

Rope Selection for Rope Drive Transmissions Used in Robotic Manipulation

by

Michael P. Summers

A PROJECT

submitted to

Oregon State University

University Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Mechanical Engineering (Honors Scholar)

Presented August 20, 2010
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Abstract approved:

Jonathan W. Hurst

Abstract Body

Wire and fiber ropes used in rigorous CBOS (cyclic bend over sheave) applications were investigated. Small diameter stainless steel, tungsten, and Vectran® ropes were tested over small sheaves at high loads and cycle speeds. Sheaves were made with Al6061-T6511 and Al7075-T651 and were coated with 0.002” hard coat anodize; some were dipped in Teflon®. Tungsten was found to have the highest bending fatigue resistance. Vectran® melted under the fast cycle speeds due to rope temperature. Neither aluminium hardness or Teflon® dip caused an increase in sheave wear resistance or rope life.

Key Words: Anodize, Rope Drive, Sheave, Synthetic Rope, Transmission, Wire Rope
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Mentor, representing Mechanical Engineering

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Summary of Rope Drive Transmissions

The current standard in rope drive transmissions is using stainless steel rope on aluminium sheaves (pulleys) that are hard coated with 0.002" thick anodize. The following list of information was found via literature review and research observations.

Power Transfer Efficiency

The highest power transfer efficiency is acquired when a very stiff rope is used in a low tension transmission stage. This can be done using wire ropes and a low torque, high speed stage.

Failure Mechanics of Ropes Bent Over Sheaves

The major sources of failure in ropes bent over sheaves are internal and external strand abrasion. Reducing frictional contact, spreading forces over larger strand surface areas, and making the wire material more abrasion and flex fatigue resistant are the basis for designing ropes that last longer in bending applications.

General Notes

- Titanium won't work. It is not a gall resistant material. Its surface reacts with oxygen creating what is known as alpha case. This is a very hard and smooth surface which lubricants cannot adhere to. This brittle surface fractures under stress and reforms, causing the rope to fail quickly.
- Synthetic ropes are stronger than wire ropes of the same diameter. However, with exception to Vectran®, they are all susceptible to creep, which is unacceptable for transmissions because they require rope pretension. Further, all synthetic ropes, including Vectran®, are subject to rope temperature build up and have low melting points. This makes them degrade under the high loads and speeds dictated by transmission applications.
- It may be possible to use synthetic ropes in transmissions that do not continuously cycle. It would allow the ropes to intermittently cool, and may prevent the rope temperature from reaching the critical temperature of the synthetic filaments. Also, new products that incorporate lubrication inside synthetic ropes may improve performance in the future.
- Lubrication makes a huge difference in rope life (by far the largest factor if the correct lubricant is chosen). It also reduces wear on the sheave or drum.
- At high loads (30% of the rope's breaking strength), the steel and tungsten ropes wore into the hard anodized coating.
- Harder substrates, such as 7075 aluminum, do not affect the wear of the coating.

- The surface finish of the pulley groove must be smooth to reduce wear. Chatter marks are unacceptable, the outer wires of the rope will snag on each chatter mark and tear away the anodize coating.

Rope Drive Recommendations

Wire Ropes

Off the shelf wire rope purchases for ropes with diameters less than 3/16" are limited to single layer strands. This means the wire sizes are the same throughout the rope. Under this constraint, a tungsten rope with seven strands and 49 wires per strand is the best rope on the market for bending over sheaves.

Custom rope manufacturers should be consulted to discuss whether they have the capability to incorporate any of the following rope design concepts.

Design Concepts that Improve Bend Over Sheave Rope Life:

- IWRC (Internal Wire Rope Core)
- Lang Lay
- Number of Strands Greater than Seven
- Preformed Strands
- Compacted Strands
- High Quality Wire Surface Finish
- Laser Hardening Wire Surface
- Lubrication
- Tungsten Wire (Manufacturer May Know of a Better Material)
- Flexible and Abrasion Resistant Construction Options: Seale, Warrington, or a Combination

Sheaves and Drums

To increase the life of the sheave it should be made out of Al6061-T6511 that has a 0.002" thick hard coat anodized surface. This maximizes wear resistance while maintaining low weight. Dipping the sheave in Teflon® and using lubricated ropes also decrease the wear rate. The effect of Teflon® is far less than lubricating the rope.

The groove profile should be oversized 6-8% to account for ropes made slightly larger than their nominal size. It should also support 120°-150° of the rope's outer surface. For helically threaded drums, the groove profile of the cutting head will be distorted along the projection of the rope path and should be designed to compensate for this.

Other Concepts that Maximize Rope Life

- The "handedness" of the cables should match the "handedness" of the spiral groove it will wrap around.
- Use a fleet angle less than or equal to 2°.
- Do not place any section of the rope under reverse bending conditions.

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Rope Selection for Rope Drive Transmissions Used in Robotic Manipulation

1 Introduction

Research was conducted to find the best CBOS ropes to be used in rope drives for robotic manipulation. These types of mechanical transmissions are highly efficient, have zero backlash, low torque ripple, low friction, high stiffness, and low cost. They have the additional advantage of placing comparatively heavy motors remotely from the joints that they drive. [1] Both the ATRIAS leg by Dr. Jonathan Hurst and the Barrett WAM™ Arm by Dr. Bill Townsend utilize a rope drive transmission for these reasons.

The majority of the information on ropes, contained in this document, comes from literary sources or interviews with company representatives. However, a rope tester was designed and implemented to fatigue test small diameter fiber and wire rope samples at high speeds and loads over small sheaves. This was done to verify some of the claims made about ropes in CBOS applications. The majority of the tests were run at 30%MBL (Minimum Breaking Load¹) and 2 machine cycles per second. The results were compared based on rope material and lubrication. The affect of sheave² design on rope life was also analyzed.

¹ A rating received from the manufacturer in units of lbs.

² A grooved wheel.

2 Wire Rope Research

Wire Ropes are comprised of individual wires that are twisted together into strands. These strands are, in turn, twisted around a core to become a complete rope. How the wires and strands are twisted is referred to as the lay of the rope. Figure 1 depicts a typical wire rope assembly.

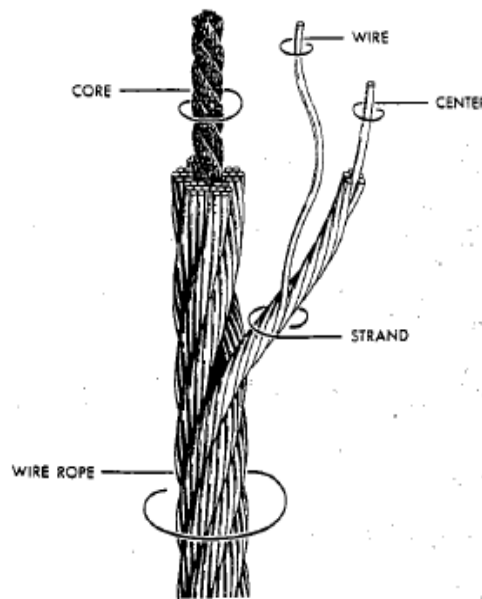


Figure 1: Typical wire rope assembly [2]

2.1 CBOS Fatigue Mechanics

The fatigue performance of wire ropes varies based on internal and external friction, and the rope material's ability to resist abrasion and wear. The design of rope constructions and the application of lubricants are used to reduce the localized friction on strands and wires. Some of the information on ropes is generic. However, manufacturing processes are not necessarily consistent across companies. For example a

company's process of drawing steel wire may create a different surface finish, tolerance on the diameter, or overall shape than another company, and ultimately change the frictional behaviour of the wire. It is unwise to assume that a rope of the same specifications will perform equivalently from two separate manufacturers. Always test the selected rope samples under application conditions before implementing them in the final design. If testing cannot be done in house, third party testing facilities can be consulted, such as TMT Laboratories (Appendix B).

Ropes that operate over sheaves are subject to bending stresses that cause rope failure. The life of the rope decreases with increasing axial load and decreasing sheave bend radius [3]. Manufacturers refer to this bend radius relationship as the $D:d$ ratio, where D is the diameter of the sheave and d is the diameter of the rope. When a rope is bent over a sheave the wires compensate for the change in shape. As shown in Figure 2 the outer most wires elongate, while the wires closest to the sheave compress. However, the outer wires have a longer distance to travel, which requires relative motion between wires and strands. The major mechanisms for wear in CBOS applications for wire ropes are “(a) contact of the outer strands of the rope with an external element, such as a sheave (commonly called crown wear³); (b) line contacts between wires within a single strand; and (c) point contacts between wires within a single strand or between strands.” [4]

When the $D:d$ ratio is reduced it increases the distance that the wires and strands must travel past one another. This leads to an increase in wear, which greatly reduces rope life. [5]

³ Crown wear refers to wear on crown wires, which are the wires on the outside of the rope that come in contact with external elements.

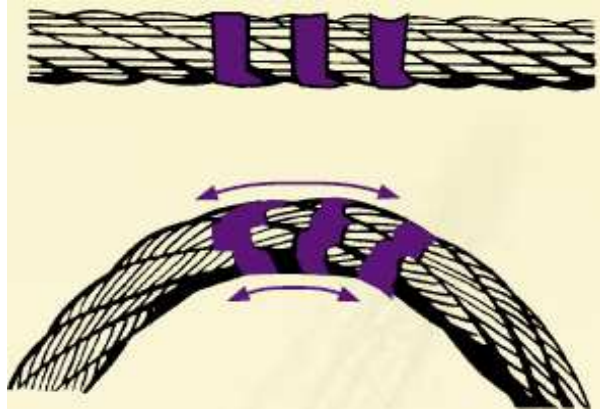


Figure 2: This drawing graphically illustrates the movement of strands when wire rope is bent over a sheave or drum. Note that the marked area on the outer strands moves as the outer wires elongate and inner wires compress. [5]

2.2 Power Transfer Efficiency of Rope Drives

Townsend and Salsbury, used a thermodynamic control volume approach (Figure 3) to derive the power transfer efficiency equation for belt and rope drives (Equation 1). For torque to be transmitted there must be a tension and velocity difference between the rope's input and output from the sheave. [6]

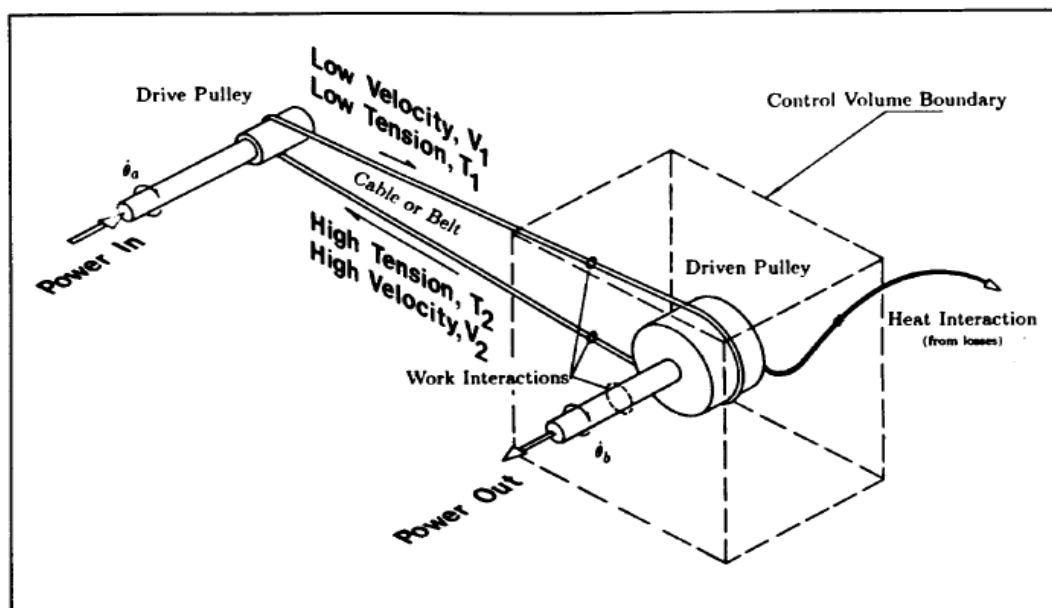


Figure 3: Tension-element (e.g. Cable, belt, etc.) drive. [6]

Their results show that the efficiency of a rope drive increases proportionally to the stiffness (E) of the tension element, and with a decrease in the tension difference between the rope's input and output. The latter can be achieved by lowering the torque and increasing the speed of a given stage of the transmission. [6] This benefits rope life, because the inherent internal rotational torque of a wire rope decreases with tension. [7]

$$\eta = 1 - \frac{T_2 - T_1}{EA}$$

Equation 1: The upper bound of power transfer efficiency η , as a function of rope tensions T1 and T2 and stiffness per unit length EA, where E is the Young's modulus and A is the metallic cross-sectional area. [6]

Their analysis assumes ideal contact between the rope and sheave. When wire ropes are run over sheaves in similar fashion to belts they rely on friction to transfer power. Since the transmission of torque necessitates rope slip from the high tension side of the sheave, the amount of friction also contributes to the wear of the rope and sheave. To idealize a transmission, the rope is terminated at both sheaves and the contact friction is minimized. The terminations and elasticity of the rope will govern torque transmission efficiency, while the low friction contact between the sheave and rope will minimize crown wear. This arrangement creates a stroke length for the transmission, but should not hinder designs for robotic manipulation.

