general the same as those of the formerly common bearing metals. Only the necessary casting temperature is higher (Table 2).

*Table 2. Physical Data.*

| Alloy Grade | Specified Nominal Composition of Alloys, percent | | | | | Brinell Hardness | | Solidus | Liquidus | Pouring Temp. |
|---|---|---|---|---|---|---|---|---|---|---|
| | Tin | Antimony | Copper | Zinc | Silver | 68°F | 212°F | °F | °F | °F |
| Optimized Alloy | 81.3 | 12.0 | 6.0 | 0.6 | 0.1 | 24 | 12 | 458 | 680 | 1000 |
| ASTM B23-2 | 89.0 | 7.5 | 3.5 | | | 24 | 12 | 466 | 669 | 795 |

### *Technical Data*

A comparison of the technical data shows considerable improvements of the optimized material over ASTM B23-2, although the physical properties have practically remained unchanged (Table 3). The yield point of 7020 psi, even at 212°F, as against 3000 psi, is more than twice as high.

*Table 3. Technical Data.*

| Alloy Grade | Yield Point, psi | | Johnson's Apparent Elastic Limit, psi (J.A.E.L.) | | Ultimate Strength in Compr. psi | |
|---|---|---|---|---|---|---|
| | 68°F | 212°F | 68°F | 212°F | 68°F | 212°F |
| Optimized Alloy | 12660 | 7020 | 11840 | 6530 | 19300 | 10300 |
| ASTM B23-2 | 6100 | 3000 | 3350 | 1100 | 14900 | 8700 |

### *Dynamic Impact Load Capacity*

ASTM B23 gives no data about material properties regarding impact load capacity. This matter was tested, using a test machine and proceeding as follows: A rod held at its two ends was rotated and, after each rotation of 72 degrees, a drop hammer radially hit on half the rod length (Figure 2). Test rods of different bearing materials were tested under identical conditions and, in each case, the number of impacts up to rupture of the rod were counted. From the marginal conditions and the number of impacts, the work resulting from the impacts can be calculated. The results are comparative values, showing the differences of the materials as to their dynamic impact load capacity. The results as to the numbers of impacts lie in the range of 285 for lead basic alloys, of 490 for tin basic alloys with lead impurities of up to 3 percent, and 3741 for ASTM B23-2, if it is lead-free. With a value of 2856, the new alloy is situated at a comparably high level. This is particularly remarkable because the reference alloy with cadmium only achieves a value of 910. This is due to the fact that cadmium enormously increases the compressive strength, but at the same time embrittles the alloy as a whole. The optimized material does not have this embrittling effect anymore.

