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Social and Economical Benefits of Remanufacturing of Bearings

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Abstract - **The substantial growth in industrial production, demand for materials and population has led to an increasing need for sustainable manufacturing process to mitigate the negative impact on the environment and meet the needs of future generations. One proposed direction is remanufacturing. It utilizes the energy and inherent value retained in products upon reaching end-of -life. It can close the loop between disposal and supply chains, extend the service lifetime of products, conserve resources and helps to mitigate the environmental impacts. By preserving the geometrical architecture of cores, remanufacturing can reduce the needs for raw material processing and many manufacturing process, hence there are associated social and economical benefits.**

Keywords: **Sustainable Manufacturing, Remanufacturing, Geometrical Architecture, Environment.**

I. INTRODUCTION

Remanufacturing is the only process where used products are brought at least to Original Equipment Manufacturer (OEM) performance specification from the customer's perspective and, at the same time, are given warranties that are equal to those of equivalent new products (Ijomah W, 2002). The reasoning here being that if a remanufactured product has quality equal to that of a new equivalent then its warranty must also be the same. Of all the current "secondary market" (used product) processes, remanufacturing involves the greatest degree of work content and as a result its products have superior quality and reliability. This is because remanufacturing requires the total dismantling of the product and the restoration and replacement of its components. Remanufacturing is particularly applicable to complex electro-mechanical and mechanical products which have cores that, when recovered, will have value added to them which is high relative both to their market value and to their original cost (Lund, 1984).

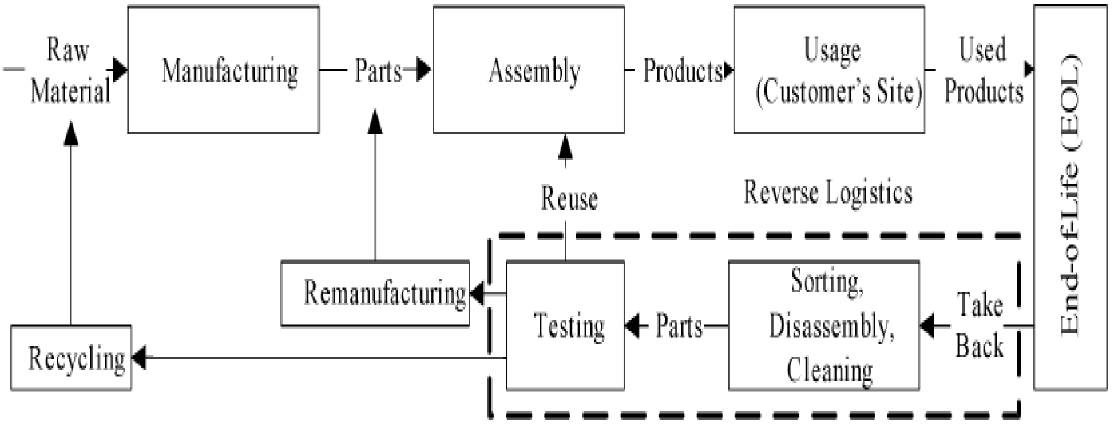
The essential characteristic from an environmental aspect is that remanufacturing preserves the embodied energy (energy) that has been used to shape the components for their first life. Lund estimates that a remanufactured product only requires 20-25% of the energy used in its initial formation (Lund R T, 1985). Thus, as well as reusing the material, the energy required to produce a new product is significantly lower. Although the environmental advantages are clear there are other benefits from remanufacturing. Bras & McIntosh state that, by receiving back old products, manufacturers can obtain feedback on reliability and durability information and can also resell into lower-priced markets, typically costing 60% of the original production cost (Bras B & McIntosh M W, 1999).

II. LITERATURE REVIEW

Classical rolling-element fatigue, which is of subsurface origin, has been considered the prime life-limiting factor for rolling-element bearings. With proper design, handling, installation, lubrication cleanliness, a rolling-element bearing will eventually fail by fatigue. Field experience has shown that less than 10 of the bearings removed from service have failed from end of life sub-surface fatigue. The remaining 90 percent of the failures are due to causes such as lubricant flow interruption, lubricant contamination, lubricant deterioration, excessive dirt ingestion, improper bearing installation, incorrect mounting fits, mishandling of bearings prior to installation, installing a contaminated bearing, manufacturing defects, ring growth in service, and corrosion. These other modes of failure are for the most part unpredictable. They tend to be of surface as opposed to subsurface originated. In general, failures due to surface defects occur much earlier than those failures due to classical rolling element fatigue [1,2,3].