2.3 Cores

The three basic core types are fiber, wire strand, and IWRC (Internal Wire Rope Core). IWRC is the best choice for CBOS applications for a given diameter of rope. [3] Fiber cores are less crush resistant. When they are subjected to high loads and bent over small sheaves they are less capable of supporting the outer strands than the other two core

types. Once the fiber core begins to deteriorate, strand placement becomes inconsistent and they begin to wear on one another and accelerate rope failure [8]. Wire strand cores are crush resistant, but less flexible than IWRCs.

2.4 Lays

The handedness of a rope depends on the strand twist direction. The wire twist direction relative to the strand twist direction defines whether the lay is regular or Lang (Figure 4).

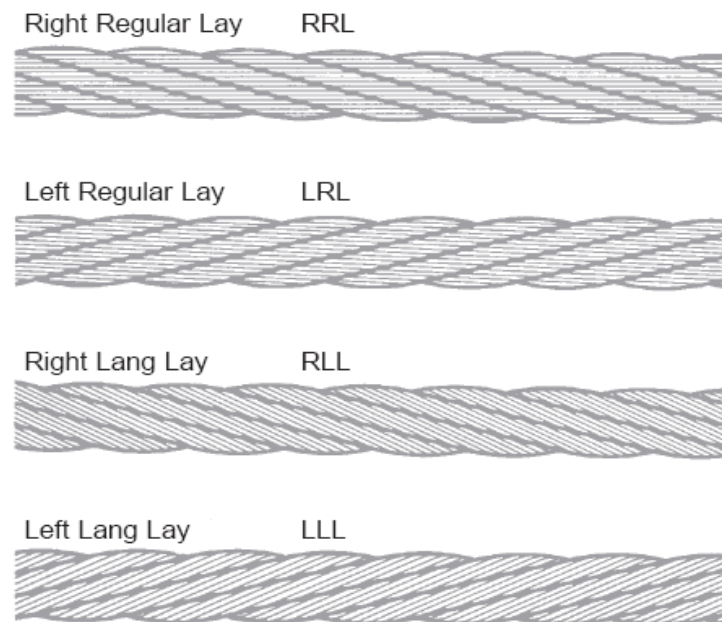


Figure 4: Wire rope lays⁴ [9]

The rope lays can also be manipulated to produce rotation resistant ropes. These constructions are designed for applications where one of the ends of the rope is free (e.g. crane hoisting). If the rope is allowed to rotate it will unravel itself and fail. [9] As previously discussed, ideal rope drive transmissions are commonly terminated at each

⁴ RRL=Right Regular Lay; LRL=Left Regular Lay; RLL=Right Lang Lay; LLL=Left Lang Lay

sheave to maximize power transfer efficiency, so rotation resistant ropes are not necessary.

It is important to never attach two ropes of opposing lay together. When loaded, the resulting torques within the ropes will give them a tendency to unravel and fatigue more quickly. When compared, Regular Lay is more crush resistant and stable, while Lang lay is more fatigue and abrasion resistant. Lang Lay is normally employed in single layer spooling applications where the rope and load do not rotate. [10, 11] An alternate lay can also be constructed, which combines regular and Lang lay strands into the same rope. It partially combines the attributes of both lays. [12]

The choice of rope hand depends on the direction of the drum groove (Figure 5). If a sheave is used, the hand of the rope will determine the wear pattern, but it is not an essential consideration.

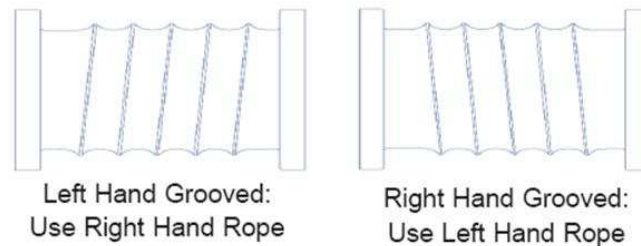


Figure 5: Choosing the correct hand of rope for groove direction [9]

2.5 The Number of Strands

The number of outer strands in a rope directly determines the contact area between the rope and sheave. By increasing this area, abrasive wear between the rope and sheave is reduced. At the same time, the stresses between strands and wires are reduced. Together these both result in an increased fatigue life. [9]

2.6 Preformed Strands

Wires in preformed strands are mechanically drawn into their helical shape before they are laid into strands. This creates a much higher bend fatigue resistant rope, because the wires and strands have minimal internal stresses. [10]

2.7 Compacted Strands

Strands are drawn and compressed before they are laid into rope (Figure 6). It increases the metallic area for a given diameter of rope and increases the contact surface area between strands, and between strands and sheave. This improves fatigue life and reduces crown wear. [8, 9]



Figure 6: Compacted Strand Rope [9]

2.8 Swaged Rope

The entire rope is assembled first and then drawn (Figure 7). This practice is normally accompanied with plastic impregnated cores. The plastic shields the outer strands from contacting each other or the core. This is similar in concept to the compacted strand design, but the plastic is not highly crush resistant and suffers the same

shortcomings as fiber cores when compared with IWRCs. Swaged ropes do have reduced constructional stretch⁵, in some cases to nearly zero. [9]



Figure 7: Swaged Rope [9]

2.9 Strength

The breaking strength of wire rope can be increased in two ways: either by increasing the wire material tensile strength or by increasing the rope's fill factor. [9]

2.10 Wire Size and Rope Diameter Affect

Generally, ropes with strands that have a few large wires are more abrasion resistant and less bending fatigue resistant than ropes with strands that have many small wires. [7, 13]

"Comparing the IWRC ropes of different diameters, the smaller rope has a better fatigue life." [3] Phil Gibson stated that this is because the wire sizes increase with increasing diameter ropes, and that the ability for a manufacturer to draw a wire to a

⁵ Stretch that occurs because the wires and strands of the rope shift to accommodate for loading.

higher strength while maintaining its ductility decreases with increasing wire size. In other words, larger wires are less ductile for the same strength as smaller wires.

2.11 Galvanizing

There is a disagreement about whether galvanizing ropes has an effect on their fatigue characteristics. A naval report claims that there is no positive or negative affect to galvanizing, with exception to ropes with small diameter external wires. In this case, galvanizing the outside of the rope improves durability. [14] Nabijou and Hobbs, on the other hand, found that galvanized ropes lasted fewer cycles than the bright⁶ ropes of the same construction. [3] Lastly, another group concluded that galvanized ropes have a lower frictional coefficient than bright ropes. [15] If this is true, galvanized ropes will wear less on the sheaves during the slip phase. It is unclear if these papers are discussing the same rope types. If galvanizing is considered for future applications, more research should be conducted.

2.12 Surface Finish

Current wire drawing practices significantly affect their surface finish, which affects the fatigue resistance of the wire rope. “Poor surface finish on drawn wires leads to early crack initiation.” [8]

⁶ Not lubricated

2.13 Laser Hardening Wire Surface

Laser hardening the surface of wires improves fatigue resistance slightly, which is expected when related to the design of ball bearings (hard surface with a ductile center). Attempts are also being made to apply hard coatings to the wires using laser surface alloying to improve fatigue resistance, but results have been inconclusive. [16]

2.14 Lubrication

Lubrication can greatly improve fatigue resistance, and is commonly overlooked. Lubricants can provide high levels of corrosion resistance and moisture displacements for use in high humidity and saline environments. They are critical for compacted strand ropes, because the compaction reduces the number and size of voids for lubrication to sit in. [8] The lubricant needs to have a high tendency of bonding to the surface of the metal wires, or it will not remain in the rope. [8] When a rope is in service it must be re-lubricated. [9] It "should be applied at a point where the rope is being bent in order to promote penetration within the strands. It may be applied by pouring, dripping or brushing." [7]

2.15 Casings

Casings are known to improve the fatigue life of ropes bent over sheaves because they prevent contact between the rope and the sheave, so that no crown wear can take place. It also shields the rope from dirt, sand, and other abrasives that can work themselves into the rope and exacerbate frictional failure mechanisms. Nylon casings are

designed for small bend radii. Other casings such as Vinyl or Teflon® will delaminate from the rope under the same conditions, in a short time. [17] The potential disadvantage to using a cased rope is that the casing will compress from the radial pressure of the sheave. This may cause force lag or backlash in the rope drive system.

2.16 Material

Information is not readily available on ropes made from tungsten and other exotic alloys. Custom rope manufacturers (e.g. Baird Industries and Jersey Strand and Cable, Appendix B) are familiar with their properties, but do not display them on their websites. This was a major reason for running tests on Tungsten. Titanium, however, is not a suitable material for CBOS applications. It has low bending fatigue resistance. Stainless steel and the certain grades of plow steel are commonly made into many constructions of wire ropes, with information readily available. See Appendix A for more information.

2.17 Constructions

Hanes lists descriptions of some of the more common wire rope constructions:



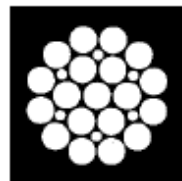
Single Size

The basic strand construction has wires of the same size wound around a center.



Seale

Large outer wires with the same number of smaller inner wires around a core wire. Provides excellent abrasion resistance but less fatigue resistance. When used with an IWRC, it offers excellent crush resistance over drums.



Filler Wire

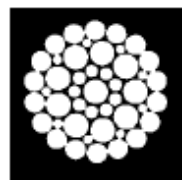
Small wires fill spaces between large wires to produce crush resistance and a good balance of strength, flexibility and resistance to abrasion.



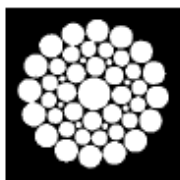
Warrington

Outer layer of alternately large and small wires provides good flexibility and strength but low abrasion and crush resistance.

Many commonly used wire ropes use combinations of these basic constructions.



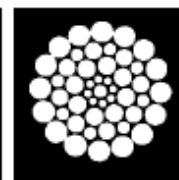
Seale Filler Wire



Filler Wire Seale



Warrington Seale



Seale Warrington Seale

Figure 8: Common wire rope constructions [7]

2.18 Off-the-shelf Ropes

Some examples of different off-the-shelf constructions can be found in Appendix A (Figure 23). Though some of them are more ideal for CBOS applications (i.e. can handle higher bending stresses while maintaining axial stiffness), they are not made in a

small enough diameter to be used in most robotic manipulation transmissions. Any construction more complex than single layer 7x1⁷, 7x7, 7x19, 7x7x7, etc., such as Seale, Filler Wire, Warrington, or a combination of these, is only available in diameters 3/16” and above. These single layer ropes are commonly called “Aircraft Cable” or “Aircraft Strand”. [7, 10, 12, 13, 18, 19]

2.19 Custom Ropes

If cost is not an issue, a custom rope can be made that best fits CBOS applications for robotic transmission rope drives. It would integrate the best attributes for bending fatigue and wear resistance from the sections above.

⁷ First number = Number of strands in the rope
Second number = Number of wires in each strand of the rope

3 Fiber Rope Research

Fiber ropes can be made from natural or synthetic materials. Filaments are normally bundled into strands and braided into rope. Standard fiber ropes are called out based on construction and strand number. They can be multi-layered (e.g. climbing rope), and can also be laid (similar constructions to wire ropes). Some common constructions are listed in Appendix A (Figure 24) from Samson Rope. Fiber ropes have been replacing wire ropes in many different applications for the past few decades. This is driven by their light weight, absence of corrosion, and low bending stiffness (ease to handle). Robotic transmissions require a rope with minimal creep and low elastic elongation that can be cycled quickly at high loads over small sheaves with high bending fatigue resistance. These requirements cannot be easily met. The latest rope technology for CBOS applications is Cortland Cable's BOB (Braid-Optimized-for-Bending) rope construction and Samson Rope's DCT (Deep Cool Technology). They are promising advancements for the future of CBOS fiber ropes.

