Introduction to Worm Gearing

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Worm gears are among the oldest types of gearing, but that does not mean they are obsolete, antiquated technology. The main reasons for the bad experiences some engineers have with worm gearing are misapplication and misuse. No form of gearing works for every application. Strengths and weaknesses versus the application must be weighed to decide which from of gearing to use. For proper application and operation of worm gears, certain areas that may differ from other types of gearing need to be addressed.

The Basics

Worm gear reducers are quiet, compact, and can have large reduction ratios in a single stage. The ideal ratio range for worm gearing is 5:1 to 75:1. This is the general range for most catalog reducers. Ratios of 3:1 to 120:1 are practical and have applications that are very successful. For ratios below 3:1, worm gearing is not a practical solution for most applications, and other forms of gearing should be considered. Worm gearing for ratios above the ranges mentioned are generally more practical as part of a multistage reduction.

In service, worm gears survive large overloads and high shocks. When properly applied, worm gearing can offer excellent performance and cost savings. Worm gearing has an inherent 200% overload (i.e., 3x rating) capacity in its rating. Other forms of gearing do not have this built-in service factor. Therefore when sizing a worm gear set, a lower service factor than normal can be used.

Explanation of Hand

The purpose of left- and right-hand gearing is to change the relative rotation of the worm to the gear. Hand refers to the direction of axial thread movement as the worm is rotated. If you point your thumb in the direction of axial movement and curl your fingers in the direction of

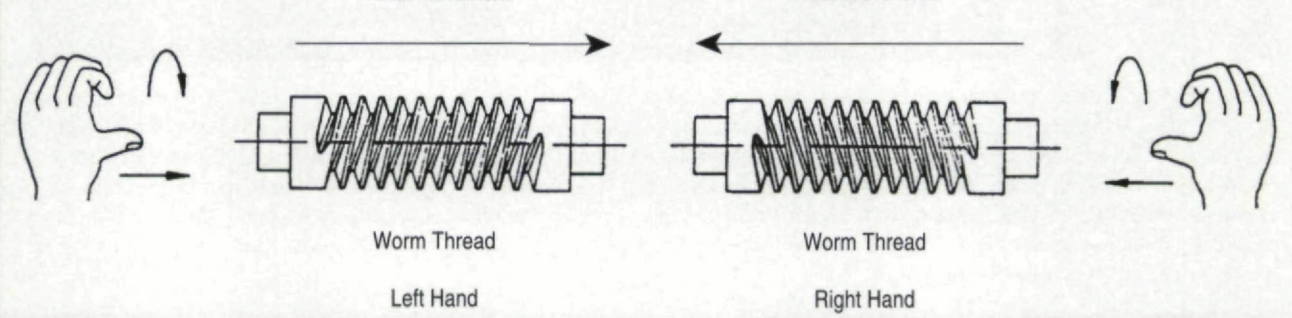

Fig. 1 - Comparison of left and right hand.

rotation, the hand that corresponds to the worm is the hand of the gear set. (See Figs. 1&2.) Bolts are a simple example. Normally they are right-handed, and experimenting with a nut and bolt will help to clarify this description.

Right-hand gear sets, like bolts, are the industry standard. More right-hand gear ratios are available as standard items, and most manufacturers will supply right-hand gearing unless otherwise specified. This does not mean there is a flaw in left-hand gearing, but left-hand ratios may not be as readily available.

Back Driving

Running a worm gear set with the gear (worm wheel) as the input member is commonly called *back driving*. Back drive efficiency of a worm gear set is lower than its forward drive efficiency. By varying design, the back drive efficiency can be reduced to zero, as in a *self-locking* or *irreversible* gear set. If the gear tries to drive the worm, internal friction causes the mesh to lock. No matter how much torque is applied to the gear shaft, mesh friction increases proportionally, preventing rotation. This is the same principle that keeps a nut and bolt from unscrewing under an applied tension load.