For nearly four decades it has been a practice that rolling element bearings removed at maintenance or overhaul be reclaimed. Bearings are disassembled, cleaned, and visually inspected. If no major imperfections are found, the bearings are reassembled, lubricated, and packaged for further service. In some cases the rolling elements are replaced with new balls or rollers [4].

Bearing rework can be divided into four levels. These are (1) Reclamation, (2) Refurbishment, (3) Restoration by grinding, and (4) Remanufacture. The following procedures are recommended by the Industry [5,6].



Reclamation Level I

Processing bearings involves inspecting a used bearing and checking/comparing it with new bearing drawing requirements. This process involves:

(a) Demagnetization.
(b) Cleaning.
(c) Non-destructive testing, if applicable.
(d) Visual/microscopic inspection.
(e) Minor repair: buffing and polishing of inactive and active surfaces, stoning of nicks and gouges in corner radii
(f) Dimensional inspection.
(g) Reassembly (to include retainer riveting or snap-in retention).
(h) Dynamic testing (if required): rotation of bearing rings to permit evaluation of noise level, torque characteristics, and/or similar functional parameters.
(i) Lubrication/preservation.
(j) Packaging.

Refurbishment Level II

Refurbishment of bearings is rework of bearings that goes beyond the scope of reclamation. This encompasses all of the operations of reclamation plus one or more of the following:

(a) Replacing rolling elements.
(b) Reworking/replacing retainers.
(c) Interchanging used components and/or substituting new components to create a different assembly identity.
(d) Grinding or polishing and/or plating of mounting surfaces as necessary to return to original drawing dimensions.
(e) Honing (superfinishing) raceways (not to exceed 12.7 µm (0.0005 in.) total metal removal per surface).

Restoration Level III

Restoration of bearings involves the removal of material by grinding operation. This term encompasses all of the operations of reclamation and refurbishment plus one or more of the following operations:

(a) Grinding races – up to 76 µm (0.003 in.) per surface.
(b) Installing oversize rolling elements.
(c) Installing original or replacement retainer when required.

Remanufacture Level IV

Remanufacturing of bearings involves rework of bearings, where new components beyond the rolling elements and retainers are manufactured. This term encompasses all the operations of processing and may involve either refurbishing or regrinding of the old parts which are reused and one or more of the following:

(a) Manufacturing of a new ring.
(b) Manufacturing of a new retainer

When a bearing raceway is damaged by fatigue spalling, it is not considered for rework. However, when there is superficial damage to the bearing raceways, caused by dirt or debris, raceways can often be restored by honing or grinding. In general, superficial damage extends to a depth less than 51 µm (0.002 in.) from the surface.

For bearing refurbishment or restoration, repairable bearings are disassembled, the components are visually inspected, and the hardness of the bearing rings is measured. The components that are determined to be restorable are dimensionally inspected. Where necessary, the bearing faces, bores, and outer diameters are ground or polished and either nickel or chrome plated to a thickness that will allow the surfaces to be reground or polished to the original blueprint dimensions.

The bearing separator is stripped of its silver plating, where applicable, inspected for cracks, and replated. If it is required, the separator is replaced with a new one. The new rolling elements are placed within the separator and the bearing is reassembled.

During refurbishment both inner and outer raceways are honed to a depth of not more than 12.7 µm (0.0005 in.),which removes all superficial damage and a small portion of the stressed material volume. The surface is finished to its original blueprint specification or better. The bearing is then refitted with new rolling elements having a diameter equal to the diameter of the elements previously contained in the bearing plus twice the depth of honing. The new rolling elements used are from the same nominal size family.