3.1 Material

Natural fiber ropes, such as manila and sisal progressively stretch every time they are loaded, up until failure. Though synthetic ropes also go through irreversible stretch under load, after about five load cycles they enter a purely elastic region of stretch for the rest of their life, with exception to creep in the material itself. [14] Additionally, synthetic ropes are “1-1/2 to over 4 times as strong as manila ropes of equal size” [14], and are especially suited for “applications involving surging or impact loads” [14].

The highest strength fiber classes are HMPE (High Modulus Polyethylene), LCP (Liquid Crystal Polymer), ARAMID (Aromatic Polyamide), and PBO (Polybenzoxazole). Their general attributes are listed below (from Cortland Cable's website):

HMPE (Plasma®, Spectra®, Dyneema®)
High modulus polyethylene fibers produced by gel-spinning ultra-high molecular weight polyethylene (UHWPE)
<ul style="list-style-type: none"> • Excellent strength-to-weight ratio • Highest abrasion resistance of any fiber • Excellent dynamic toughness • Very low elongation (3%-5%) • Excellent flex fatigue resistance • Low resistance to heat • Susceptible to creep

LCP (Vectran®)
High modulus fiber produced by melt-spinning from thermotropic liquid crystalline aromatic polyester
<ul style="list-style-type: none"> • Excellent strength-to-weight ratio • Zero creep • Excellent flex fatigue resistance • Good abrasion resistance • High resistance to heat (melting point of 626°F/330°C)

ARAMID (Kevlar®, Twaron®, Technora®)
A manufactured high modulus fiber in which the fiber-forming substance is a long-chain synthetic aromatic polyamide in which at least 5% of the amide linkages are attached directly to aromatic rings
<ul style="list-style-type: none"> • Excellent strength-to-weight ratio • Excellent resistance to heat (chars at 800° F/427° C) • Negligible creep • Susceptible to axial compression fatigue • Poor abrasion resistance

PBO (Zylon®)
PBO consists of rigid rod chain molecules of poly (p-phenylene-2, 6-benzobisoxazole)
<ul style="list-style-type: none"> • Highest strength-to-weight ratio of any fiber
<ul style="list-style-type: none"> • Highest resistance to heat of among high modulus fibers (decomposes at 1200°F)
<ul style="list-style-type: none"> • Negligible creep
<ul style="list-style-type: none"> • Poor abrasion resistance
<ul style="list-style-type: none"> • Should be protected against degradation from light sources

Table 1: High strength synthetic fiber attributes

Within these classes the highest flex fatigue resistant are HMPE and LCP. HMPE is susceptible to creep, which removes it from selection for ropes made of a single fiber type. Vectran® is the best choice for CBOS, but, as will be discussed, fiber blends are becoming popular. They can be used to maximize the attributes of different fiber types to make higher quality ropes.

3.2 CBOS Fatigue Mechanics

The major failure modes for synthetic ropes in CBOS applications are strand on strand abrasion and temperature. Though smoother filament surface finishes can be made, lubricants can be added, and constructions can be modified to reduce the wear between strands and the wear between strands and the sheave, synthetic filaments have low melting temperatures and low heat conduction. When heat is generated within the rope, from friction, it takes a while for the heat to escape. The internal temperature of the rope increases until it begins to degrade the synthetic filaments to failure. Wire ropes also generate heat during bending, but metal wires have a much higher melting point than synthetic filaments. Under normal operating conditions wire ropes do not fail in this way. The temperature build up in rope is directly related to an increase in line tension and

the bend cycle rate. It is also proportional to a decrease in sheave diameter. [20]

Synthetic rope failure in transmissions is likely, because the cycle speeds are very fast (7-14k cycles per hour). Figure 9 shows an increase in rope temperature with cycle speed (load and bend radius are held constant).

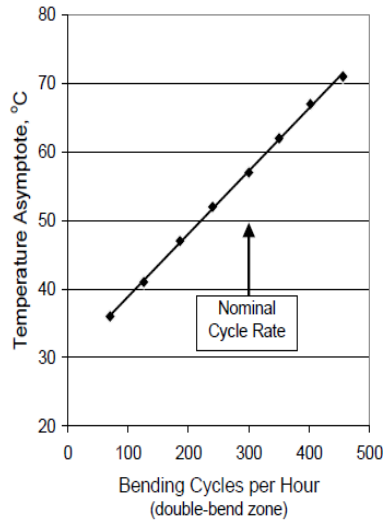


Figure 9: Temperature rise with increased cycling rate [23]

Cortland Cable performed a cycle speed test on HMPE and found that the CTF rating dropped close to 50%, at 720CPH (Figure 10). [21] As is shown in these figures, failure is occurring at relatively low cycle speeds when compared to transmission cycle speeds.

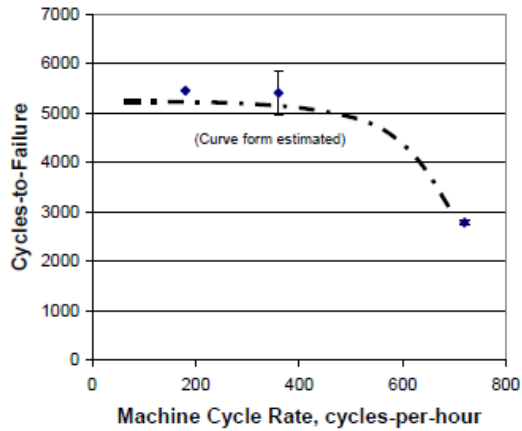


Figure 10: CTF vs CPH of HMPE with a D:d of 12.8 and load less than 20%MBL [21]

3.3 Fiber Rope Jacketing

It was found that jacketing strands, to protect them from inter-strand abrasion greatly increased the fatigue life of the rope. [22] Arguably, because it delays the onset of abrasion between strands and between strands and the sheave. [23] These jackets may be susceptible to the complications discussed about wire rope casings.

3.4 Lubrication

Lubrication reduces the friction between fibers and strands. This is important for any CBOS application. Samson rope has a specialty coating called Samanthane that they apply to each filament to reduce the internal friction of the rope. As with most rope manufacturers, it is a proprietary lubricant. They published test results where different lubricants were applied. It was found that all of the lubricants increased rope life for CBOS, and that PTFE and silicone based lubricants were the most beneficial. [20] This is an interesting find, considering that a study done by Cornell University in 1995 reported the exact opposite. Their lubricants (PTFE and Silicon Oil) did not help and, in some cases, degraded the life of the rope. [22] Further, no information was found on the reapplication of proprietary lubricants.

3.5 BOB Rope

Cortland Cable's patented BOB rope design comes in either 12-Strand or 12x12-Strand constructions. It is an HMPE and LCP fiber blended rope with a specialty coating. [21] This combination improves the fatigue life, even though it lowers the

rope's absolute strength. "Presumably by hindering any heat-induced creep elongation of the HMPE while the HMPE provided additional lubrication and support for the LCP."

[23] It increased the fatigue life by a factor of five, and is inherently torque balanced because it is a 12-Strand construction. This is an advantage in certain applications where Lang lay wire ropes are used. Though Lang Lay has a high bending fatigue life it produces high torques. [21]

3.6 Deep Cool Technology

This product, by Samson rope, uses the Samanthane fiber coating along with Omnibend fibers (ePTFE solid-lubricant fiber) in a veneer construction (Figure 11) to greatly reduce the inter strand abrasion. By doing this, the heat generated in the rope is also greatly reduced, so a much higher life can be reached in CBOS before failure (seven to ten times over "untreated" synthetics). It is a very slick and flexible fiber, but it lacks strength, so it must be blended with high strength low stretch filaments such as HMPE or Vectran® to make a rope that can bend under high loads. [20]

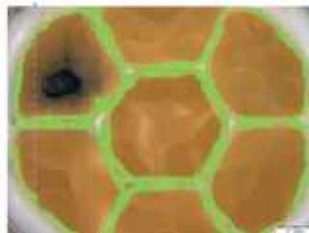


Figure 11: ePTFE in a veneer construction [20]

Unfortunately, this product cannot be used in small diameter ropes because it requires contact with every non-solid-lubricant fiber while also maintaining a low volume percent of the rope (to maintain sufficient rope strength). When the diameter is decreased

to small diameters there is not enough physical room in the rope to manipulate the packing structure to gain this low volume percent.

3.7 Filament Size and Rope Diameter Effect

Similar to wire ropes, smaller diameter synthetic ropes are more resistant to bending fatigue. When the rope size increases so does the working load. The filament diameter does not change with rope size, yet it is subjected to higher radial pressures from the sheave. [24] In addition, the lack of heat conduction inherent with fiber rope material allows larger diameter ropes to trap more heat. In CBOS applications the core temperature increases faster in larger ropes. [20]

4 Sheave Research

The performance of a rope in CBOS applications depends upon the sheave design just as much as the rope. Hobbs found that ropes tested on sheaves made from different manufacturers with the same nominal machining specifications had distinctly different CTF (cycles to failure). [3] This provides evidence that microscopic changes in the groove profile can cause changes in rope performance.

As discussed previously, by terminating the rope onto the sheave a higher power transfer efficiency can be attained without reliance on the frictional contact between the rope and sheave. This leaves two major points of focus for sheave design: the groove profiles ability to support the rope and its resistance to wear.

4.1 Rope Support

It is commonly recommended that the groove support at least 120° - 150° of the rope's circumference. The profile should be a circular shape to maximize surface contact between the rope and sheave. The majority of wire rope manufacturers recommend that the groove be oversized 6-8% larger than the nominal rope diameter, for ropes less than an 1/8" in diameter. This accounts for wire ropes that are made to a slightly larger diametric tolerance. [5, 7, 12, 25, 26] A study by Cortland Cable revealed that fiber ropes have better fatigue resistance with tight grooves (~5% oversize of nominal). [21] This agrees with the concept that a fiber rope that is not supported will ovalize, which creates an increase in inter-strand abrasion.

4.2 Failure Modes Based on Groove Design

A groove that is too small or large for the rope it is supporting will have a negative effect on its fatigue life. An oversized groove causes the rope to flatten. This is indicated by wear on less than 90 degrees of the rope. If the groove is too small it increases the groove pressure at the localized points of contact. This results in "two parallel planes of wear and/or breakages 120-150 degrees apart". [5]

Lastly, a groove that is sized correctly will create crown wire bending fatigue fractures along the outer strands. All three failure modes are depicted in Figure 12.

Narrow path of wear resulting in fatigue fractures, caused by working in a grossly oversize groove, or over small support rollers.

Two parallel paths of broken wires indicative of bending through an undersize groove in the sheave.

Typical wire fractures as a result of bend fatigue.

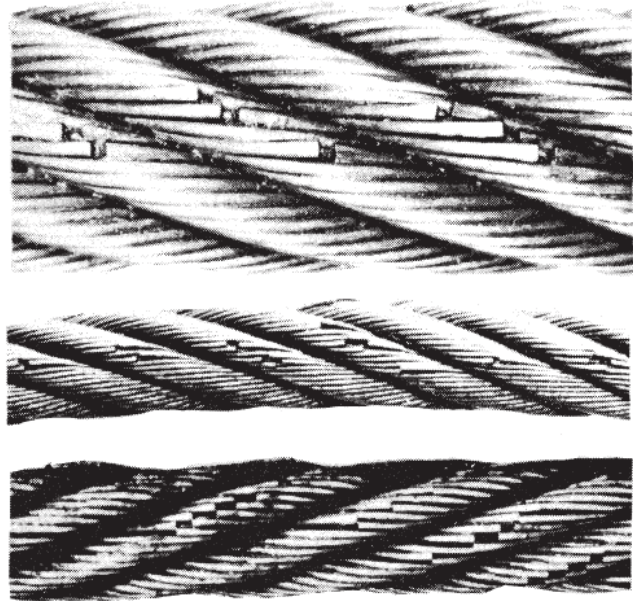


Figure 12: Failure mechanisms [27]

4.3 Material

High quality robotic manipulation depends upon force control. In order to increase the operational bandwidth of a robotic system the inertia of any dynamic part should be minimized. For this reason the sheaves should be made from a light weight

material. There is a trade-off between the life expectancy of the rope and the life expectancy of the sheave. The softer of the two will wear out first.

David Hewitt thinks that it is exceedingly difficult to design a groove that adequately supports the rope. For this reason, he believes that drums should always be less hard than the rope, so that the rope can machine its own groove into the sheave, giving it the maximum amount of support. [28] However, drum designs in rope transmissions tend to have complex and costly machining processes. It is more cost effective to make them out of a hard and wear resistant material so that they do not need to be replaced frequently. Anodized aluminum sheaves were used in this research because of their light weight and resistance to abrasion. For further information about anodizing see Appendix C.