Back driving can occur in many applications. A worm gear speed increaser is the most obvious, but it is rarely used because of its low efficiency. It also occurs in lifting applications, such as cranes, hoists, and crank arms. When lowering the load, the gear is the input member. Worm rotation controls the rate of descent. Also, during braking or coast-down, the momentum of a device will back drive a worm.

A self-locking worm gear can be designed by making the lead angle less than the *friction angle*, which is defined as the arc tangent of the coefficient of friction. The static coefficient of friction is .20 to .15, equating to a friction angle of 11.3° to 8.5°. Vibration in a non-rotating gear set can induce motion in the tooth contact. The mesh velocity is zero, but the tooth contact is dynamic. At a mesh velocity of zero, the theoretical dynamic coefficient of friction is .124, or a friction angle of 7.0°. To provide a safety factor, a 5.0° lead angle is recommended as the upper limit of self-locking, and a 15.0° lead angle is recommended as the lower limit to assume a worm gear will back drive.

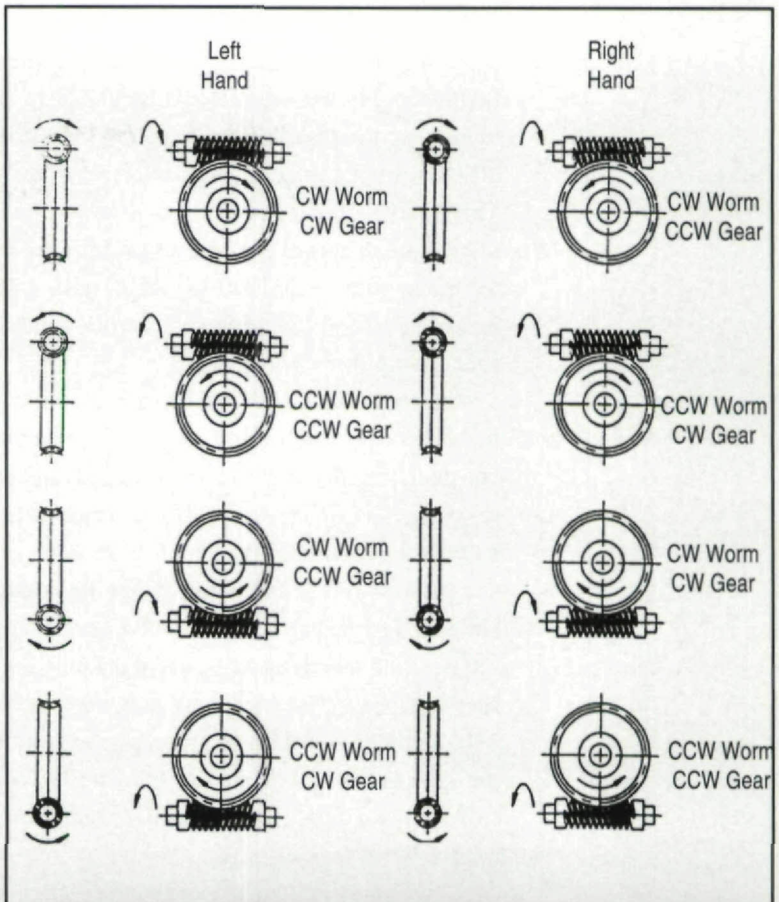

Fig. 2 - Relative rotations.