During restoration both inner and outer raceways are ground to a depth of not more than 76 µm (0.003 in.),which removes all superficial damage and a portion of the stressed material volume. The surface is finished to its original blueprint specification or better. The bearing is then refitted with new rolling elements having a diameter equal to the diameter of the elements previously contained in the bearing plus twice the depth of regrinding. For the cylindrical roller bearings the roller length as well as the roller diameter is increased. The new rolling elements used usually exceed the original nominal size family. This large increase of the rolling elements may require the rework of the separator pockets or replacement of the cage.

BEARING LIFE ANALYSIS

1) NOMENCLATURE

A	material-life factor
a	semimajor axis of contact ellipse, m, (in.)
b	semiminor axis of contact ellipse, m, (in.)
C_D	dynamic load capacity, N (lbf)
c	stress-life exponent
e	Weibull slope
F	probability of failure, fraction or percent
h	exponent
L	life, number of stress cycles or hr
L_{10}	10-percent life or life at which 90 percent of a population survives, number of stress cycles or hr
L_{50}	50-percent life or life at which 50 percent of a population survives, number of stress cycles or hr
L_β	characteristic life or life at which 63.2 percent of population fails, number of stress cycles or hr
LF	life factor
l_r	roller length, m, (in.)
l_t	race track length, m, (in.)
N	life, number of stress cycles
P_{eq}	equivalent radial load, N (lbf)
p	load-life exponent
r	number of bearings failed
S	probability of survival, fraction or percent
S_{max}	maximum Herts stress, GPa (ksi)
V	stressed volume, m^3, (in.3)
V_x	stressed volume removed by honing or grinding, m^3, (in.3)
V_{1-x}	remaining stressed volume after honing or grinding, m^3, (in.3)
x	fractional percent of depth to maximum shear stress
Z	depth below surface, m, (in.)
Z_o	depth to the orthogonal shearing stress, m, (in.)
Z_{45}	depth to the maximum shearing stress, m, (in.)
τ_0	orthogonal shearing stress, GPa (ksi)
τ_{45}	maximum shearing stress, GPa (ksi) Subscripts
b	ball
ir	inner race
or	outer race
r	roller
re	rolling elements
I,II,III,IV	Level I, II, III, or IV rework

Lundberg–Palmgren Equation

In probabilistic life models, the bearing physical characteristics, applied load, operating profile, and environment determine the probability of failure, assuming that the life is represented by a known probability function. W. Weibull [9,10,11] was the first to suggest a reasonable way to estimate material fracture strength with such a probability function. Based upon the work of Weibull [9,10,11].

G. Lundberg and A. Palmgren [7] in 1947 showed that the probability of survival S could be expressed as a power function of the orthogonal shear stress τ_0, life N, depth to the maximum orthogonal shear stress Z_o, and stressed volume V. That is,

$$\ln\frac{1}{S} \sim \tau_0 \frac{N^e}{Z_0^h} V \qquad (1)$$

From equation (1),

$$L = N = A\left(\frac{1}{\tau_0}\right)^{c/e} \left(\frac{1}{V}\right)^{1/e} [Z_0]^{h/e} \qquad (2)$$

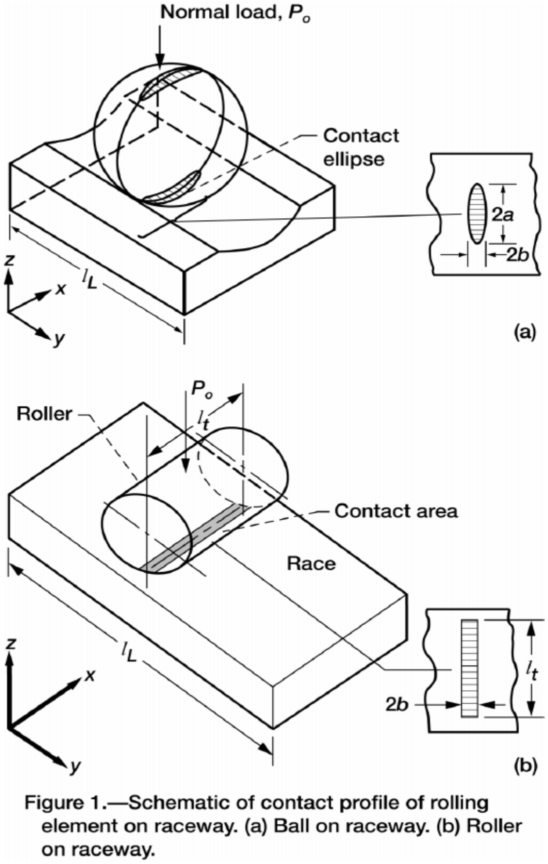


Figure 1.—Schematic of contact profile of rolling element on raceway. (a) Ball on raceway. (b) Roller on raceway.