5 Rope Tester

A rope tester was designed and implemented for CBOS tests of small diameter ropes (less than 1/4"). A single direction 302CMI Magnapack DC motor is connected to a link arm through a 5 to 1 gear reduction belt wheel. This reduction keeps the motor from approaching its torque limit during high load tests. This maintains a more consistent velocity per revolution. The link arm translates the rotational motion of the motor to the oscillatory motion of the 8" diameter drive sheave. Rope samples are wrapped around test sheaves and terminated at the back side of the drive sheave. Figures 13 and 14 show the layout of the rope tester. Figure 15 has a better view of how the drive ropes are terminated on the drive sheave. Additional process descriptions of how to setup and maintain the rope tester are in Appendix C.

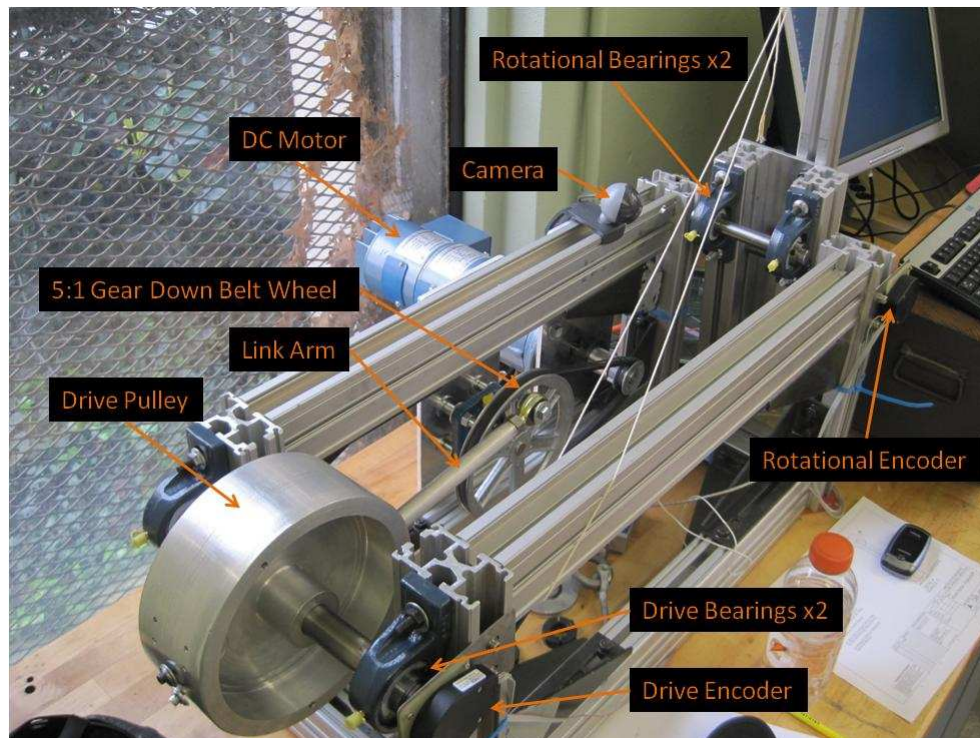


Figure 13: Rope tester (top view)

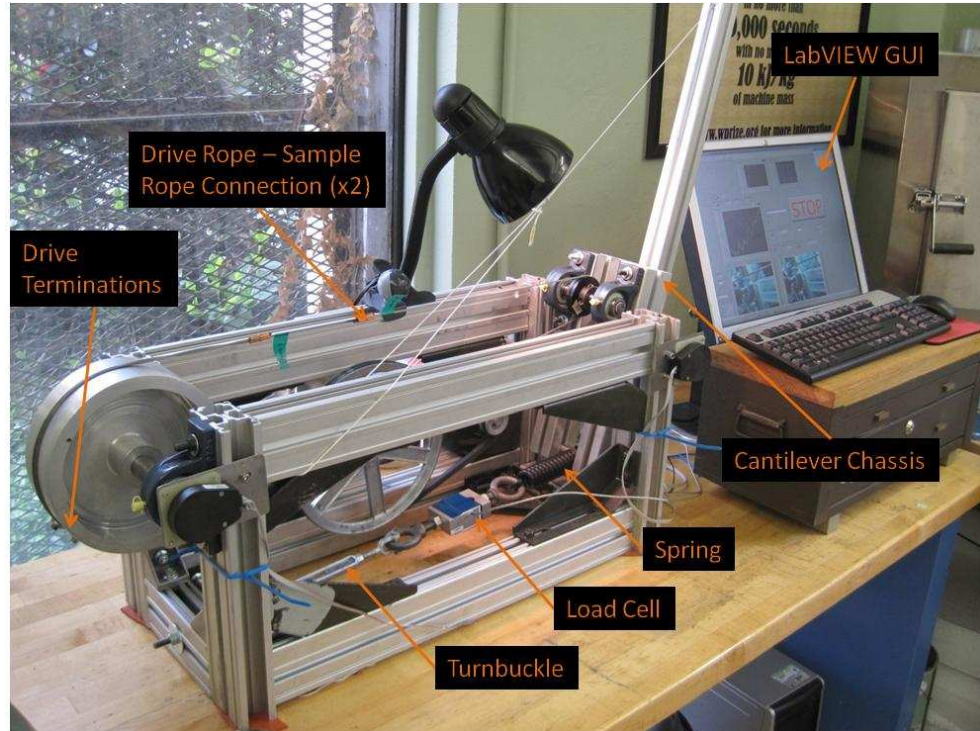


Figure 14: Rope tester (side view)



Figure 15: Drive rope termination point on drive sheave

5.1 Cantilever Loading

A 1000lbf capacity SM-1000 Interface S-type load cell is connected in series with an anchored turnbuckle and extension spring. The spring connects to one side of the cantilever chassis, the other point of contact is the test sheave shaft. It is located a quarter of the distance from the cantilever pivot than the spring connection. This creates a rope

tension equal to twice the load cell reading. The turnbuckle is the tensioning mechanism, while the spring acts as a low pass load filter to dampen vibrations and prevent shock loading.

5.2 Sample Setup

Rope samples come in small quantities. In order to maximize the number of tests two drive rope systems using 3/32" 7x19 lubricated stainless steel rope were designed (Figure 16 and 17). The loops are hooked into the termination points on the drive sheave (Figure 15) and a small section of rope sample is attached between the straight sections of drive ropes. Once a test is completed, the sample is cut off and a new one can be attached. A pair of drive ropes can be used three times with wire rope samples and numerous times with synthetic rope samples (the samples are tied not crimped), before they are retired. Manufacturing steps for this system can be found in Appendix C. Though the drive ropes are less flexible and go through many more cycles than the rope samples attached to them, the large bend radius of the drive sheave prevents them from fatiguing.



Figure 16: Drive ropes for wire rope samples

The drive rope design for fiber rope samples has permanent eyelets crimped into the ends for sample attachment (Figure 17).

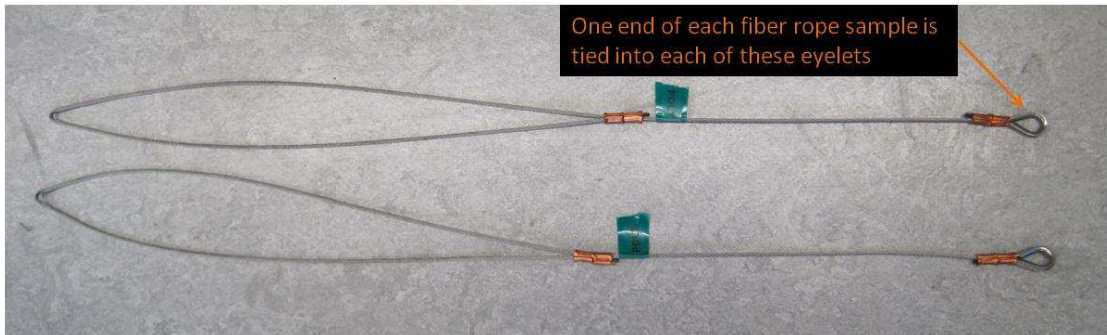


Figure 17: Drive ropes for fiber rope samples

5.3 Proof Load

Before using the rope, it is stretched axially by applying a 60% MBL load. It is advised that the rope undergo minimal handling after the proof load is applied and before it is installed for application. [29] The duration of the proof load was not defined. It was found that cycling the rope over the test sheave a few times would cause the load to drop below the proof load, due to constructional stretch. The rope was retightened to its proof load and cycled a few times further. This process was repeated until no appreciable load loss occurred after a few machine cycles.

5.4 Sheaves

Sheaves were turned from 6061-T6511 and 7075-T651 to see if the anodize would have more wear resistance if grown on a harder aluminum. The grooves were oversized 15%⁸ of the nominal diameter of the rope sample, with a root diameter⁹ based on manufacturers' recommendation for 20% MBL loading conditions. The surface finish

⁸ Before hard coat anodize process. The finished groove profiles 13% oversize.

⁹ The diameter of the surface on the sheave that the rope contacts.

was smooth, with no visible chatter marks (see Appendix C for comments). The sheaves were chemically polished, anodized with a 0.002" thick hard coat, and dipped in Teflon®. A few were not dipped, to see if the Teflon® had an appreciable affect on rope life or sheave wear resistance.

5.5 Samples

The wire ropes were provided by Sava Industries, Inc.. None came with preformed, compacted, or laser hardened wires. The constructions were all single lay. The synthetic ropes came from Samson Rope. The BOB rope was not available for sampling from Cortland Cable. This is unfortunate, because they have not performed high speed tests on it yet. See Table 2 for a listing of the samples used and their properties.

Rope Samples					
Construction	Lay	Core	Material	Diameter	MBL (lbf)
7x49	LRL	IWRC	302/304 Stainless Steel	3/32"	800
7x49	RRL	IWRC	99.95% 350ksi Pure Tungsten	2.5mm	1050
7x19	RRL	IWRC	302/304 Stainless Steel	3/32"	1760
12-Strand	Braid	NA	Vectran® T97	1/8"	1800

Table 2: Rope sample specifications

5.6 Tests

Both wire and synthetic rope manufacturers recommend a maximum working load of 20%MBL for most applications. [25, 30] Depending on the rope, a sheave diameter is also predefined for use at this working load. Since the goal of this research is to compare the bending fatigue resistance of ropes the testing conditions can be rigorous

as long as they are consistent across samples. The advantage of designing tests to break the ropes quickly, is that it shortens the testing period.

Tests were run to compare the following:

- Fatigue Life: Stainless Steel vs Tungsten
- Sheave Hardness and Teflon® Dip: Effect on Sheave Wear and Rope Life
- Lubrication: It's affect on fatigue life
- Cycle Speed: Can Synthetic Ropes be Used in Rope Drives

5.7 Bend Zone

All of the ropes tested had both a SBZ (single bend zone) and DBZ (double bend zone) portion, with exception to the 7x19 SS sample (largest sheave used). An SBZ is defined as a rope going through three stages: straight-bent-straight or bent-straight-bent. A DBZ requires an additional bent-straight or straight-bent stage. [24] The rope has a stroke length of 6" during a single machine cycle. The sheaves are small enough to allow a rope segment to travel from the straight section on one side of the sheave to the straight section on the other. In contrast, the 7x19 SS rope, a section of rope starting on side of the sheave does not make it to the other side. This is important because the DBZ section of rope has twice as many cycles as a SBZ section of rope for each machine cycle.

6 Test Results and Analysis

The wire rope D:d ratios were recommended, based on construction, by Sava Industries, Inc.. The Vectran® sample was placed at the same D:d for comparison. The 15% oversized groove was too large. The wire ropes had ~37°-42° of support instead of 120°-150°. This was back calculated from the wear patterns on the sheaves. The wear pattern was difficult to match to one of the of the Southwest Wire Rope examples. Samples should have displayed a narrow wear path, but since the ropes are small in diameter the area of wear is a high percentage of the outside of the rope. However, most of the rope samples rocked back and forth in the groove during cycles, this is indicative of an unsupportive groove.

Each rope sample was cycled to failure, but this must be defined. The tension in the rope was measured with the load cell. Failure of a rope sample was classified by a loss in tension of greater than 50% of its original tension. Synthetic and wire ropes elongate and loose strength as they are cycled. [9, 31] During all of these tests the rope tension decreased as the number of cycles increased. It was inferred that the tension loss during cycling was related to a loss in rope strength. The strands of the wire ropes would eventually fail, defining a specific time of failure. The synthetic ropes merely frayed and stretched until the tension dropped below 50%. Future research should define synthetic rope failure with higher accuracy. However, since the test conditions are all similar and the analysis is comparative it does not affect the conclusions.