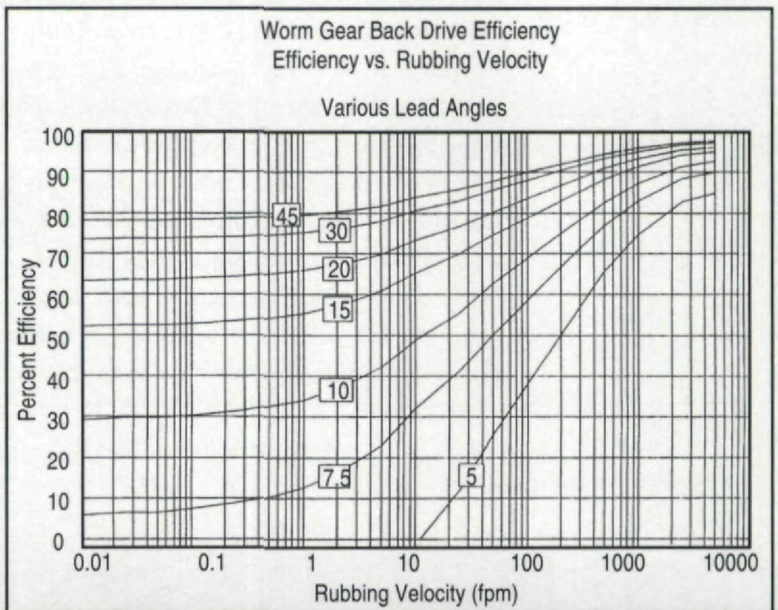

Fig. 3 - Worm gear back drive efficiency.

Back drive efficiency decreases with decreasing speed. The slope of this curve is exponential and is affected by the lead angle. (See Fig. 3.) This factor should be considered when sizing a brake and its rate of application. Often a brake placed on the worm can be smaller than normally anticipated. Self-locking worm gear

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sets will coast because of dynamic effects.

Using a brake on self-locking designs must be thoroughly analyzed. Most brakes have an increasing torque rate when applied. Also, the efficiency will be decreasing during slow down. This double effect can cause the effective braking torque to rise at a surprising rate, causing a sudden stop. High inertial loads with self-locking designs should have controlled motor speed ramp down for braking.

On the other hand, back drive efficiency increases with increasing speed. Therefore a constant back driving torque restrained only by a worm gear will have a rate of acceleration that increases exponentially. This is a very important point to remember when designing hoists. Unless it is properly designed, relying solely on self-locking mechanism to suspend a load may be dangerous. The load may stay suspended until an outside influence starts a vibration in the gear mesh. At first, the load will creep slowly. As it falls, it accelerates at an exponentially increasing rate.

Since many factors influence the coefficient of friction, gear set designs should be tested for their back drive suitability. Break-in of a gear set will reduce the coefficient of friction. This may make a gear set self-locking when it is new and not self-locking after use. Also, synthetic lubricants can have an effect on the coefficient of friction and may be used in the field without the knowledge of the gear designer.

If self-locking is critical to safety, a brake or "*back stop*" should be used. A back stop is a clutch device that permits rotation in one direction only. It is sometimes referred to as a "Sprag" or "roller" clutch and is commonly used on conveyors that lift material to prevent reversal if power is lost.

"*Plugging*" is a method of braking generally used in large crane wheel drives that use reversal of the drive motor. Plugging applications can cause extremely high torque spikes. The worm system inertia consists of the worm, drive motor, and any miscellaneous components. The gear system inertia consists of the gear and the entire braked device. When plugging, the worm can reverse rotation before the drive train loads in the back drive direction. The worm system's momentum is in a direction opposite the gear system. At impact, the worm must again reverse rotation to follow the gear, crossing a point where the mesh rubbing velocity is zero. The gear system's momentum will generate whatever torque spike is required to force the worm to reverse rotation and overcome the motor plugging torque and the mesh back drive efficiency at zero speed.

Torque spikes are a transient impact effect and not a problem when the system is properly designed. Plugging designs should limit the use of brittle materials, such as grey cast iron. Bolted joints and drive train mountings should be designed for impact. In wheel drives, the wheel slip torque limits torque spike and can be used as a maximum design point. Peak torque can be reduced by slowing the rate of reversal.