where for ball bearings (fig. 1(a)),

$$V = al_{vl}z_0 \qquad (3)$$

and for roller bearings (fig. 1(b)),

$$V = l_t l_L Z_0 \qquad (4)$$

Lundberg and Palmgren [7] incorporated into their analysis a method and distribution function for statistically describing the fatigue life of materials developed by Weibull (ref. 15) referred to as the two-parameter Weibull distribution function.

$$\ln\frac{1}{S} = \ln\left(\frac{L}{L_\beta}\right) \text{ where } 0 < L < \infty; 0 < S < 1 \qquad (5)$$

From equation (5), Lundberg and Palmgren [7] first derived the relationship between individual component life and system life. A bearing is a system of multiple components each with a different life.

As a result, the life of the system is different from the life of an individual component in the system. The system life can be expressed, to a first order as

$$\frac{1}{L_{10}^{e}} = \frac{1}{L_{100r}^{e}} + \frac{1}{L_{100r}^{e}} \qquad (6)$$

where the life of the rolling element by inference is incorporated into the life of each raceway.

In properly designed and operated rolling-elements bearings fatigue of the cage or separator should not occur and, therefore, is not considered in determining bearing life and reliability.

From equations (1) and (6), Lundberg and Palmgren [7] derived the following relation

$$L_{10} = \left(\frac{C_D}{P_{eq}}\right)^{p} \qquad (7)$$

For equation (7), the load life exponent equals 3 for ball bearings and 4 for roller bearings. However, for roller bearings, Lundberg and Palmgren [12] choose to use *p* equal 10/3.

Zaretsky Equation

The work of E.V. Zaretsky [13] builds upon the work of Weibull (ref. 15) and Lundberg and Palmgren [7]. Zaretsky eliminates the dependency of the stress-life relation on the Weibull slope e. The depth to the critical shearing stress Z_o is eliminated as a variable. He also uses the maximum shear stress τ_{45} instead of the orthogonal shear stress τ_0 as the critical shearing stress. Equation (1) becomes

$$\ln\frac{1}{S} \sim \tau_{45}^{ce} N^{e} V \qquad (8)$$

For ball bearings, the stressed volume is

$$V = a l_L Z_{45} \qquad (9a)$$

and for roller bearings,

$$V = l_t l_L Z_{45} \qquad (9b)$$

From equation (8), the life of the raceway is

$$L = N = A\left(\frac{1}{\tau_{45}}\right)^{c}\left(\frac{1}{V}\right)^{1/e} \qquad (10)$$

Using Zaretsky's rule (ref. 13), equation (6) should be written as follows:

$$(1/L_{10})^{e} = (1/L_{ir})^{e} + (1/L_{re})^{e} + (1/L_{or})^{e} \qquad (11)$$

where the Weibull slope e is the same for each of the components as well as the bearing as system.

For radially loaded ball and roller bearings, the life of the rolling element set is equal to or greater than the life of the outer race. Let the life of the rolling element set (as a system) be equal to that of the outer race.
From equation (11)

$$(1/L_{10})^{e} = (1/L_{ir})^{e} + 2(1/L_{or})^{e} \qquad (12)$$

Where:
$L_{re} = L_{or}$

For thrust loaded ball and roller bearings, the life of the rolling element set is equal to or greater than the life of the inner race but less than that of the outer race. Let the life of the rolling element set (as a system) be equal to that of the inner race.
From equation (11)

$$(1/L_{10})^e = 2(1/L_{ir})^e + (1/L_{or})^e \qquad (13)$$

WHERE:
$L_{re} = L_{ir}$

Examples for using equations (11) to (13) are given in Zaretsky [8].

As previously stated, the resulting values for L_{ir} and L_{or} from these equations are not the same as those from equation (6). From the Zaretsky analysis, equation (7) remains unchanged.

