TORSIONAL ACTUATORS TWIST ROTOR BLADES IN FLIGHT, PAGE 70

MACHINE DESIGN

MAY 5, 2005
www.machinedesign.com

AMERICA'S MOST USEFUL DESIGN ENGINEERING MAGAZINE

A PENTON PUBLICATION
Periodicals
USPS 100 Approved Poly

Keep Rolling

NEW BRONZE-ALLOY BEARINGS HANDLE EXTREME LOADS, page 82

EMBEDDED SYSTEMS
The first wave of wireless controls and sensors, page 92

THE MOVE TO METRIC COMPONENTS, PAGE 98

Threading through the myths of ball-screw grinding, page 106

Bearing up under 300 tons

Spinodal bronze alloys help ensure lubricant-starved bearings keep mining equipment rolling under extreme loads and in corrosive environments.

David Krus
Brush Wellman Inc.
Cleveland, Ohio

David Juba
Director, Engineering
Pioneer Solutions LLC
Cleveland, Ohio

To solve a recurring problem with steel-sleeve bushings on a continuous mining machine, Joy Mining Machinery, Warrendale, Pa., switched the bushing material to ToughMet 3 CX105 alloy. The original dynamic linkage pins needed complex lubrication systems that weren't always maintained well in the field. The result was that figure-of-eight channels machined into the bushings did not distribute enough lubricant to keep components from galling. The inherent low friction and lubricity of the ToughMet alloy let designers build more compact bearing arrangements that continue to function even when starved of lubrication.

Surface and underground mining operations use some of the world's largest mobile machinery. Continuous mining equipment and large tonnage dump trucks often run around the clock regardless of whether or not they get regular maintenance. But lax maintenance can lead critical components such as kingpin bushings to seize or fail from corrosion and extreme wear. A worn, broken, or seized bearing can shut down equipment for days, drastically cutting into a mine's profits.

Bronzes make up the most versatile class of bearing alloys. But when dump trucks have tipped the scales at 180 tons and carried payloads of over 300 tons, designers historically have relied on high-strength steel and sophisticated lubrication techniques to keep bearings running freely. The problem is, surface and underground mining isn't always the most conducive environment for keeping to rigorous maintenance schedules, so bearings may not get lubed at optimum intervals.

Lubrication-starved steel bearings in heavy-duty mine machinery are prone to galling, erosion, and corrosion. Copper-based bronze alloys are an option for overcoming these problems. But it can be tough to find an alloy with the strength to withstand the extreme dynamic loads involved. Recently developed spinodal bronze alloys, however, boast excellent tribological (low friction) properties to help prevent galling. They also have tensile strengths to 160 kpsi (1,100 MPa) making them candidates for replacing steel. Additionally, this class of bronze alloys has extremely low (rate depends on environment) corrosion rate and thermal conductivities of between 20 and

EH5000, 180-ton dump trucks from Hitachi Construction Truck Mfg. Ltd., Guelph, Ont., had lubricated-steel upper and lower kingpin spindle bushings on the front suspension that were wearing quickly. This caused slackness in the steering and, ultimately, damage to other components. But it was tough to replace a bushing that has a bore of 9.5 in., a 1-in. wall thickness, and is 8 in. long, especially out in the field. To evaluate replacement parts made from aluminum bronze and ToughMet 3 CX105, engineers built a test rig that replicated one side of the front suspension to simulate field conditions. Tests showed that the ToughMet had one-third the wear rate of aluminum bronze, which equates directly to a threefold increase in the service life of the vehicle.

40 Btu/ft-hr°F (39 to 72 W/m°K), so they dissipate heat well.

BEARING BRONZES

Copper (Cu)-based bronze alloys have played an important role in high-performance bearings for years. They offer a broad range of strengths, ductility, and hardness. They have good antifriction and antiseizing properties, can conform to surface irregularities, and tolerate dirty operating environments. They also may resist corrosion better than other bearing alloys and work well at high temperatures.

Key to designing a bearing for heavy, off-road equipment, however, is to look beyond just the mechanical attributes the metal brings to the table. Designers must define working loads, shaft hardness, lubrication, working temperature, and speed of rotation of the bearing regardless of the bearing material.

Ideally, the bearing material will have enough compressive and impact strength to withstand permanent deformation from static as well as suddenly imposed loads. High fatigue and creep strengths let bearings withstand variable stresses. Good thermal conductivity allows dissipation of frictional heat from bearing surfaces.