Contact Pattern

The area of contact the worm makes on the gear as it rotates into mesh is the *contact pattern*. The ideal contact pattern for worm gearing uses 90% of the full face, with the remain-

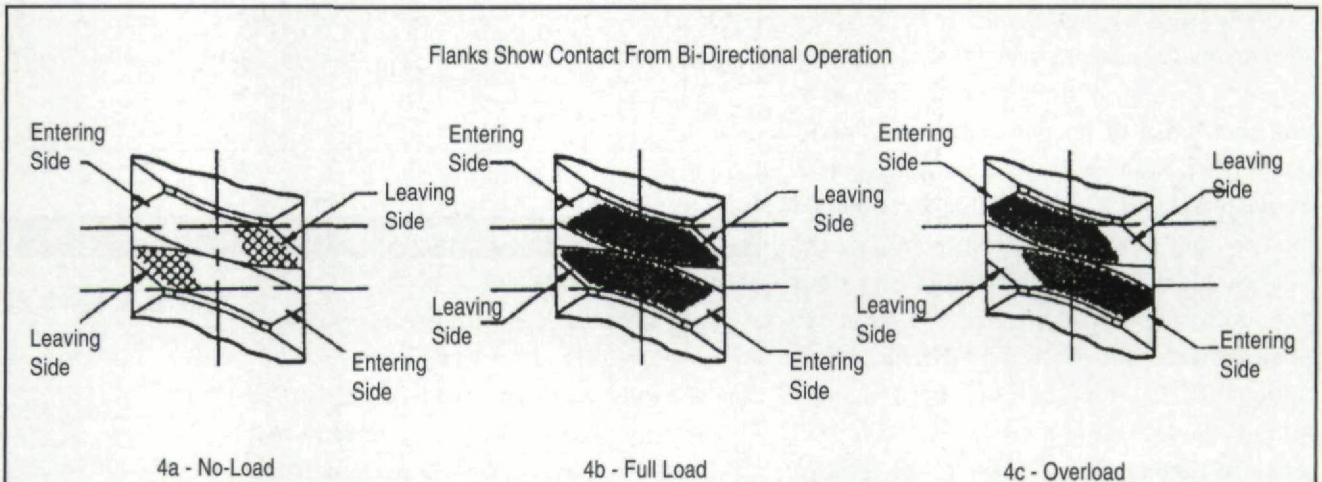

Fig. 4 - Typical contact patterns of a worm gear set.

ing 10% open on the entering side (Fig. 4b). This has maximum area for load distribution and still allows oil to be dragged in for lubrication. If the entering side has contact, (Fig. 4c) the oil would be wiped off the worm as it rotates into the gear. Without oil being drawn in, the gear set will not generate an oil film and will quickly fail. (See the section on lubrication for more details.)

Under load the gearbox, worm, and gear will deflect. These deflections cause the contact pattern to spread across the gear face toward the entering side. To compensate for contact pattern spread, the gear can be moved axially in relationship to the worm. This will increase the open face at no load (Fig. 4a), so as not to close off the entering side at full load. A no-load pattern of approximately 30% of full face on the leaving side is desirable.

Since deflections occur in opposite directions for opposite rotations, the two flanks of a gear tooth cannot be directly in line. The flanks need to be shifted axially with respect to each other when the gear is cut. The axial movement of the gear required for the contact pattern to go from 90% full face to 90% full face on the opposite tooth flank is the *total shift*. Total shift anticipates deflections that will occur from full load forward to full load reverse.

The no-load contact pattern is determined by lightly coating the worm threads with Prussian Blue (i.e., high spot blue). This transfers to the gear teeth when rotated by hand. Although not required, coating the gear teeth with a mixture of powdered orange paint pigment and grease makes the pattern easier to see. The orange grease paint improves the contrast of the blue transfer pattern and adds lubricant to the mesh. To observe the contact pattern under loaded conditions, a coat of layout blue can be sprayed on the gear teeth. This will quickly wear off, revealing the full load contact pattern. Be sure the surface is oil-free when spraying and wait until the blue dries before operation. Oil may wash the coating off if it is not completely dry.