6.1 Stainless Steel vs Tungsten

Stainless Steel vs Tungsten Test Results									
Rope	Proof Load	Load	Pulley Material	D:d	Sheave Drawing	Teflon Dip	Groove Oversize	Avg. CPH	CTF
7x49 SS	60%MBL	30%MBL	6061-T6511	15	DRL-P02	Yes	13%	14220	12948
7x49 SS	60%MBL	30%MBL	7075-T651	15	DRL-P02	Yes	13%	14340	15876
7x49 SS	60%MBL	30%MBL	7075-T651	15	DRL-P02	Yes	13%	~14400	17222
7x49 SS	60%MBL	30%MBL	6061-T6511	15	DRL-P02	No	13%	~14400	16330
7x49 W	60%MBL	30%MBL	6061-T6511	15	DRL-P04	Yes	13%	14520	76380
7x49 W	60%MBL	30%MBL	7075-T651	15	DRL-P04	Yes	13%	14420	59600

Table 3: Stainless steel and tungsten rope test conditions

Based on average cycle life, tungsten outperformed 302/304 stainless steel by a factor of ~4.5. This is probably caused by a higher abrasion resistance of the material.

Originally, the LRL 7x49 stainless steel rope was crimped to a RHR lay drive rope. As expected, the opposing torques generated by the two ropes had a detrimental affect on fatigue life. The results of the test showed that it decreased the life by half, compared to ropes attached to an LHL drive rope.

6.2 Bright vs Lubricated

The first lubricated rope that was tested did not fail. It was at a lower load and also on a chatter marked groove. During the second lubricated rope test, the encoder alignment prevented getting an accurate drive count. However, the test ran for three days at an average of two machine cycles per second. Any inaccuracies related to estimating the exact start and end time of the test (rounding to the nearest two hours) are surpassed by the stark difference between the bright and lubricated rope samples (Table 4).

Lubricated vs Bare Wire Rope Test Results								
Rope	Proof Load	Load	Lubrication	D:d	Sheave Drawing	Groove Oversize	Avg. CPH	CTF
7x19 SS	60%MBL	20%MBL	Yes	15	DRL-P05	13%	~7200	>271040
7x19 SS	60%MBL	27%MBL	Yes	15	DRL-P05	13%	7260	>518400
7x19 SS	60%MBL	27%MBL	No	15	DRL-P05	13%	7280	33158
7x19 SS	60%MBL	27%MBL	No	15	DRL-P05	13%	7240	39440

Table 4: Bare and lubricated rope comparison

This is direct evidence that lubrication is one of the most important attributes to a CBOS rope. This is not a surprise, since the major failure modes are based on friction.

6.3 Synthetics at High Cycle Speeds

Vectran High Speed Test Results								
Rope	Proof Load	Load	Pulley Material	D:d	Sheave Drawing	Groove Oversize	Avg. CPH	CTF
Vectran	31%MBL	20%MBL	6061-T6511	15	DRL-P03	13%	14660	273714
Vectran	31%MBL	20%MBL	6061-T6511	15	DRL-P03	13%	14660	66194
Vectran	31%MBL	22%MBL	6061-T6511	15	DRL-P03	13%	8000	160034
Vectran	31%MBL	22%MBL	6061-T6511	15	DRL-P03	13%	8000	135864

Table 5: High cycle speed tests of Vectran®

The 1/8” Vectran® sample has a much higher MBL than 3/32” 7x19 SS, so the drive rope could not handle a 60%MBL proof load of the Vectran® sample.

The load and speed of the tests were varied to see their affect. It seems that the load has a greater affect on the rope temperature than the rope speed. All of the rope samples were stiffer in the SBZ and DBZ, after failure. This can be attributed to high temperatures in the rope causing fiber fusion. This decreases the life of the rope because of both load sharing and material degradation from temperature. [20]

Appendix A has a “Comparison of Fiber Characteristics” section (Table 6). In it, LCP has a critical temperature of 149°C (300°F). Figure 9 can be linearly extrapolated to show that this temperature is reached in the DBZ of an HMPE rope at 1215CPH.

Since HMPE is known for its low COF (coefficient of friction) fibers, it is expected that

LCP will have a higher running temperature than HMPE for a given CPH. This rope life degradation at higher cycle speeds is verified by an HMPE rope test run at 720CPH (Figure 10). Further, the results from the DCT rope by Samson Rope, ran at 360CPH, [20] shows that rope innovations are creating increased performance in synthetic CBOS ropes, but have not yet reached the capabilities required for the speeds in rope drive transmissions.

6.4 Sheave Hardness and Teflon® Dip

The stainless steel and tungsten tests listed in Table 3 show that there is no difference between using 6061-T6511 or 7075-T651. Figure 18 compares groove wear on both of these materials.

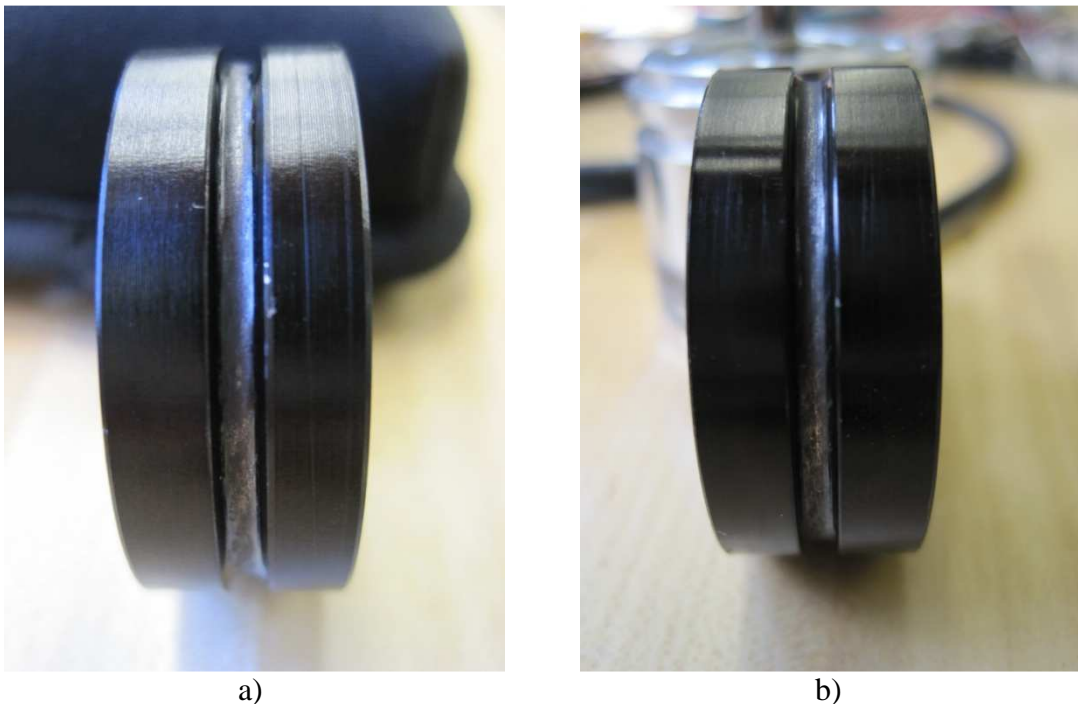


Figure 18: Post stainless steel rope test. a) Groove wear pattern in anodized 6061-T6511 (13,000CTF); b) Groove wear pattern in anodized 7075-T651 (16,500CTF)

The tungsten samples did not wear the sheave any more than the stainless steel samples. It appears that the tungsten worn sheave (Figure 19) is smoother than the stainless steel worn sheaves, but the tungsten had many more cycles before failure. The rope slip during cycles moves the wear location of the crown wires. Eventually, enough cycles create a smooth looking surface.



Figure 19: Wear induced by tungsten rope sample on an anodized 7061-T651 sheave (60,000CTF)

The Teflon® dip also had little affect on fatigue life (Table 3). It is a thin enough coat that the rope probably wore through it within the first few hundred cycles (Figure 20). These are only visual observations on sheave wear, additional research utilizing microscopy should be pursued for higher level analysis.



Figure 20: Groove wear pattern in anodized 6061-T6511 (No Teflon® Dip), by S.S. rope sample (16,300CTF)

6.5 Lubricated Ropes and Sheave Wear

Interestingly, lubricated ropes wore the sheaves less than bare wire ropes. The lubricant seeped onto the sheave during the tested which more than likely added in decreasing the friction at the slip zone between the rope and sheave (Figure 21).

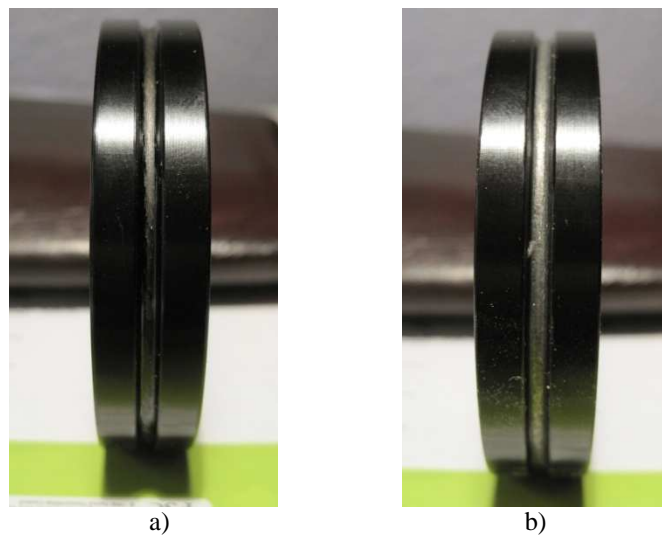


Figure 21: Groove wear from 3/32" 7x19 S.S. rope samples. a) Lubricated rope (518,400CTF); b) Non-lubricated rope (33,150CTF)

6.6 Sources of Error and Deviation

Samples were tested under the same operating conditions at least twice. This was done to show any large scale variation in cycle life results based on the testing methods. The samples themselves are assumed to have inconsistencies that affect performance, but the deviation in rope life between identical tests was greater than expected. The following sources of error affected the cycle life of the samples to varying degree.

6.6.1 Cantilever Chassis Angle

The largest source of error was found near the end of testing. The angle that the cantilever chassis makes with the rest of the frame has a large impact on how the tension in the rope is calculated. Since the load cell reading is the force on one side of the cantilever then the angle that the load makes in relation to the pivot determines what the resulting rope tension must be to hold the system in static equilibrium. Therefore, when the cantilever chassis is at a different angle and the load cell reading is the same, the tensions in the rope sample is actually different.

6.6.2 Test Sheave Bearing Alignment

Since the machine is based on a cantilever load arrangement the tension in the rope must be calculated from the load cell reading. The bearings for the test sheave shaft need to be detached and reattached between each sample test in order to replace the testing sheave. Locating the bearings onto the cantilever chassis in the exact location is

difficult. Misplacement was expected, up to $\pm 1/16''$ (Figure 22). This creates a load reading error of $\pm 1\%$ MBL.

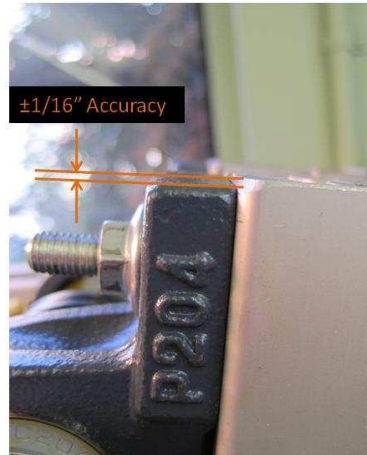


Figure 22: The alignment of the testing sheave bearings

6.6.3 Load Cell Accuracy

The load cell has a 1000lbf capacity with an accuracy of $\pm 0.03\%$ over its full scale, which translates to ± 0.3 lbf.

6.6.4 Load Profile

The linkage system generated load profiles in the rope ranging between 6 and 10lbs. So the rope tension did not remain constant, but was cycled.

6.6.5 Cable Twist

Under load the drive ropes had a tendency to twist the sample ropes. This was particularly relevant on the Vectran® sample because it is a torque balanced rope. In

actual service it should heat up less, because the additional twists created more inter-strand friction.

6.6.6 Groove Tolerance

The grooves themselves were not identical. The lathe tools were cut to precise tolerances using a Wire EDM. The sheave machining process with those tools created additional variation. Any vibration in the tool head would cause the width of the groove to change and make a U shape (on a very small scale). This vibration along with the depth tolerance creates deviation in the groove depth, slightly changing the D:d ratio.