According to the **Copper Development Assoc.**, New York, the best known bearing bronzes fall into the following categories:

Tin bronzes: The main function of tin (Sn) is to make alloys stronger. Zinc (Zn) also boosts alloy strength with better economics. However, at about 4% Zn the alloy starts to loose antifrictional properties. Tin bronze alloys must be relatively hard so they don't conform well to rough or misaligned shafts. They also don't embed dirt particles easily and therefore must be used with clean, reliable lubricants.

C90300 (88Cu-10Sn-4Zn) has hardness values in the range of 300 to 400 Bhn and are strong yet ductile. The alloy works well under heavy loads at low speeds. It resists corrosion from seawater and stands up to impacts and wear. It also machines easily and can be cast. Typical applications include aircraft landing-gear bushings, trunnion and trolley wheel bearings, and wristpin bushings.

C90500 (88Cu-10Sn-2Zn) also serves in bearings that see heavy loads and low speeds. It highly resists impacts and wear and is used in piston-pin and linkage bushings as well as rocker-shaft bushings for internal combustion engines.

Leaded-tin bronzes: Small amounts of lead (Pb) improve machinability without degrading alloy bearing

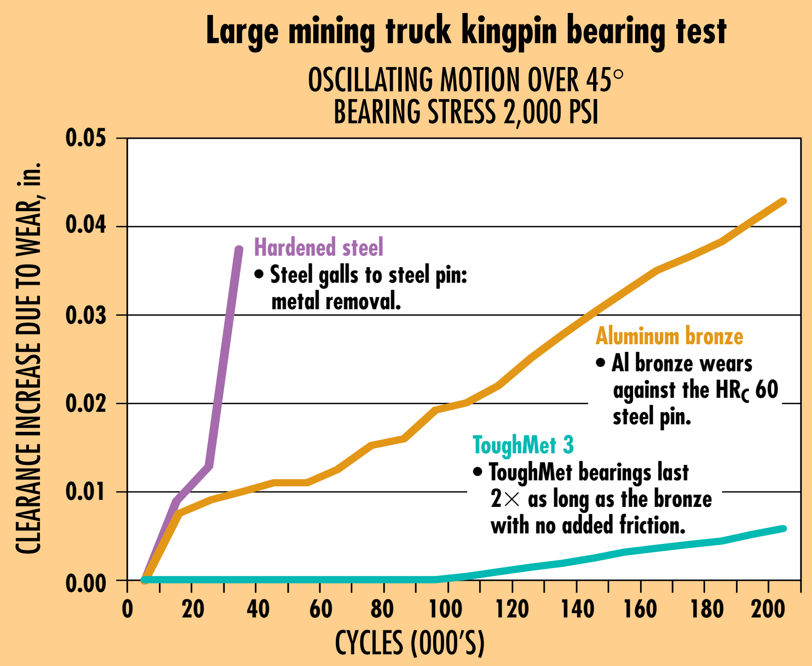
KINGPINS WEAR WELL

Engineers at heavy-equipment engineering firm **Pioneer Solutions LLC** (formerly part of **Euclid-Hitachi**) designed a test rig to find a bearing alloy that would work better than aluminum-bronze. The test rig simulated Hitachi EH5000 front axle loads. The 180-ton dump trucks had lubricated-steel upper and lower kingpin spindle bushings on their front axles that were wearing quickly. The task of replacing worn bushings is labor intensive, so engineers wanted to find a material with a longer service life.

The fixture simulates a 1-G load and ran test samples for 120,000 cycles. Tests took place on bushings made from ToughMet CX, a cast alloy with a yield strength of 105 psi and a hardness of 30 HR_C; and on ToughMet AT, a wrought version with a 110-si yield strength and a 32 HR_C hardness. Technicians greased the bearings approximately every 1,000 cycles for the first 10,000 cycles and every 20,000 cycles thereafter.

ToughMet AT had good wear resistance compared to steel and aluminum-bronze. But galling and metal transfer between it and the steel kingpin caused some damage to the kingpin.

ToughMet CX bushings also stood up well to wear. Metal transfer was an issue, but metal transferred only from the bushing. The steel kingpin was used in a second test of a CX bushing.



A 3.5-in.-diameter, 2.5-in.-long plain bearing slowly rotated back and forth at an angle of 45° around the HR_C steel kingpin. The temper of the Toughmet was T3CX105.

properties. A few leaded-tin alloys also use Zn to help get cost down.