In severe applications under heavy loads, the fully loaded pattern should be checked. The amount of shift cut into a gear may not compensate for an overly flexible housing or higher-than-anticipated loads. For one direction loading, such as hoists or conveyers, shift-cut into a gear is not a major concern. Since the opposite flank is never loaded, the pattern is adjusted on the drive flank only, ignoring the non-drive flank. When adjusting the gear to favor one flank, care must be taken so that the gear does not lose all of its backlash. If this happens, the worm is wedged into the corner of the gear. This will generate excessive heat and cause premature failure.

In most reducer designs, axial gear adjustment is accomplished by shims placed between the gear shaft bearing caps and the housing (Fig. 5a). First, determine the total shim stock for proper bearing end play. Then transfer shims from one side to the other until an optimum

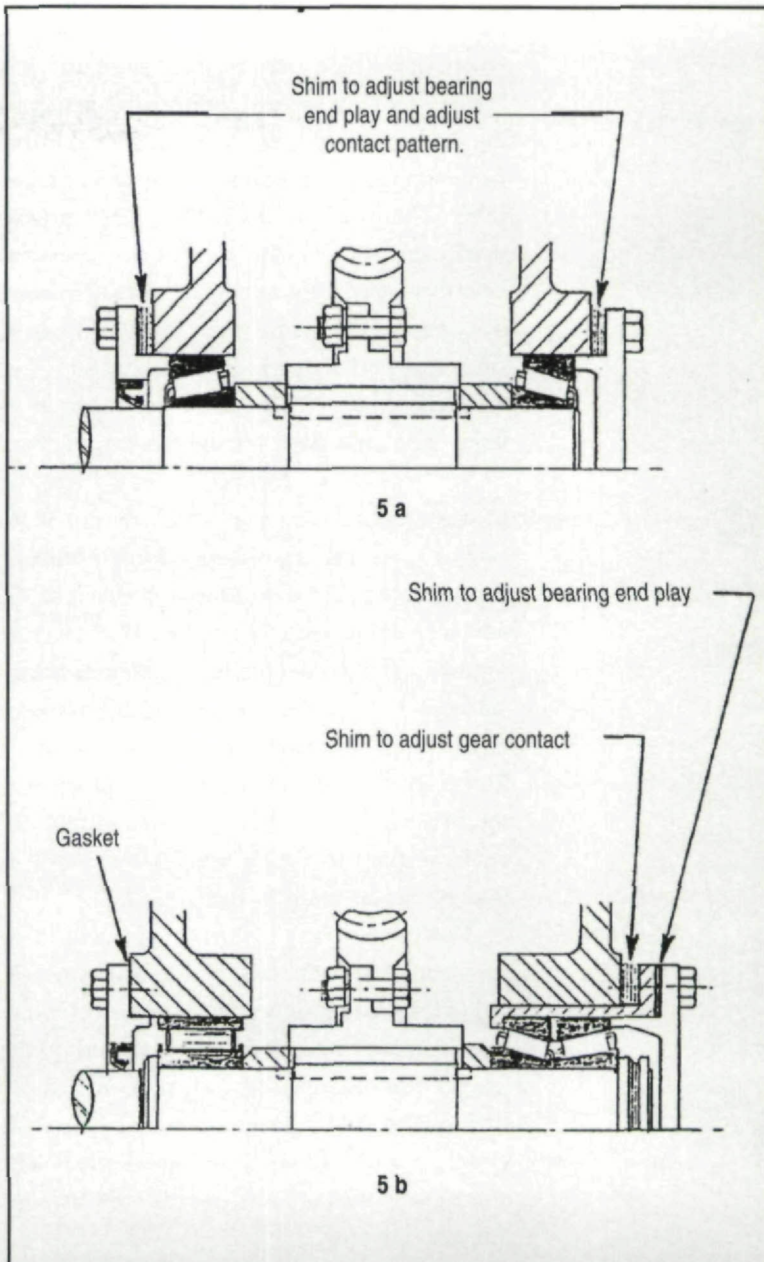

Fig. 5 - Typical gear shaft assemblies.