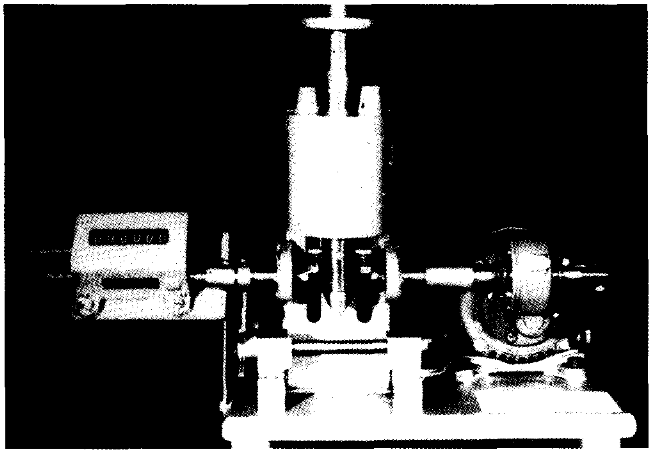


*Figure 2. Impact Load Test Machine.*

*Reduced Creeping Behavior*

The difference is particularly marked when comparing the Johnson's apparent elastic limit (JAEL) value. The new material has a value of 6530 psi, at 212°F, and ASTM B23-2 of only 1100 psi (Table 3). This is due to the following reason: A typical stress-strain diagram for common white metal-bearing alloy is curved along its total length. The stress-strain behavior of the new material is different. This material has long straight ranges on the stress-strain diagram, and the JAEL point is close below the yield point. This means that the new material has a wide elastic range up to a level of around six times the JAEL point of the ASTM B23-2 alloy at 212°F. The consequence is a marked reduction in plastic deformation during high load and temperature conditions. The creep behaviors of the new material and ASTM B23-2 alloy are shown in Figure 3. Under the same conditions, the creep behavior of the new material is eight times lower. That means higher dimensional stability even in critical operating states, resulting in a longer lifetime. This fact leads us to the next examination.

*Increase of Usable Yield Strength as a Function of Layer Thickness of Bearing Metal*

Previously, examinations had been carried out to find whether, in case of compressive strength, the layer of bearing metal profits from the compound with the steel backing, and, if so, to what extent. It turned out that with decreasing thickness of the bearing-metal layer, the usable compressive yield strength increases. This is, in fact, logical, because the thinner the bearing-metal layer, the stronger, under compressive strength, the support of the steel backing in compound. Through empirical results achieved in practice as well, one knows that a higher compressive yield capacity is to be expected when the bearing-metal layer is thin. For the bearings used in rolling mills, one has been utilizing this empirically found knowledge for a long time. The author found this matter so interesting that it was examined anew. To get an exact result curve in the newly performed tests, a very simple trick was used: two identical compound test specimens were arranged in such a way that the bearing-metal surfaces contacted each other. In this arrangement, the specimens were inserted into the test machine and subjected to compressive stress. Both specimens are subjected to the same forces; both bearing-metal layers are stressed in the same way and undergo identical deformations. Therefore, there is no differential deformation in transverse extension and, consequently, no hindrance of the transverse deformation of the bearing metal. This was confirmed by the evaluation of the test results. Unambiguous curves could be recorded (Figure 4). These starting values had been measured before on solid bearing metal, and they remain valid in the compound practically for a bearing-metal layer thickness of approximately 0.2 inch and more. If the layer thickness in the compound is less than 0.2 inch, the compressive yield point clearly rises. With a layer thickness of 0.06 inch, the value almost doubles. These results coincide with the empirically determined data for rolling-mill bearings. However, this requires a considerable expenditure. The rolling-mill bearings of 35 inch diameter are provided with a bearing-metal layer of about 0.04 inch thickness. This requires very high production expenditure with correspondingly high costs. Therefore, one must find for each individual application an optimum between cost and benefit. Generally, it can be said that backings made of grey cast-iron with dovetail grooves and the resulting necessary casting with bearing metal of 0.4 inch thickness are out of date. When using steel backings without dovetail grooves and a bearing-metal layer of 0.1 inch thickness, the usable compressive yield strength is already 25 percent higher. At the same time, the costs are lower because of less production expenditure through the absence of dovetail grooves and less bearing metal needed. Additionally, there is a reduced quality risk in the foundry because the binding between bearing metal and steel, contrary to cast-iron, can be realized on a high quality level. Furthermore, the binding can be checked on the smooth steel surface completely. That means that in this way, the quality can be increased with simultaneous cost reduction. If one does not take advantage of the higher yield strength, the rate of utilization of the alloy will decline, and the lifetime of the bearing will increase. Thus, higher load-bearing reserves are available in case of overloads of short duration due to malfunctions. The risk of damage in case of short overloads is also reduced.