C92700 (88Cu-10Sn-2Pb) is hard and strong with good resistance to wear and corrosion. It is for heavy, slow applications in severe working conditions. It machines well and can be cast but needs good lubrication and a shaft hardness of 300 to 400 Bhn. Typical applications include bearings in earthmoving machines, gear bushings and connector rods, trunnion bearings, mechanical linkages, and spindle bushings.

C83600 (85Cu-5Sn-5Pb-5Zn) has excellent thermal conductivity, moderate strength, and best suits light loads operating at low to medium speeds. It has good machining and casting properties and is found in applications such as automotive-transmission thrust washers, low-pressure valve bearings, manifold bushings for earth-moving equipment, automotive spring bushings, and bearing shells and backing for Babbitt-lined bearings.

High-leaded tin bronzes: This class of alloys is the workhorse of the bearing bronzes. The metals serve in a wide range of applications under medium loads and speeds.

C93200 (83Cu-7Sn-7Pb-3Zn) has excellent antifrictional properties, machines and casts easily, and is hard, strong, and wear resistant. It suits such applications as farm-equipment mechanical linkages and camshaft bushings; guide bushings for valves, rams, and piston rods; motorcycle-engine bearings; and conveyor roller bushings.

C93400 (70Cu-5Sn-25Pb) has excellent antifrictional properties, conforms well, and suits bearings operating under light loads, high speeds, with little lubrication. This alloy does not have good wear or impact resistance and can't handle extremely heavy compressive and shock loads. Typical applications include hydraulic pump and rod bushings, carburetor bearings, and water-lubricated bushings.

C93700 (80Cu-10Sn-10Pb) has good strength and wears well under heavy loads, at high speeds (500 to 1,000 fpm), despite shocks and vibration. It has excellent antifriction properties and is a good candidate for applications prone to poor lubrication. It also resists mild acids found in mine water. Typical applications include piston pins for diesel engines; armature bearings; and bushings for crankshafts, spindles, connecting rods, and aircraft controls.

C93800 (78Cu-7Sn-15Pb) is a general-purpose alloy for moderate loads and high speeds. It resists corrosion from seawater, some concentrations of sulphuric acid, and mild mine acid, but only offers fair wear resistance. It has good antifriction properties and serves well under poor lubrication. Applications range from kingpin bushings for earthmoving-equipment and drum bushings for cranes to general-purpose bearings for passenger and freight cars.

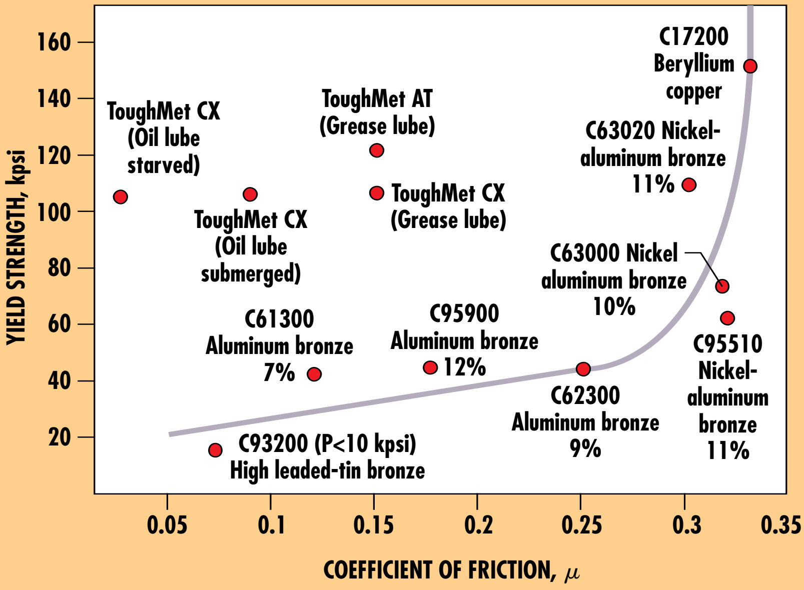
Aluminum bronze: Aluminum (Al) bronzes have historically been the strongest of the copper-based bearing

MECHANICAL PROPERTIES OF BEARING ALLOYS

Materials	ToughMet 3	Manganese bronze	Aluminum bronze	Leaded tin bronze
UNS number	C96900	C86300	C95400	C93200
Yield strength, kpsi	100 to 120	60	30	14
Tensile strength, kpsi	105 to 130	110	75	30
Elongation, %	15 to 2	12	12	10
Hardness	HR_C 26 to 34	HR_B 90	Bhn 150	Bhn 65
Modulus of elasticity, 10^3 kpsi	18.5	14.2	15.5	14.5
Fatigue strength,* kpsi	40	25	28	10