6.6.7 Alignment

Depending on the alignment, some samples ran directly in the center of the groove, to one side, or rocked back and forth within the groove. All of these should cause an effect on rope life. None of the samples were worn by the shoulders of the groove profile. Evidence of this would have been apparent by chipped away anodize on the groove shoulders.

7 Conclusions

Lubricating wire rope significantly increases rope fatigue life. It should be the first consideration when making rope selections for a rope drive transmission.

Tungsten rope outperformed stainless steel rope under the same operating conditions and should be used when longer rope life is of interest. Since the tests were rigorous (30%MBL, D:d of 15), if the conditions are less severe (20%MBL, D:d of 15) the difference in performance between tungsten and stainless steel should increase by a large margin.

High loads with high cycle speeds are detrimental to synthetic ropes in CBOS applications. There is a potential that these ropes could be used in transmissions that are not run continuously, because the rope is able to intermittently cool. If the rope temperature does not reach the critical temperature of the filament material, it should outperform wire ropes of the same diameter. However, for continuous and rigorous CBOS applications, this research indicates that there are no synthetic products that can compete with wire ropes. Fiber rope technology is rapidly growing in innovations, so it should be watched closely for advancements in this area.

Rope drive transmissions commonly utilize sheaves and drums that are expensive to machine and are internal to the assembly. Sheaves and drums made from Al6061-T6511 with a 0.002" thick hard anodized coating work well in these systems; they are light weight and wear resistant. The ropes used with them will wear out first, which makes replacement costs and lead times lower. It also makes the system easier to maintain. Neither the hardness of the aluminium (pre-anodize) or dipping the sheaves in

Teflon® increased the life of the ropes. The Teflon® did seem to reduce the amount of wear on the sheave, but higher level analysis is required. A more drastic reduction in wear was seen when lubricated ropes were used.

8 Future Research

A custom wire rope should be made with the recommendations from this research, and tested to see if it greatly outperforms the 7x49 W rope.

Laser alloying a hard coat onto the wires may increase rope life. This research topic should be followed for further developments.

The current rope tester is not outfitted to measure or apply torques on the rope samples. If it is adapted to do so, wire ropes with Nylon casings should be tested to see if they induce unacceptable values of torque lag or backlash.

A consumable lining should be applied to the anodize coating of the sheaves. It should be thicker than the Teflon® dip that was used. It may be able to preserve the rope and sheave. Ideally, it would be a substance that can be reapplied to the sheave as it wears out. [16]

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Appendices

Appendix A – Additional Rope and Sheave Information

Forms and Grades of Plow Steel

The most common steel wire grades are: IPS (Improved Plow Steel), EIP (Extra Improved Plow Steel) and EEIP (Extra Extra Improved Plow Steel). [1] Generally, the higher the strength of the wire, the lower its ductility will be.

Stainless Steel Wire Rope (Sava Industries, Inc.)

Greg Soja, of Sava Industries, Inc., stated that their 7x49 LRL 302/304 stainless steel wire rope is “loosely wrapped”. He went on to say that there is room for improvement for this rope, but they have not had the time to address it yet.

Tungsten Wire Rope (Sava Industries, Inc.)

The wires are made from 99.95% full hard (350ksi) tungsten. Its current price is \$20/foot. Stainless Steel of equivalent construction is around \$2-3 foot. [2]

Titanium Wire Rope

When titanium is exposed to oxygen it reacts to create what is called alpha case. This is a very hard, brittle, and smooth surface. Titanium is not very wear or gall resistant. Under the notching stresses and internal abrasion of wire ropes in CBOS applications titanium fatigues quickly. To make matters worse, no current lubricants can adhere to the alpha case. Further developments in titanium wire surface preparation may allow lubricants to bond, which would greatly improve titanium rope bending fatigue performance. [3]

Common Wire Rope Constructions

Wire Rope Cross Sections (past & present)

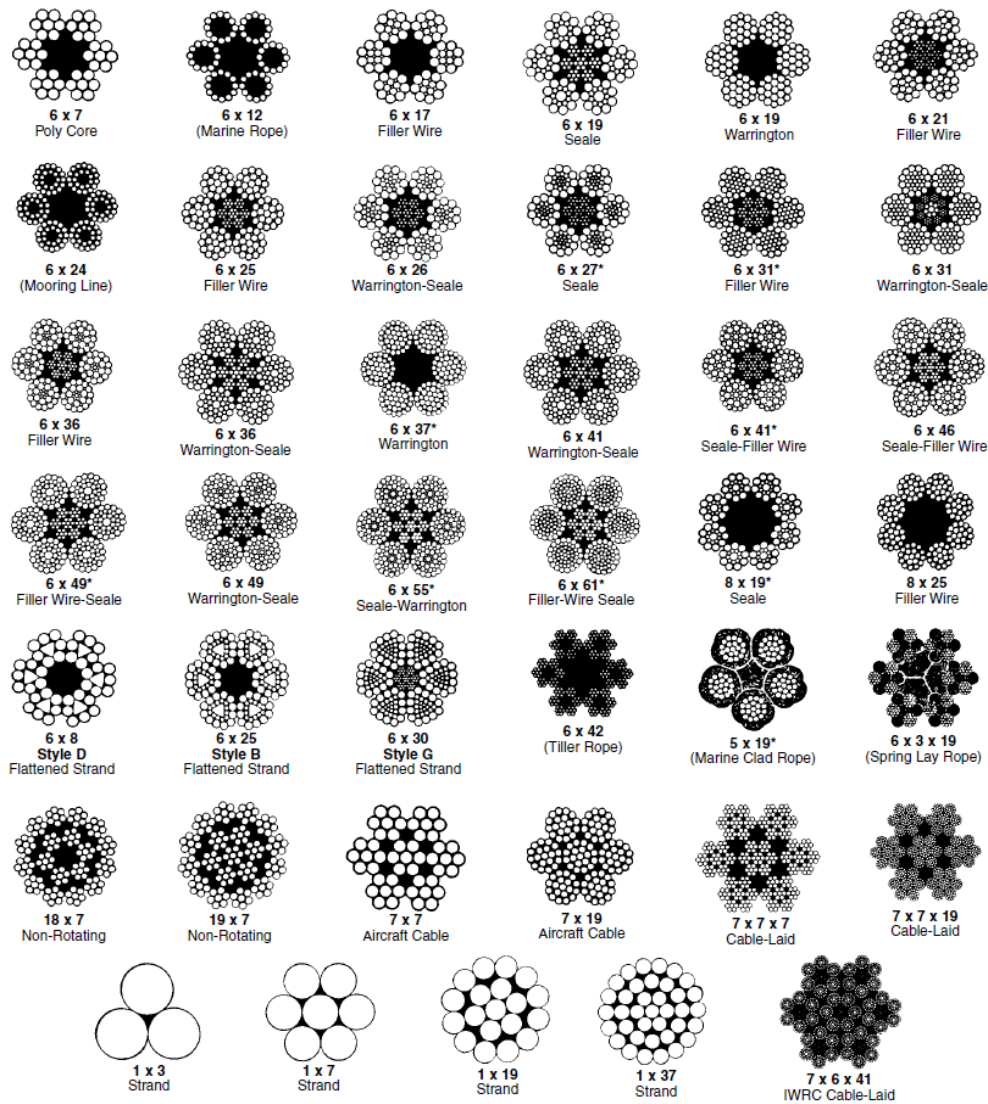


Figure 23: Common wire rope constructions [1]

Comparison of Fiber Characteristics

GENERIC FIBER TYPE	NYLON	POLYESTER	POLYPROPYLENE	HMPE	LCP	ARAMID	PBO
Tenacity (g/den) ¹	7.5 – 10.5	7 – 10	6.5	32 (SK-60) 40 (SK-75)	23 – 26	28	42
Elongation ²	15 – 28%	12 – 18%	18 – 22%	3.6%	3.3%	4.6%	2.5%
Coefficient of Friction ³	.12 – .15	.12 – .15	.15 – .22	.05 – .07	.12 – .15	.12 – .15	.18
Melting Point	425°– 490° F	480°– 500° F	330° F	300° F	625° F	930° F*	1200° F*
Critical Temperature ⁴	325° F	350° F	250° F	150° F	300° F	520° F	750° F
Specific Gravity	1.14	1.38	.91	.98	1.40	1.39	1.56
Cold-Flow (Creep) ⁵ In Mooring Line Use	Negligible	Negligible	Negligible to high	Negligible to high	Negligible	Negligible	Negligible

* Char temperature — does not melt

Table 6: Comparison of fiber characteristics [4]

Common Fiber Rope Constructions

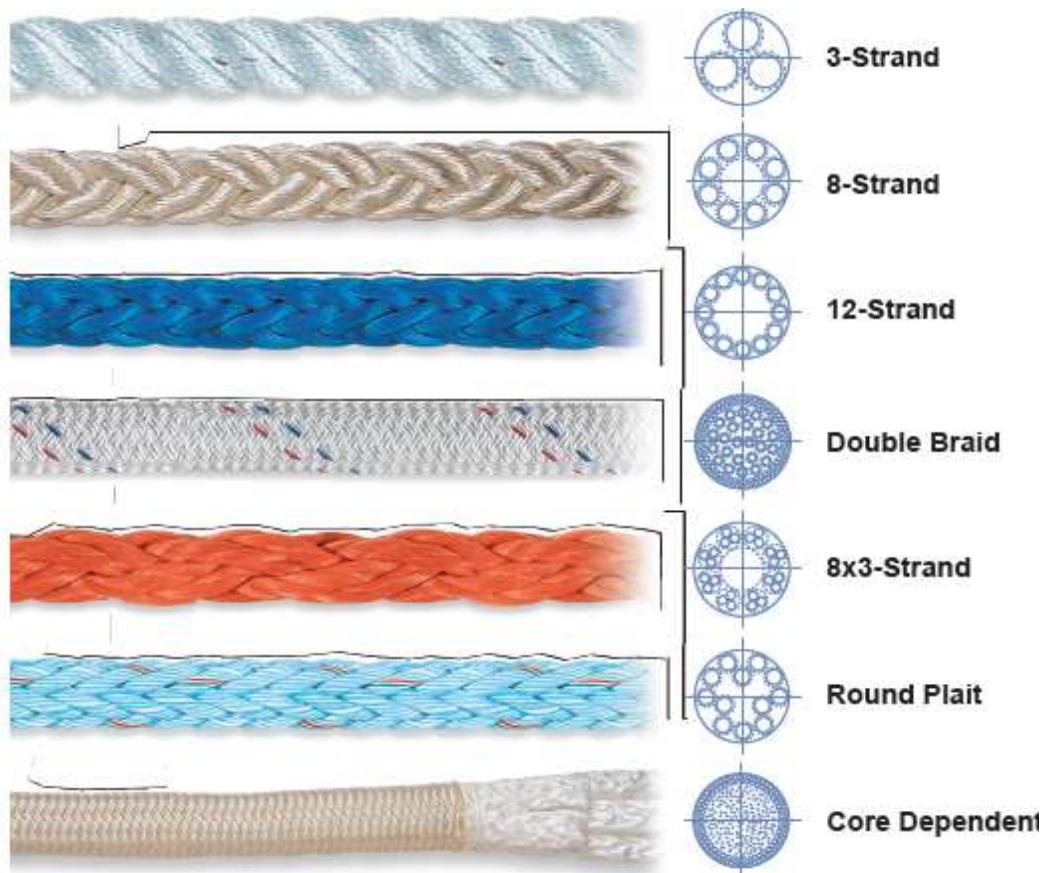


Figure 24: Common fiber rope constructions [4]