pattern is obtained. In heavy duty applications where one would like to adjust the gear fully loaded, moving shims requires disconnecting the shaft couplings, removing the gearbox from its mounting, and removing the gear shaft coupling. This is a very difficult process in large machinery. A common method to adjust the gear from one side is to put both thrust bearings in a carrier on one side (Fig. 5b). The opposite side is supported by a radial bearing that is free to move axially. There are other methods of adjustment, but these are the most common.

Pitting

Gear tooth pitting results from the combination of several forces. Normal force (referring to a direction 90° to the tooth surface) at the contact point produces Hertzian stress. Friction produces a tangential force, which induces subsurface shear stress. Friction also generates heat. Temperature at the contact point is much higher than the surrounding area. Differential thermal expansion (the phenomenon that can cause a glass to break when a hot liquid is poured into it) induces stress.

Constant cycling as the tooth goes through the mesh can cause a surface fatigue crack. Oil in the gear mesh is under extreme pressure from contact forces. The oil is forced into the fatigue crack, and hydrostatic pressure tries to lift a piece out. Continuing cycles cause the crack to encircle the high stress area. The crack grows deeper, until a piece literally pops out, leaving a pit.

In most gearing, a pitted tooth surface signals impending failure. For worm gearing, pitting is part of normal operation. Corrective pitting is a break-in process. In manufacturing a worm, the thread is generated by a continuous line that can be described by the grinding wheel. It produces a continuous (i.e., smooth and uniform) surface curved in all three planes. The gear is hobbed by a gashed cutting tool that is in effect a worm having a discontinuous or interrupted surface. It produces gear teeth which have a series of short flats or discontinuous surfaces that approximate the desired tooth form. Because of the flats, the gear tooth form is imperfect. Where two flats join there must be a peak. At such a point, the contact street would be infinite if deformation did not occur.

The break-in process is the gear tooth form being improved by the worm. This is done by elastic or inelastic deformation, wearing away the high spots or pitting them away. After the many high spots are either worn or pitted away, the worm rides on the larger flat areas. The pit areas retain pools of oil, which help support the load by hydrostatic pressure and aid in lubrication. Corrective pitting ceases after a sufficient area has been developed to sustain the load and normal wear takes over. A new worm gear will pit at an alarming rate, then quickly stop. No additional pitting will occur for a long time. Then the surface will again pit rapidly and quickly stop, the cycle recurring throughout the life of the gear.

Destructive pitting is a case of the gear not being able to correct itself enough to support the imposed load. It is the result of overload, improper gear adjustment, improper tooth profile, or improper lubrication. In this case, pitting continues until the gear tooth surfaces are completely destroyed. This is not a common problem, because most errors large enough to cause failure will normally show up as the gearbox overheating.

Materials

Worm gearing has a high sliding component in its tooth meshing action. Sliding contact materials are selected to make one member hard and strong and the other soft and ductile. Friction is generally proportional to the combined hardness of the mating surfaces. Two hard surface cannot deform to broaden the contact area and distribute the contact stress. By hardening only one part and having the other ductile, the combined hardness is increased, while still being able to distribute stress. Also, using dissimilar hardness reduces the chance for galling. Steel and bronze have been the materials of choice because they balance strength, ductility, lubricity, and heat dissipation. Shaft bushings are common examples of sliding components using this arrangement.

The worm is the hard member, and the gear is the ductile member. There are several reasons for this arrangement. Contact stress in both members is equal. The worm goes through more contact cycles because of the ratio of the gear set. Compared to steel, bronze has a lower strength, a lower endurance ratio, and a higher number of cycles required for infinite life. Fig. 6 uses these factors in a generalized, theoretical S-N curve. Stress levels that have a finite life for bronze would have an infinite life for steel. Since the bronze will fail at a fewer cycles, it is used for the member requiring the fewest cycles.