* 10^8 cycles

Strength and frictional comparison



Strength and frictional comparison of copper-based bearing alloys. Alloys mated with steel in uncoated, grease-lubricated systems unless otherwise noted.

alloys. The Al content not only gives them high strength, it also lets them be heat treated. Their high strength comes at a loss of ductility so bearings will not conform well nor embed. Bearing surfaces that need extreme smoothness (1,520-μin. rms) and lubrication need careful monitoring because they lack antiseizing properties typical of leaded-tin bronzes. They have excellent corrosion resistance and perform well at elevated temperatures.

C95400 (85Cu-11Al-4Fe) is an extremely hard, abrasion and severe-impact-resistant alloy that maintains high strength at elevated temperatures — compressive strength at 500°F equals that of tin bronzes at ambient temperatures. But it has relatively poor antiseizing performance and needs reliable full-film lubrication to prevent scoring from metal-on-metal contact. Shaft hardness must be 550 to 600 Bhn and surface finish on both bearing and shaft should be 15 to 20-μin. rms. This alloy serves in bushings for earth-moving equipment and machine-tool and roll-neck bearings.

Manganese bronzes: C86300 and C86400 alloys are modifications of the Muntz metal-type alloys (60Cu-40Zn) and contain small amounts of manganese (Mn), iron (Fe), and AL, plus Pb for lubricity, antiseizing, and embedability. They are strong, resist corrosion, and can operate under heavy loads at low speeds. But the shaft must be hard and lubrication reliable. Typical applications range from large valve stems, gears, and bearings to hydraulic cylinder parts and impellers.

SPINODAL BRONZES

Until recently, OEMs could get ternary spinodal bronzes only in thin sections available through powder metallurgy. However, a recent EquaCast processing technique now produces ternary copper-nickel (Ni)-tin alloys that include ToughMet 2 (Cu-9Ni-6Sn) and ToughMet 3 (Cu-15Ni-8Sn) in 25-in.-diameter billets. The alloys were developed for high-performance bearings in aerospace and heavy-duty mobile industrial equipment as well as for undersea and oil and gas exploration.

Most copper-base alloys develop high strength from solid solution hardening, cold working, precipitation hardening, or by a combination of these strengthening mechanisms. ToughMet alloys, on the other hand, get their high mechanical strength from a controlled thermal treatment called spinodal decomposition.

The EquaCast process uses a closed-head continuous casting process with a patented top cap and direct slots interposed between the top of the mold package and the liquid in the large holding furnace. Cyclic withdrawal of the billets at high rates of speed create alloys with an ultrafine microstructure.

With spinodal decomposition, a continuous diffusion process takes place spontaneously when the various metal atoms are nearly the same size and have sufficient mobility in the parent matrix. There is no nucleation step and two chemically different phases develop with the same crystal structure. Heat treatment at a temperature above the miscibility gap (a region where the single-phase alloy separates into two phases) makes atoms diffuse evenly to form a homogenous solid solution of a single phase.

Next the alloy sees a rapid quench to room temperature and then is reheated to a temperature within the spinodal region to initiate the spontaneous decomposition reaction. The alloy stays at this temperature until the reaction completes.

Alloys strengthened by spinodal decomposition develop modulated microstructures — thin layers that are often described as "waves." Transmission electron microscopy is the only way to see these structures. The spinodal Cu-Ni-Sn alloys have threefold more yield strength than the base metal. The high strength comes from the coherency strains produced by the uniform dispersions of Sn-rich phases in the copper matrix. Other conventionally produced Cu-Ni-Sn alloys don't show such uniformity and are likely to undergo segregation that frequently leads to hot shortness during hot working. Segregation also results in highly variable final mechanical properties in cast or wrought products.