Sheave Drawings

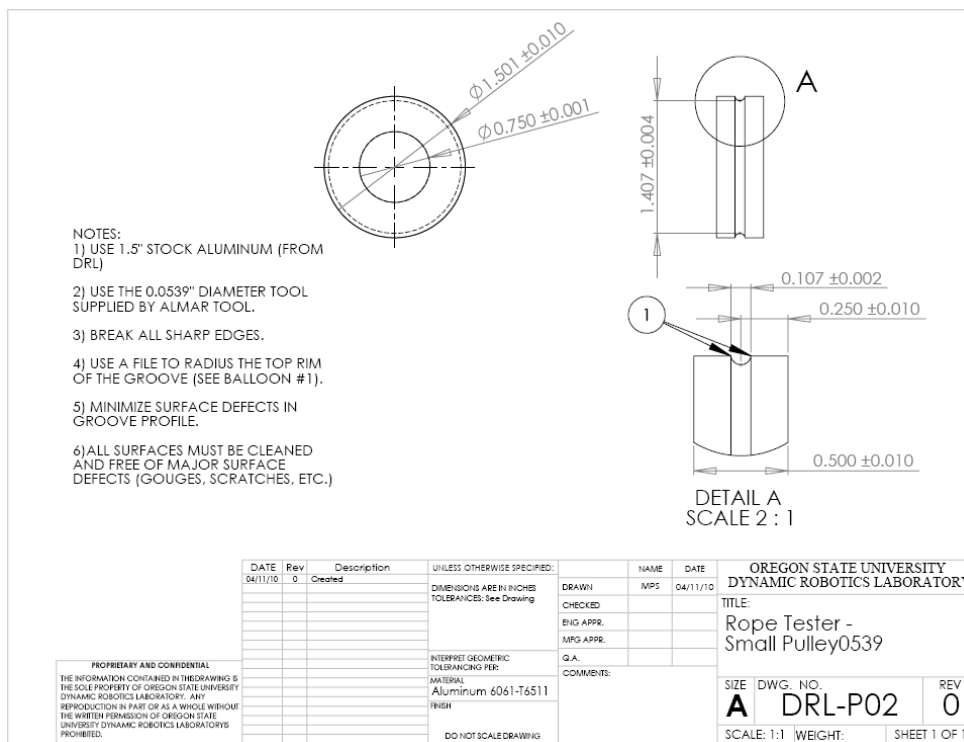


Figure 25: DRL-P02 Machining Drawing

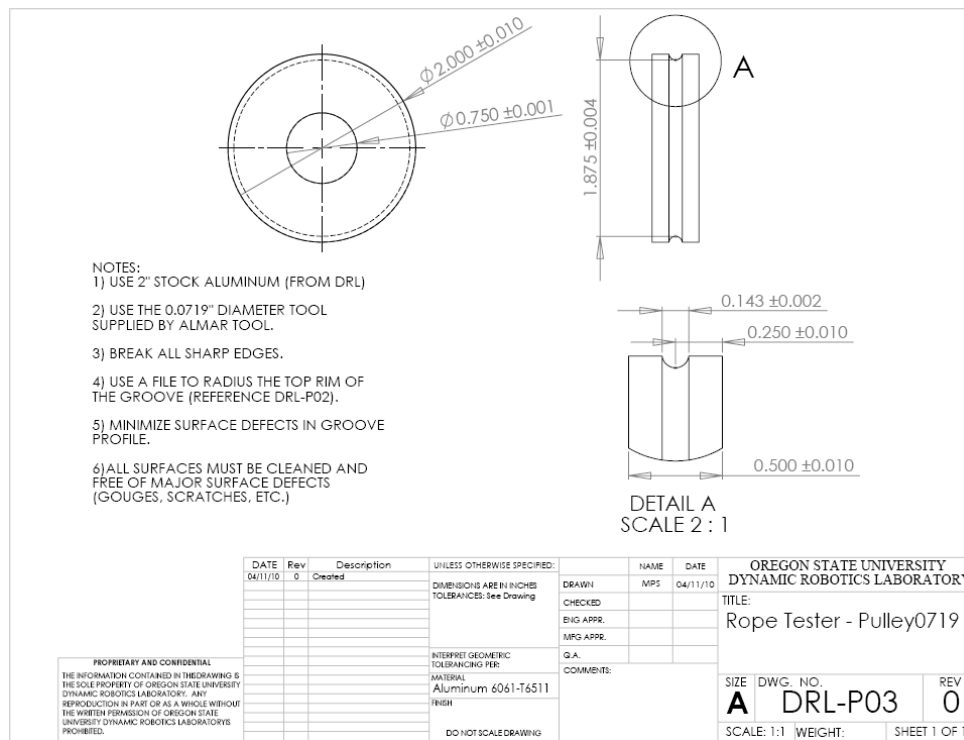


Figure 26: DRL-P03 Machining Drawing

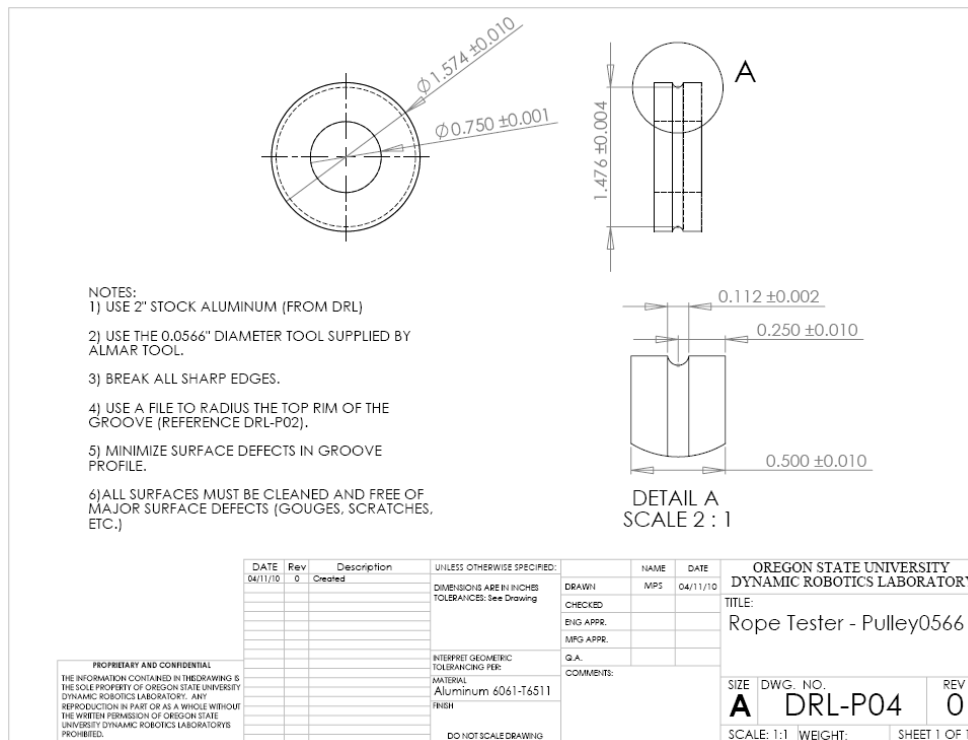


Figure 27: DRL-P04 Machining Drawing

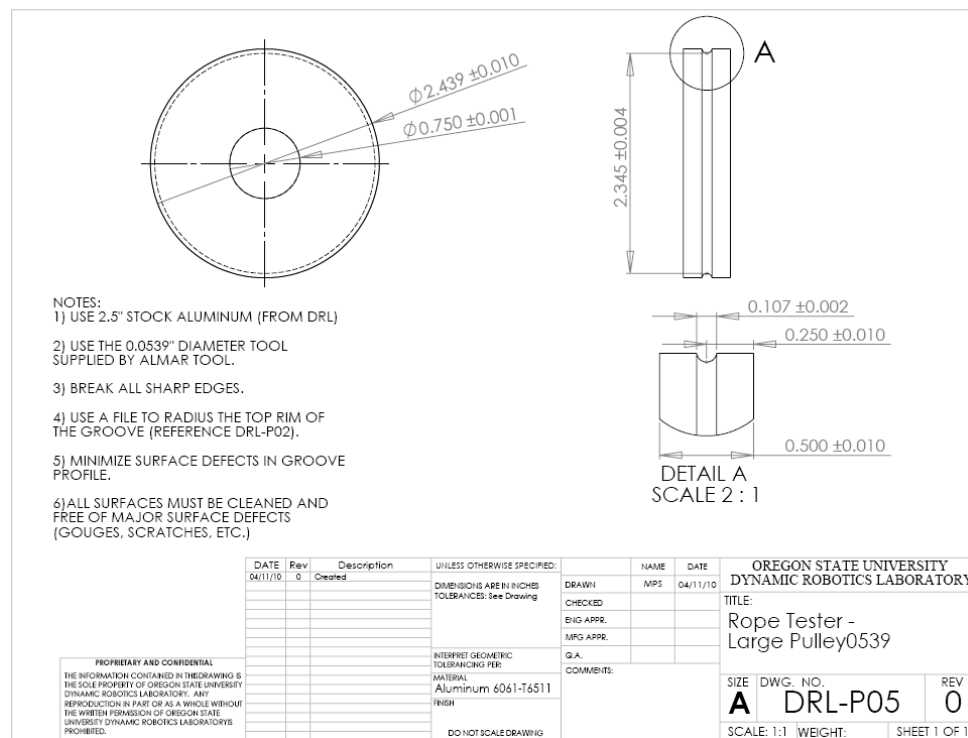


Figure 28: DRL-P05 Machining Drawing

Anodize Coatings

Anodizing is the process of growing aluminum oxide on the surface of aluminum by submerging it in a sulphuric acid bath and running low voltage current through the solution. Hard Coat anodize, under MIL-A-8625F Type III, is a thicker coating gained by lowering the acid bath temperature close to freezing and increasing the electrical current. It is thicker, tougher, and meant to increase the wear resistance of the part.[5] However, the surface tends to have micro cracking caused by residual stresses, which makes the entire part more susceptible to bending fatigue [6]. The benefit of this process is that it is much easier to machine an aluminum part and anodize it to gain corrosion and wear resistance, than to use stainless steel. The end product is also lighter, if weight is a design constraint. [5]

Anodize grows half into the part's surface and half outside. So a coating thickness of 0.002", which was used on the sheaves, built up all surfaces by 0.001". Anodizers normally etch or chemically polish parts in an acid bath before processing. This smooths the surface roughness. It is not a procedure designed to remove large amounts of material. Joe Kilduff said that if the etch is used in this way it "will pit the surface and may initiate intergranular attack, which can cause cracking and corrosion." [7] David Hammerich, in response to the same inquire, stated that "Sodium hydroxide etch attacks the grain boundaries of the alloy. Etching to such an extreme would affect the quality of the anodic coating." [8]

Chatter Mark Effect

Originally, tests for this research used anodized sheaves that had chatter marks in the groove, from the machining process. These small ridges could be seen visually and felt with a finger nail (Figure 29).



Figure 29: (Left to right) Chatter marked groove with wear pattern from 7x19 SS rope, tear out initiation of the groove, fully removed anodize coating.

The wire ropes were tested at high enough loads that they would tear into and wear out the aluminum sheaves. This created a rough unresponsive surface for the rope and induced variability in the test results. The best explanation is that stress concentrations occurred at the base of each chatter mark when it contacted a crown wire of the rope. This caused brittle failure. Over the course of a CBOS test the crown wires touch the majority of the groove surface, so it is not surprising that it would chip out the entire

groove. The resulting groove caused the wire ropes to fail quickly. This spurred research into groove surface finishes with anodizing. It was also suspected that the methods employed by the anodizer (CG Anodize), may have resulted in a poor quality coating (thickness <0.002”).

Surface Roughness

A high quality sheave groove should be as smooth as possible, to reduce the friction between the rope and the groove surface. “The general rule of thumb is that the anodize process doubles the starting surface roughness, however this relationship is not linear. If the substrate is a 16 micro-inch Ra, the anodize finish will be about 32 Ra. As the starting roughness increases the slope is reduced. At about 100-125 Ra, the anodize will not change the roughness. Anything above this, the anodize will make the surface smoother.” [8] Etching itself, causes an increased surface roughness, but can be mitigated if it is less aggressive “acid etching in lieu of alkaline etching.” [8] It is also possible to polish the anodize coating after processing. There is a difference between etching and chemical polish, which Duralectra offers. Their process reduces high aspects of surface down by 30%, under ideal conditions. [9]

Electrical Contact Point

All anodized parts need a point of electrical contact. A threaded hole can be used with some companies, but the most flexible procedure is to connect wires to the part directly. This leaves small points of contact that will not be anodized, so be sure to choose a surface that is not dimensionally critical or aesthetic.

Teflon® Dip vs Thermal Set

Teflon® impregnation is a misleading industry claim. The pores of the oxide are far too small to be filled by PTFE (Teflon®). There are bush and dip applications which do not impart any measurable dimension to the surface while "sealing" the pores at the surface. A thermal set PTFE resin is a more robust option. [8] Dave DiBiasio partially agreed with this statement. He said that the Teflon® rests in the pores and is exposed on the surface. [9] For applications with wire ropes, no one was confident that the Teflon® would remain on the sheave, but they also didn't admit that it would be removed quickly.