Gear mesh reaction forces are equal and opposite in both members. The worm is much smaller in diameter than the gear and has a greater span between supports. Therefore bending stress is greater in the worm, requiring it to be made from the stronger material.

Manufacturing methods also play a part in material choice. Grinding is generally used for accurate finish of high-hardness, heat-treated steels. Grinding the worm is a simple process, using the flank of a straight-sided grinding wheel. Grinding the gear requires a complicated process using a form dressed grinding wheel and a three-axis grinder.

Tin bronze has proved to be the most successful alloy for worm gears. It has a low coefficient of friction and a low rate of wear. Good heat conduction carries away heat generated in the mesh and dissipates it throughout the gear. Aluminum bronzes have higher strength, but also a higher coefficient of friction. A less obvious disadvantage of the higher strength alloys is lower ductility. Theoretical contact between a worm and gear is a line. In practice, the bronze deflects under load broadening the contact line to an area. The material deflects until the contact area broadens enough to support the load. A low-ductility material may have localized failure before reaching a large enough area. Small contact areas of a lower ductility material have higher localized contact temperatures, which further increase the sub-surface stresses.

The unique properties of tin bronze can be traced to its grain structure. When the bronze solidifies, partial segregation of the copper and tin occurs. High tin areas or grains are commonly called the delta phase. Hardness of the delta phase is approximately 320 Brinell. The high copper matrix supporting it is approximately 145 Brinell. The hard grains provide wear resistance and help reduce friction. The softer matrix allows surface deformation to distribute stress. A simple model would be to picture marbles (delta phase) imbedded in clay (matrix).

Alternate gear materials may increase certain properties, but losses in others will tend to make them unsuitable for general use. For special applications bronze alloys other than tin bronze may perform better. Gear materials, such as cast iron, plastic, and even steel, have worked very well in certain applications. Each application must be thoroughly analyzed by a gear engineer before selecting alternate materials.

Worms are generally made from an alloy steel. Steel worms can be divided into hardened and non-hardened. Hardened worms are superior in most applications. When surface hardness of approximately 58Rc is used, several benefits are gained. Material strength is increased, friction is lowered, and wear is reduced. Often a worm can be reused after the gear has worn out.

Non-hardened refers to the surface being lower than the typical 58 R_c. Non-hardened worms may actually have a heat treatment to bring up the core hardness for increased strength. In industrial applications, a core hardness of 300 Brinell is typical. Non-hardened worms are useful in applications with low continuous power and very high peak or shock loads. These applications are most often machine adjustments or mechanisms that are infrequently activated. Heat treating for increased surface hardness may be eliminated in low power applications to decrease cost. If a worm

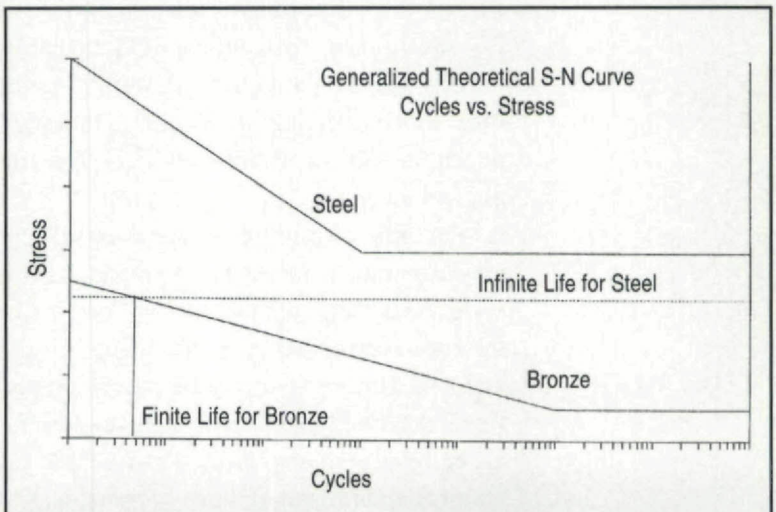

Fig. 6 - Generalized theoretical S-N curve.

is used with a cast iron or steel gear, it should be non-hardened.

