Comparison of Aluminum and Copper Compression Sleeve Materials Used for Terminating and Splicing Wire Rope

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The National Telephone Supply Co. - manufacturer of Nicopress Products

1.0 Abstract

Metal sleeves are compressed onto wire ropes for the purposes of: mechanically terminating, splicing, providing cable stops, and securing the ends of wire or cable used in hoists and other apparatus. The purpose of this paper is to describe the differences in material properties and mechanical behavior between aluminum and copper materials and, the effects these differences have on swaged compression sleeve performance.

2.0 Overview

We begin with a description and pictorial views of typical components used in the cable connector industry with circular and oval sleeves both in their original and compressed states. Next, a brief review of tensile testing followed by some basic theory of the behavioral influences of: tensile strength; fracture toughness and micro-cracks; fracture work areas; and thermal expansion as they apply to sleeve materials. Finally, some conclusions and recommendations are included to provide assistance when specifying compression sleeves.

3.0 Components

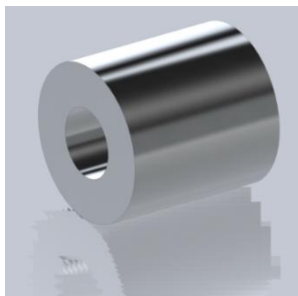
There are a number of methods to terminate a wire rope including, but not limited to an eye-splice and an end-stop. The following figures depict 2 sleeve types: an oval type used for eye splicing and a stop sleeve for a cable stop. For each sleeve type, the unpressed sleeve is first shown followed by its pressed form on a cable:

3.1 An unpressed Copper Oval Sleeve - Figure 1

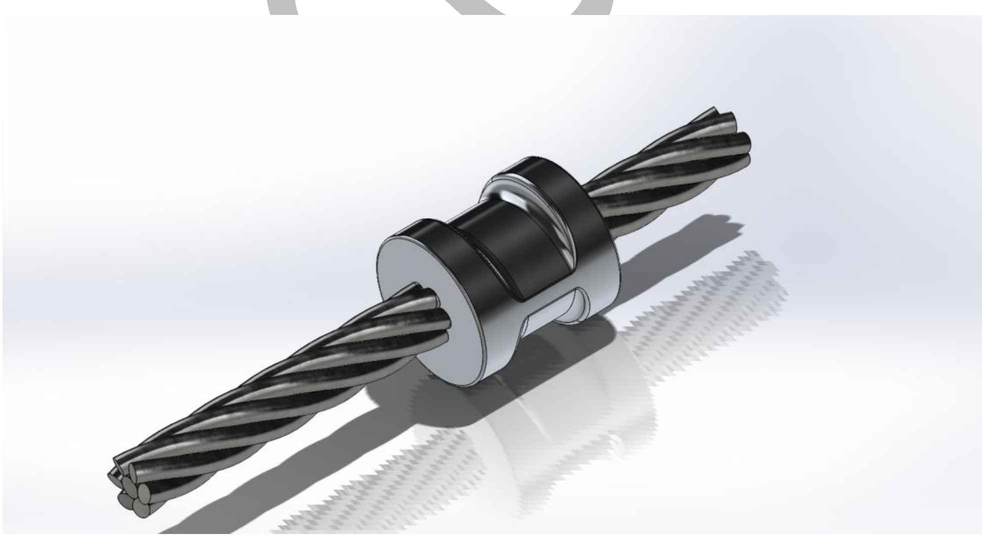
NICOPRESS

3.2 A pressed Copper Oval Sleeve Assembly – Figure 2

3.3 An unpressed Aluminum Stop Sleeve - Figure 3



3.4 A pressed Aluminum Stop Sleeve Assembly – Figure 4



COPRESS

4.0 Ultimate Tensile Strength (UTS) and Tensile Testing

One common measure of material failure is dependent on exceeding its property of: "Ultimate Tensile Strength" (UTS), "TS", or, "$\mathbf{s}_u$", occurs at the onset of "necking', then breaks. Commonly this definition is shortened to "Tensile Strength", and represents the amount of "pressure" or "stress" a material will support before failure. UTS (or stress) is force per unit area and is often identified in units of: pound force/inch^2 (psi) or Mega-Pascals (MPa). Why do we need to know the ultimate tensile strength of a material? It provides a relative quantity of strength compared to other materials and serves as one important factor in the material selection process. It allows us to use this strength property to approximate the maximum load (force or weight) a part will support if the minimum cross-sectional area perpendicular to the axis of applied force is known. An example of a material with high UTS is steel, e.g. 50,000 lbs./inch^2 or 50 kpsi. In the special case of a load member with a cross sectional area of one square inch, the value of force equals the UTS (or, when area = 1 in^2 , then the UTS = force/area = force/1 = force). We use this special case in tensile testing to simplify the determination of stress (or UTS) since the measured value of applied force will equal the applied stress. The method by which the UTS is determined is based on placing a standard 'dog bone' test sample[1] with a cross sectional area = 1 in^2, either flat or round, into a tensile testing machine (see Figure 5), and pulling it while recording the force. This provides a convenient method to determine stress by simply measuring the applied force.

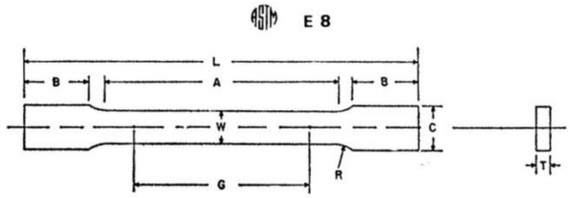
Figure 5 [2]

[1] 1984 Annual Book of ASTM Standards, Nonferrous Metals Products, © by American Society of Testing and Materials 1984, p1058

[2] ©University of Kentucky

The size and configuration of the test specimen is defined by an ASTM standard such as shown in figure 6 below:

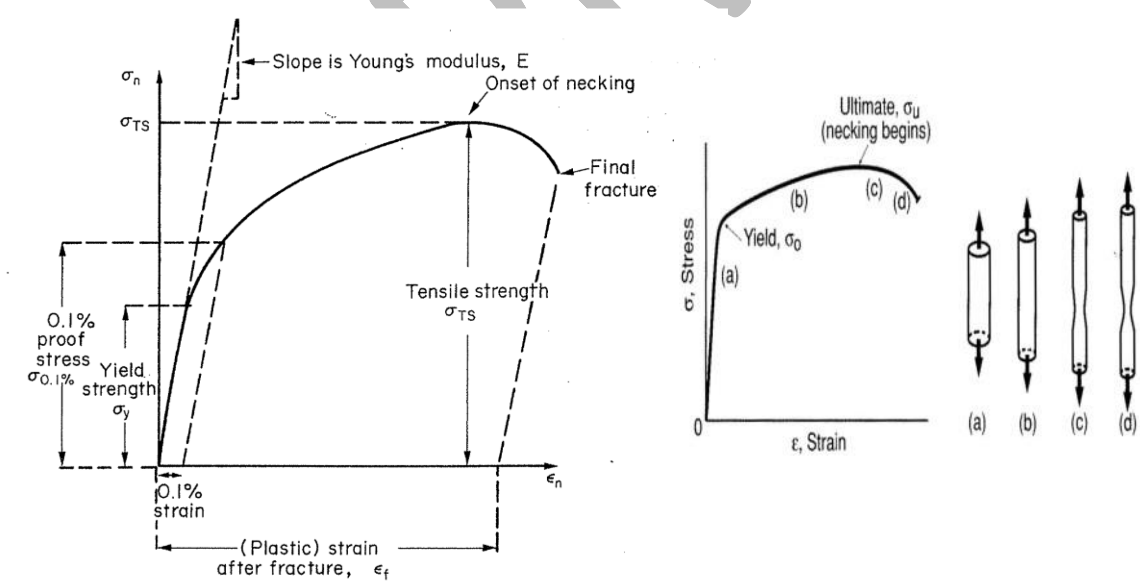
<u>Figure 6</u>



<u>5.0 Tensile load behavior</u>

When an increasing force is applied to a material sample, it begins to stretch in a linear relationship to displacement (elastic region fig. 7a), then at σ_Y , enters a range (fig. 7b) of nonlinear yielding (or the onset of plastic flow), necking begins at σ_{TS} (fig. 7c), and finally fracture occurs (fig. 7d). A typical plot derived from a tensile testing machine of "engineering stress" versus strain is shown in figure 7 below. [18]