Gaining Hard Coat Thickness of 0.002”

Some companies did not have the capability of Hard Coat Anodizing to 0.002” thick. This is because once the anodize begins to build, it also insulates the aluminum from the electrical input. In response the anodizers have to increase the electrical input to perpetuate the growth. This is a delicate balance, because too much of an electrical increase can cause the aluminum to “burn up”, which was interpreted to mean arcing between the wrought aluminum and the anodic coating. Some companies found a way to handle this issue and others didn't. Duralectra uses the patented Sanford Process™, which is well documented on the internet.

Appendix B - Contacts Related to this Research

Fiber Rope Manufacturers

Cortland Cable
44 River St. Box 330
Cortland, NY 13045
(607) 753-8276

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Title: Sales and Application Engineer
E-mail: Aaron.Vodnick@cortlandcable.com

New England Ropes
848 Airport Road
Fall River, MA 02720-4735
(508) 678-8200

Name: Bill Shakespeare
E-mail: bshakespeare@neropes.com

Samson Rope
Corporate Office
2090 Thornton Street
Ferndale, WA 98248
Customer Service
(360) 384.4669

Name: Greg Mozsgai
Title: Senior R&D Engineer
E-mail: gmozsgai@samsonrope.com

Fiber Rope Terminations

Applied Fiber
Corporate Headquarters
25 Garrett Drive
Havana, FL 32333
(850) 539-7720

Wire Rope Manufacturers

Carl Stahl® Sava Industries, Inc.
4 North Corporate Dr.
PO Box 30
Riverdale, NJ 07457-0030
(973) 835-0882

Name: Greg Soja
E-mail: greg@savacable.com

Baird Industries
1 Hollywood Avenue
Hohokus, NJ 07423-1433
201.652.6335
201.652.1741

Jersey Strand and Cable, Inc.
259 Center Street
Phillipsburg, NJ 08865
U.S.A.
(800) 528-3900
(908) 213-9350

Rope Testing Facility

TMT Laboratories
5721 Research Dr
Huntington Beach, CA 92649
(714) 898-5641

Name: Phil Gibson
E-mail: phil@tmtlabs.com

Hard Coat Anodizers (up to 0.002" coating thickness)

Duralectra
61 North Ave. Natick, MA 01760
(800) 274-3388
(508) 653-79000
and
1 Shorr Court
Woonsocket, RI 02895
(401) 597-5000

Symcoat
10840 Thornmint Road
San Diego, CA 92127
(858) 451-3313

Praxair Electronics
(602) 333-7521
Development/Engineering Mgr

Name: David Hammerich
Title: ASC Product
E-mail: David_Hammerich@praxair.com

Appendix C – Rope Tester Setup and Maintenance

This section lists, in more detail, some of the major processes in setting up and maintaining the rope tester.

Wire Rope Terminations

Crimping two wire ropes together using metallic sleeves is the fastest and strongest in-house method to connect ropes.

Stainless steel can be torched (Figure 30) and cut to length, which is necessary, because heating up the rope to such a high temperature causes the wires to lightly stick together. If the rope is cut without torching it unravels. Be sure to cut it in the area that received the most heat (the center of the discoloured zone). Caution, if the cut end is disturbed too much it can still unravel.



Figure 30: Torched 3/32" 7x49 stainless steel rope

Two standard 3/32" sleeves crimped in the #2 setting should be used on 3/32" ropes (Figure 31).

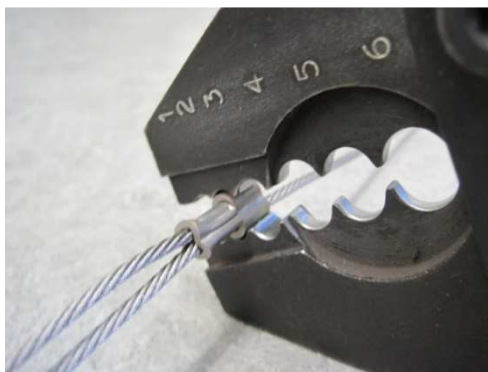


Figure 31: Crimping 3/32" 7x49 stainless steel rope

Tungsten ropes do not have the advantage of torching. The wires do not stick together, no matter how hot the rope gets. They must be taped and then cut. The tape should be stiff. If it stretches it will allow the rope to slightly unwind, after cutting. Though two standard 3/32" sleeves will fit over the tungsten sample the tape increases the diameter, so sleeves for 1/8" ropes must be used. They can be crimped in stages: #4 then #3 (Figure 32).



Figure 32: Crimped 1/8" sleeves over 2.5mm 7x49 tungsten rope

Synthetic Rope Terminations

Tested Terminations

Splicing, knotting, and gluing the synthetic ropes were tested as alternative terminations. A Samson representative was confident that the 1/8" diameter synthetic samples could be spliced with a paper clip and a bit of work. Our team was unable to successfully splice the 1/8" diameter sample, even though the splicing guide from Samson Rope ("Rope Eye Splice for Class II, 12-Strand Ropes") was consulted. Also, fids¹⁰ on the market do not come in a small enough size for 1/8" ropes. The figure eight knot (Figure 33) was chosen for testing because it has a breaking strength around 80% MBL of the rope [10]. This is acceptable for CBOS applications because the ropes are not loaded above 30% MBL. A disadvantage is that the loop and knot section of rope is longer than a spliced loop so more room is needed around the termination.



Figure 33: Figure Eight knot

Lastly, a 3/32" 7x49 SS rope was threaded into the center of an 1/8" 12-Strand Vectan® rope and glued with adhesive. The wire rope was terminated on the machine and the rope connection was placed under load. The rope tension reached 750lbs without slipping. This was due, in part, by the adhesive and also by the synthetic rope's constriction onto the wire rope when it was placed under tension. The machine was manually cycled a few times, before the stress broke the adhesive and ropes slipped apart

¹⁰ A tool used to push one end of rope through the center of a section of rope. It can be used to create an eyelet shape in the rope.

(Figure 34). Thus, this termination style was unreliable, and all Vectran® rope tests were performed with figure eight knot terminations.

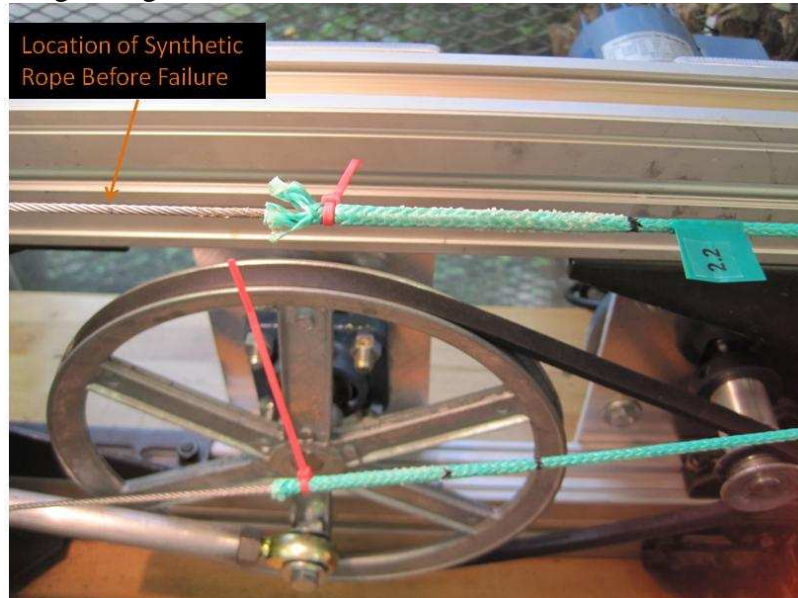


Figure 34: Failure of innovative wire-synthetic rope termination

Potted Terminations

Applied Fiber offers a potted termination for fiber ropes. They are very strong because the rope is frayed so that all of the fibers come into contact with the adhesive (Figure 35). The disadvantage is that the nominal pot sizes may be inconveniently large. They cannot be downsized because the overall size is determined by the process of spreading out the fibers. Smaller pots would result in a smaller number of fibers contacting the adhesive and reducing the terminations overall strength.



Figure 35: Potted fiber rope termination

Rope Drives

For Wire Ropes

Blow compressed air over work area to remove small particles that can work into the ropes and exacerbate failure mechanisms.

Cut a 41" long section of 3/32" 7x19 SS rope. Bend it so that the double-backed portion is 16" in length. Zip tie the loop and then crimp it with two sleeves (Figure 36). This leaves a 9" straight section of rope. Repeat this process and then connect a wire rope sample between the two straight sections with two crimped sleeves each.



Figure 36: Drive rope termination loop assembly for wire ropes

The sample length changes with each use of the drive rope because of the material that is cut away. It also depends on the length of sleeves being used (Table 7). A more accurate system should be used to maintain the same angle of the cantilever chassis. This will maintain an accurate calculation of the tension in the rope.

Sample Cut Lengths (in)			
Use Number	#1	#2	#3
3/32" Sleeve	25	28	31
1/8" Sleeve	25	29	32

Table 7: The cut lengths for wire rope samples depending on how many times a drive rope has be used

For Synthetic Ropes

Repeat the process described above, with a few exceptions. The original cut length should be 45". Wrap the end of the straight portion of the drive loop assemblies around an eyelet. There should be a 9" straight section between the termination loop and the eyelet (Figure 37). Cut away excess after crimping. Once a set of synthetic rope drives are made they can be reused over and over, because the samples are tied in, not crimped.

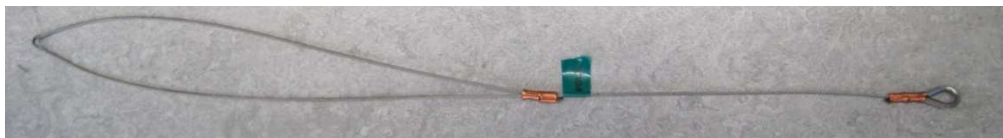


Figure 37: Drive rope termination loop assembly for fiber ropes

Cut fiber rope samples to a length of 36". Tie the first stage of the figure eight in both ends with 8" between the knot and the free ends (Figure 38).



Figure 38: Initial Figure Eight knot setup

Loop through the drive rope eyelet and tie it off as shown in Figure 33.

Bearing and Turnbuckle Grease

Molykote® 44 high temperature, medium bearing grease was used for all ball bearings in the rope tester. It is an NLGI No. 2 lithium based grease. Greases are made with different base types. They should never be mixed because they can react with one another and greatly reduce or entirely eliminate their effective lubrication. [11] This

grease was applied to all of the bearings every few hundred thousand machine cycles. Use a Zerk gun and inject grease until it pushes out of the bearing. It may seem worthwhile to clear out discoloured grease by continuing to pump grease into the bearing. This is not advised because it runs the risk of pushing the seals out.

This grease should also be used on the turn buckle (Figure 39). Lubricating the threads improves thread life and makes it easier to tighten.



Figure 39: Turnbuckle

Alignment

Currently, the best method for aligning the rope in the sheave groove is to view the rope sample from above and line up the ropes so that one is on top of the other (Figure 40). Then check to see that the same proportion of the shoulder of the groove is visible on each side of the rope.

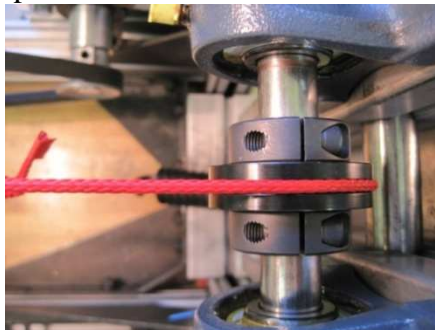


Figure 40: A rope sample slightly out of alignment

Tighten Set Screws Hard on Flanges

There are set screws that hold the test sheave shaft in the bearings. These need to be tightened down using an Alan Wrench and an extended lever arm. If they are not tightened down hard enough they will loosen during the test and the shaft will move out of alignment. Flanges have been filed into the shaft for the set screws (Figure 41).



Figure 41: Flanges filed into shaft for bearing set screws

Appendix D – Additional Transmission Design Considerations

Groove Projection Distortion

If a cutting tool is made to cut the groove profile of a sheave, it is designed to be normal to a turning shaft and plunged to a specified depth. However, when a helically threaded groove needs to be machined into a drum the profile of the groove is distorted with respect to the rope direction. This projection will have a decreased width and the same height of the original profile. To account for this, the profile of the cutter should be distorted to a wider shape.

Reverse Bending

Reverse bending "accelerates the fatigue of wire rope by compounding the bending stresses on the wires" [12] It should be avoided if possible.

Shock Loading

Stiff ropes are better for load control, but are more susceptible to shock loading, which causes premature failure of the rope. [13] The two primary failure modes are bird caging and core protrusion. [14]

Fleet Angle

For optimum efficiency, the fleet angle should not exceed 2 degrees for a grooved drum. [15, 16]

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