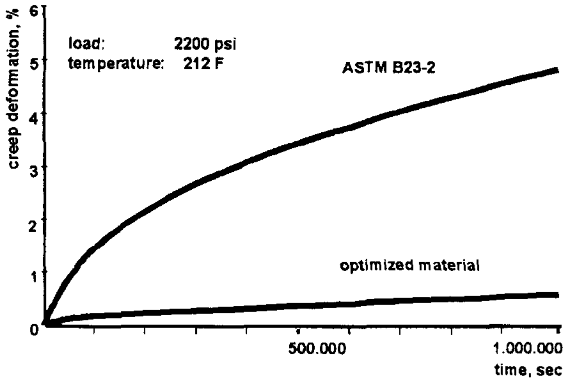


*Figure 3. Reduced Creep Behavior of Optimized Material.*

*Long Time Behavior*

A higher compressive strength increases, however, the risk that strain in creep is also growing. In such case, the bearing metal is

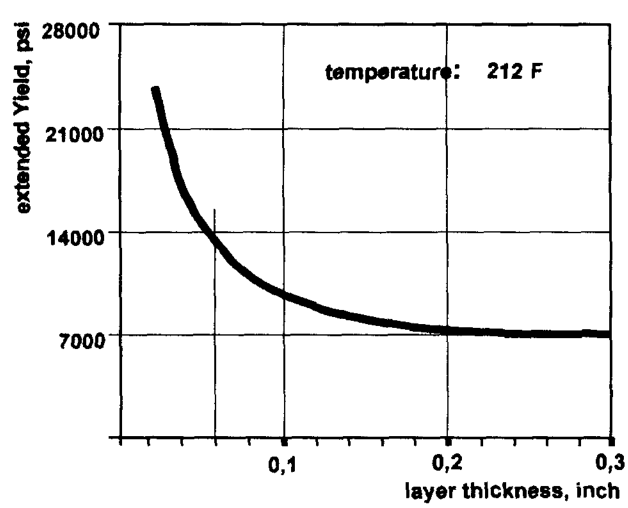


*Figure 4. Extended Compressive Yield in Relation to Reduced Layer Thickness in Compound with Steel Backings. Tested with Optimized Material.*

first shifted in the running direction, without cracks. A bead is developed. The geometry in the narrowest lubrication gap is disturbed. Mixed friction, local overheating, and, finally, damage to the bearing occurs. Therefore, under high compressive strength, bearing materials with a low strain in creep are needed. To use, in addition, the advantage of higher yield strength as a function of the layer thickness, a bearing material with minimum creep is needed. The new material fulfils this condition. It creeps less than all other bearing metals.

### *Further Examinations*

The above stated facts inevitably lead to the question to what extent the additional yield strength as a function of layer thickness can be made use of in the future, without reducing the lifetime of the bearing due to creep deformation. An examination was started with the aim—in simplified words—of combining the curves from Figures 3 and 4 in one curve for the new material. The curve that is generated will show the increased compressive yield strength, similar to Figure 4, but in reduced form, because the longtime creep behavior is included. Tests are already running. As these tests are, however, longtime tests and a large number of individual tests will be performed, these results will probably not be available before the end of 2003.

## PRACTICAL EXAMPLES

There are some practical experiences from industry to evaluate the significance of the reduced creep and the improved technical data of the new bearing alloy.

### *Rolling Mill Industry*

In an old design rolling mill in Great Britain, the rolling loads have increased because, steel grades of higher strength are rolled and, most recently, the intermediate reheating of the rolled stock has been omitted. Through these new marginal conditions, the operating temperature in the bearing varies between 280°F and 570°F. The load on the bearing varies between 3600 psi and 4800 psi. Due to these extremely high loads, the bearings are always completely destroyed after three to four days. The development of the destruction is always the same. First of all, the approximately 1.3 inch thick bearing-metal layer is heavily deformed. Then, mixed friction occurs in the bearing, and the bearing metal is squeezed out in the axial and radial direction. The bearing metal used is a British standard alloy similar to ASTM B 23-2. Modernizing the bearings through a change of design was suggested, e.g., thinner layer of bearing metal, modified arrangement of the oil pockets, and, finally, use of the improved bearing metal. As the change of design requires quite some time, the operator of the rolling mill decided to change over immediately to the new bearing material, maintaining all other marginal conditions. The subsequent operation showed the following result: After 30 days, the bearing showed substantial damage. This was not an accidental result, but has been repeating for more than six years. Each time, the service life was at least 30 days, i.e., about 10 times longer than that of the standard alloy. This example shows clearly that in addition to the high load-bearing capacity, it is in particular the geometrical dimensional stability due to a low strain in creep of the new alloy that leads to a longer lifetime. It would not be appropriate to conclude from this result that every bearing provided with the new bearing metal will reach the tenfold lifetime. It is, however, certain that with the new material, the dimensional stability is considerably improved through the lower strain in creep. In the past years, the European steel-milling industry changed to the improved bearing metal.