However, the values of the load life exponent *p* becomes 4 and 5 for ball and roller bearings, respectively.

III.CASE STUDY

Remanufacturing of Bearings at SKF

Introduction

SKF has established a state of the art Bearing Remanufacturing facility at Wit field premises. This forms part of a global SKF project to offer quality remanufacturing facilities to service local markets. Custom designed washing machines, polishing stands, measurement equipment, preservation machines and a cage sandblasting machine were imported based on specifications from the SKF Industrial Service Centre in Steyr, Austria.

The total capital expenditure for the project, including imported machines, local facility modifications, a new overhead crane, compressor, measurement equipment and forklift, was Rs27 million.

The new 450m^2 centre offers increased capacity/throughput and the highest possible quality for remanufactured products. Today SKF expertly remanufacturers bearings that were previously destined for scrapping, thereby saving costs, raw materials and energy.

Suitable Bearings

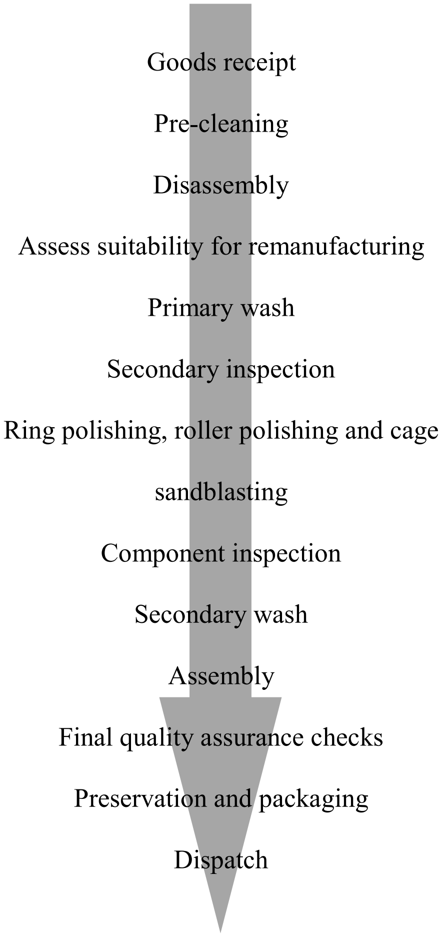
a. Bearings with a bore diameter greater than ± 250mm can generally be economically remanufactured.
b. Small bearings can be accommodated but the price of the remanufactured bearing can be close to that of a new bearing.
c. Bearings that can be non-destructively disassembled.
d. Spherical roller bearings and CARB bearings
e. Spherical and cylindrical roller thrust bearings
f. Single row angular contact ball bearings
g. Certain 4-row cylindrical, taper roller and slew ring bearings. [14]

Detailed Bearing Assessment

Before any bearing is remanufactured it is assessed by a skilled SKF technician. A comprehensive bearing assessment report is compiled that includes:

a. A summary of the condition of the components
b. A description of any damage observed on components
c. Measurements taken to assess dimensional accuracy of components and internal raceway and rolling element wear levels.

THE BEARING REMANUFACTURING PROCESS



Goods receipt

Pre-cleaning

Disassembly

Assess suitability for remanufacturing

Primary wash

Secondary inspection

Ring polishing, roller polishing and cage

sandblasting

Component inspection

Secondary wash

Assembly

Final quality assurance checks

Preservation and packaging

Dispatch

Remanufacturing Level IV

Level IV bearing remanufacturing usually comprises replacing one of the rings with a new component. In some applications, the outer ring of the bearing is also a structural member of a turbine engine (usually a flanged outer ring). It is therefore cost effective to keep the outer ring and only replace the inner ring and the rolling elements. However, for cylindrical roller bearings where there is an inner-ring riding cage/rolling-element assembly it is cost effective to keep the inner ring and separator and replace the outer ring and the rollers.