Backlash Measurement

Backlash is the measure of the free clearance between the worm and the gear teeth. Measurement is done by locking the worm against rotation, setting a dial indicator on a gear tooth at the pitch radius, and rocking the gear back and forth. The total indicator reading is the measurement of backlash. Locking the gear and measuring worm rotation does not measure backlash. In an assembled unit where the gear teeth are not readily accessible, backlash can be approximated by placing the indicator on any convenient point that is fixed to the gear, such as a shaft keyway or coupling. This measurement must be multiplied by the ratio of the gear pitch radius to the measurement radius. Note that if the selected point is on the radius smaller than the pitch radius a multiplication of measurement error will occur.

$$Backlash = (Measurement) \times \frac{Gear\ Pitch\ Radius}{Measurement\ Radius}$$

Lubrication

Worm gearing has a high slide-to-roll ratio when compared to other types of gearing. Because of a high sliding component, it relies heavily on the generation of an oil film between the worm and gear. The oil film produces an effect similar to what happens when a speeding car hits a rain puddle. The car tire has a tendency to float on a wedge of water. In a car this is called hydroplaning; in gears it is called elasto-hydrodynamic lubrication (EHL). This is a simplistic description with other modes of lubrication coming into play, depending on conditions, but it gives the general idea.

For EHL to be the only lubrication mode, it must generate a film thickness greater than the surface roughness of the contacting parts. Film thickness is proportional to the sliding velocity and lubricant viscosity and inversely proportional to the unit load. High unit loads possible at the relatively low speed of worm gearing requires a very high viscosity lubricant. Viscosities of over 400 cSt at 40°C are normally used to prevent premature wear and high contact temperatures. Under high loads the film can collapse, causing the surfaces to contact. This is called "boundary lubrication." In this lubrication mode, other properties (i.e., lubricity or slipperiness) of the lubricant become more important than the viscosity. In a worm gear set, a mixture of EHL and boundary lubrication are at work.

A satisfactory lubricant for most average applications is a AGMA 7 compounded oil. Low speeds require the higher viscosity of AGMA 8 compounded oil. Both are petroleum based mineral oils compounded with 3% to 10% fatty oils. These lubricants are sometimes referred to as steam cylinder oils. The compounded oil provides lower friction and better wear characteristics than a straight mineral oil. At the high pressures and temperatures in the contact area, a chemical reaction occurs on the tooth surface, forming a protective skin.

Extreme pressure oils (EP oils) are another type of lubricant that uses a surface acting chemistry. Most EP oils use sulfur, phosphorus, and/or chlorine additives, and are designed to work in steel-on-steel applications. When these oils are used with bronze under high temperature and pressure, conditions common in the mesh contact, the chemical reaction can go awry. The surface of the bronze can begin to flake off, causing massive wear, and intergranular stress corrosion can cause the teeth to break. There are EP oils designed for use with bronze that use a different additive package, and in certain applications a standard EP oil may work very well. When selecting a EP oil for bronze gearing make sure it was carefully reviewed.

Synthetic lubricants are also very common. They are more viscosity-temperature stable than mineral oils. This allows one lubricant to provide adequate service over a broader temperature range. They have longer service life, reducing the number of oil changes required. They reduce wear and friction, increasing gearbox life. Efficiency increases of 20% of the lost power are possible. Under severe conditions properly selected synthetic oils are outstanding. Many companies have found cost advantages using the more expensive synthetic oil for normal applications. ■