### *Hydro Power Industry*

In a hydro power plant in Austria with six similar machines, they had problems again and again with one of them. This machine was set vibrating sympathetically through the water flow. It was not possible to eliminate the problems, so the friction bearings had to be exchanged every year due to dynamic overstress damage. Finally, the improved bearing-metal alloy was used, and now the bearings have been running damage-free.

### *Turbine and Generator Industry*

On a new steam turbine, the play in the friction bearings was too small, due to a defect of manufacture. This led to an increased operating temperature of 280°F. The friction bearings survived one year of trial operation under these conditions, without damage. German and Austrian power generation and the generator industry are using the improved bearing-metal.

### *Ship Propulsion Industry*

Companies of the ship propulsion industry in Norway are using friction bearings with the improved bearing metal.

### *Gear Industry*

For highly stressed gears, the improved bearing material is increasingly being used.

### *Railways*

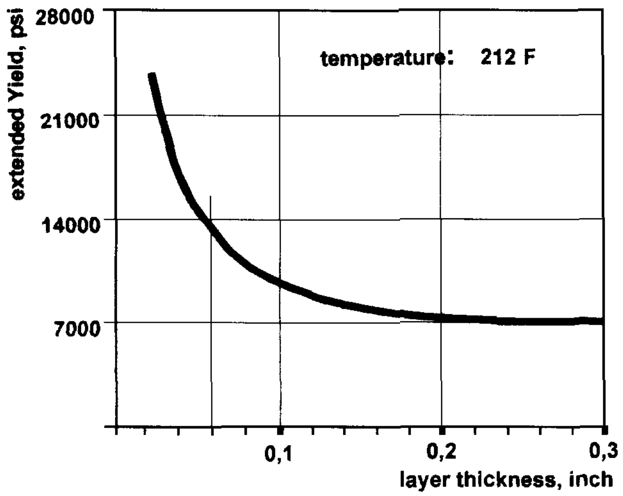
In Europe there are electric locomotives with a construction in which the drives are supported in friction bearings on the wheel undercarriage. After several years of trial runs with the improved bearing metal, longer service life was proved, and all locomotives have been converted to the improved material.

### *Tilting-Shoe Journal Bearings*

A large German manufacturer of tilting-shoe journal bearings changed over completely to the improved material and supply the bearings to a wide range of market segments.

### *Turbomachinery Industry*

The above-mentioned bearing producer supplies high numbers of bearings to the European turbomachinery industry every year. A German producer of generators and steam and gas turbines also uses only the new material. In Europe, every year some thousands of bearings for turbo applications are produced with this material. The formerly used material in Europe was equivalently loadable, but ecologically harmful because of cadmium. The European turbomachinery industry continues with the new material at a comparably high standard without environmental problems. No spectacular damages occurred, so examples cannot be presented.



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A large German manufacturer of tilting-shoe journal bearings changed over completely to the improved material and supply the bearings to a wide range of market segments.

### *Turbomachinery Industry*

The above-mentioned bearing producer supplies high numbers of bearings to the European turbomachinery industry every year. A German producer of generators and steam and gas turbines also uses only the new material. In Europe, every year some thousands of bearings for turbo applications are produced with this material. The formerly used material in Europe was equivalently loadable, but ecologically harmful because of cadmium. The European turbomachinery industry continues with the new material at a comparably high standard without environmental problems. No spectacular damages occurred, so examples cannot be presented.