Assume that the inner ring of the deep-groove bearing is replaced along with the ball set. The Level IV L_{10} life for the deep-groove ball bearing

$$\frac{1}{L_{10}^{1.11}} = \frac{1}{(13796)^{1.11}} + \frac{1}{(51872)^{1.11}} + \frac{1}{(55183)^{1.11}}$$

$$L_{10} = 9905\text{hr} \tag{14}$$

The Level IV life factor is

$$LF_{IV} = 9905/10000 = 0.99 \tag{15}$$

The Level IV life of the angular-contact ball bearing

$$\frac{1}{L_{10}^{1.11}} = \frac{1}{(20486)^{1.11}} + \frac{1}{(79418)^{1.11}} + \frac{1}{(20468)^{1.11}} \tag{16}$$

The Level IV life factor is

$$LF_{IV} = 9970/10000 \tag{17}$$

Assume for purposes of example that a cylindrical roller bearing having an inner ring riding separator (cage) is removed at its predicted L_{10} life of 10 000 hr. and is subject to Level IV restoration. The inner raceway is honed whereby 5 percent of the surface material is removed. The outer race and roller set are replaced with new ones. If the life or the outer race is 4 times that of the inner race, then the L_{10} lives of the inner race, outer race and roller set are 13 796, 55 183 and 55 183, respectively. The life factor for the inner race after honing is calculated from table 1 and equation (33a) where,

$$LF_{ir} = 0.87 + 0.05(1 - 0.87) \approx 0.88 \qquad (18)$$

The life of the restored inner race is 12 140 hr. (0.88 X 13796 = 12 140) and the calculated life of the restored bearing is 9 127 hr. The Level IV life factor (LF_{IV}) for this bearing is 0.91 (9127/10000 ≈ 0.91). Where the inner race is reground removing 20 percent of the material from the raceway, the resultant Level IV life factor (LF_{IV}) is increased from 0.91 to 0.92 or approximately 1 percent. However, the resultant increase in cost from grinding additional material from the raceway may not be justified by the small increase in calculated life for this example.

From the above analysis, Level IV restoration has the potential to restore the life and reliability of bearings removed from service to nearly that of new bearings.

CUSTOMER BENEFITS

Significant cost savings

a. Spherical roller thrust bearings with a bore diameter of 460mm
b. Application - Gearbox
c. Quantity - 4
d. Manufacturing lead time for new bearings - ± 26 months
e. Cost savings
f. Approximate new bearing replacement cost -
g. 4 x Rs667000 = Rs2668000
h. Total cost of remanufactured bearings
i. 4 x Rs300150 = Rs1200600
j. Cost saving = Rs1467400

Extended service life

Removal of stress concentrations on internal surfaces prolongs residual bearing service life

Risk minimisation due to:

1. Bearings assessed by an experienced SKF Engineer/Technician
2. Optimised process based on input from SKF manufacturing units and global bearing remanufacturing centres
3. Stringent quality control requirements are an integral part of the process
4. Clearly defined acceptance criteria
5. Use of a unique SKF designed ring wall thickness gauge to assess raceway wear

Reduced scrap rate

Replacement components for damaged bearings can be sourced from manufacturing units

Short term availability

1. Remanufactured bearings can alleviate production stoppages associated with extended lead times for certain large size bearings
2. Lead times for remanufactured bearings vary from 1 day to three weeks, depending on the scope of work

Suitability for long term storage

1. Remanufactured bearings are preserved and wrapped according to stringent SKF global standards
2. Use of an automatic preservation machine prevents dirt ingress after Remanufacturing

TABLE I ENERGY SAVINGS AND POLLUTION PREVENTION FROM PRODUCTION OF REMANUFACTURED BEARINGS

Categories of savings in the production of remanufactured bearings	Savings (%)
Energy saving	68% to 83%
Carbon dioxide emissions reductions	73% to 87%
Carbon monoxide reductions	48% to 88%
Sulphur oxide reductions	71% to 84%
Nonmethane hydrocarbon reductions	50% to 61%
Reductions of raw material consumption	26% to 90%

IV. CONCLUSIONS

By remanufacturing it is observed that the following social and economical benefits could be realised:

1. Cost is between 10 and 50% of the price of a new bearing.
2. Reduction of Green House Gases.
3. Less Raw Material Use.
4. Reduction of Energy Use.
5. Using remanufactured products lowers the operating costs for equipment.
6. Remanufacturing is a high-labor content business.
7. Remanufactured parts can bring “high-quality” safe solutions.
8. Sense of making an environmentally friendly choice.

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