The ToughMet alloys have five to eight times the thermal conductivity of steel and twice the conductivity of aluminum. This lets them quickly dissipate frictional heat from bearing surfaces. Additionally, compared to aluminum bronze C95400 with a yield strength of 52 kpsi (359 MPa) and a hardness of 92 HR_B, a casting made from ToughMet 2 CX90

TIPS FOR REDESIGN

In applications where the exact fit of the pin and bushing is not highly critical, it is possible to just replace a hardened-steel bushing or other bronze-type bushing with ToughMet. However, key factors determine whether this is practical:

- The pin should be harder than the ToughMet. Normally, this is the case, but the hardness of the pin should be at least 40 HR_C, and preferably closer to 55 HR_C.
- Ensure that any sharp edges are broken, especially in the grove area. Particles of the material can work harden between the pin and bushing to create galling.
- The grease grove pattern is important especially in oscillating applications. Typical rotational-type grease groove patterns can leave areas of the joint lubrication starved.
- Maintain proper clearance between the pin and bushing.

has a typical yield strength of 95 kpsi (655 MPa), 28 HR_C hardness, and a lower coefficient of friction.

Similarly, ToughMet 3 CX105 15Ni-8Sn spinodal Cu-based castings have the strength of steel (105-kpsi (724 MPa) yield strength) and also has a lubricity typically associated with lead bronzes. This lets designers build more compact bearing arrangements that still function when starved of lubrication. And unlike conventional bronzes, the alloy vigorously resists damage from contaminants that might migrate into the bearing (some damage is possible in extreme situations).

THRUST-BEARING PERFORMANCE

A recent test shows how a spinodal bronze compares to two common leaded-tin bronzes used for building dynamically loaded thrust washers. The test interested manufacturers of drive-train components because spinodal bronze bearings had performed well in underground continuous mining machinery and large off-road dump trucks. Of specific interest was the wear-rate and PV (pressure × velocity) limit behavior of ToughMet 3 CX105 compared to the leaded-tin bronzes C93200 and C93700.

An oil-lubricated sleeve-bearing test determined the PV limit. In a bearing system the PV limit is defined as the maximum bearing pressure (applied load/projected area) and surface speed at which the material can maintain its bearing properties. The test takes place at a constant rotational speed equivalent to 90 surface meters per minute (smpm). The bearing load rises incrementally. Technicians wipe lubricant on the shaft before the test and apply additional drops of lubricant as needed to keep the friction coefficient below 0.1 as the load rises. The bearing has "failed" when the coefficient of friction exceeds 0.15 or the measured temperature rises about 100°C regardless of the quantity of lubricant applied.

Both the ToughMet and C93200 reached the PV limit by exceeding the 0.15 friction coefficient while the temperature remained below 100°C. The ToughMet PV limit exceeded that of the leaded tin by a factor of three (609,000 to 158,000 MPa-smpm, respectively). This information about PV limit, while useful for comparing bearing materials performance, should not be used as a design criterion.

For the wear-rate tests, a Falex #6 thrust-washer test setup approximates conditions transmission thrust bearings see. Wear testing uses two lubrication conditions — "normal lubrication" and "limited lubrication." For normal lubrication testing, technicians applied a liberal amount of Mobilith SHC 460 grease. For limited lubrication conditions the grease was applied and the excess removed. No additional lubrication was added during the test.

Wear is determined by measuring the weight loss after 20 hr of running at a constant PV of 840,000 MPa-smpm. Under normal lubrication all the samples ran for the full 24 hr without difficulty. The wear rates for the ToughMet 3 CS105 was the lowest at 0.1 mg/hr, while the C93200 gave the highest at 1.6 mg/hr. The coefficient of friction values were also lower for the ToughMet alloy, 0.02 compared to 0.3 for both tin bronzes. Likewise, the maximum temperatures (measured using a thermocouple in a stationary sample 3 mm from the surface) for the ToughMet were also lower, 110°C compared to 170°C for both C93200 and C93700.

Under limited lubrication, no sample ran for the full 20 hr test because the lubricant smoked excessively. In all cases the friction coefficient rose with C93200 the most severe at 0.1. Additionally, C93200 also had both the biggest increase in temperature (280°C) and wear rate at 4.2 mg/hr.

On the other hand, C93700 saw a slight rise in friction coefficient with a maximum of 0.04. Its temperature rose to 166°C while its surface roughness hit 0.5-μm R_a in the wear track. The wear rate was 1.2 mg/hr.

The ToughMet 3 CX105 under limited lubrication has a friction coefficient nearly equal that of the C93700. The temperature rose to 202°C and the steel-surface roughness climbed to 0.42-μm R_a in the wear track. The alloy's wear rate of 0.3 mg/hr is 14 times less than C93200 and four times less than C93700.

A final examination via a light microscope revealed that both tin-bronze alloys had cracks initiating in the wear tracks and on the edges. The ToughMet sample did not show any signs of cracking, spalling, or smearing. ■