<u>Figure 7[3,18]</u>



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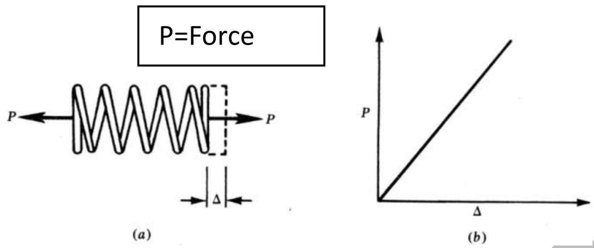
[3] Dowling, Norman E., <u>Mechanical Behavior of Materials</u>, ©1999 by Prentice-Hall, Inc., p.112

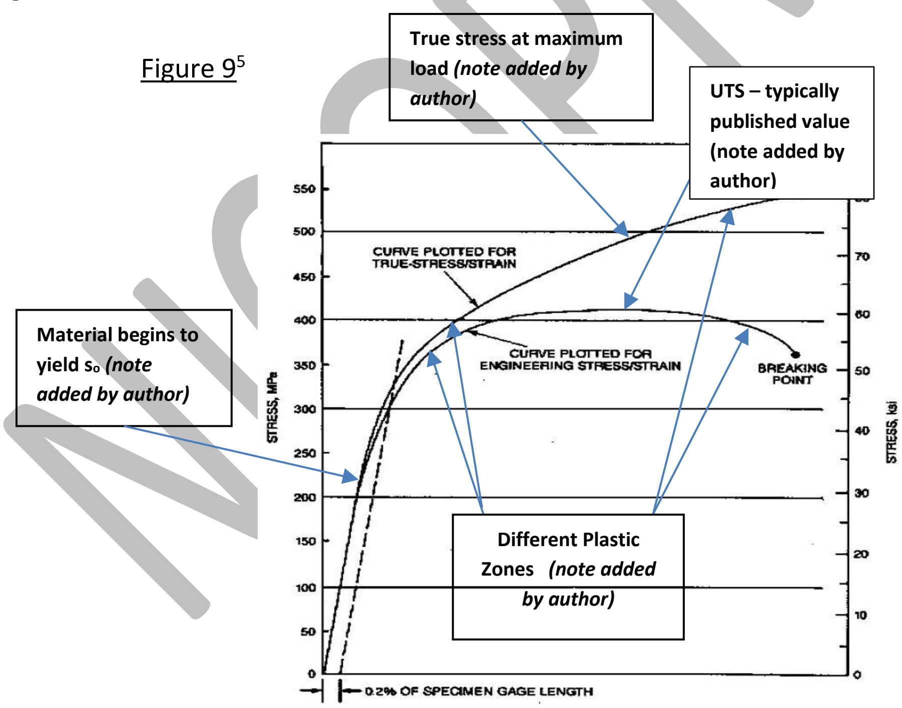
Most products are engineered to operate in a linear elastic manner so that when it is loaded and deforms, it will return to its original form after the load is removed. An example of a part designed to operate in a linear elastic manner (the "a" region of Figure 7) is a spring; see Figure 8a below. In the linear plot of the spring "Figure 8b" its force increases linearly with increases in deflection, and will return to its original length after being pulled.

Figure 8[4]



As seen in Figures 7 & 9, when a sample of material continues to stretch beyond the linear region, it eventually exceeds the yield point (**s**$_o$) and begins a path along the plastic region (**s**$_o$ -> **s**$_u$), then eventually fracture. In Figure 9, two curves are superimposed: the lower curve represents "engineering stress" and is based on force with area assumed constant, the other curve is true stress based on force and measured diminishing area. At **s**$_o$ the measured yield stress and the true stress paths will begin to diverge.

Figure 9[5]



The differences between measured yield and true stress highlight an important concept: the measured yield (or "engineering stress") is calculated based on the cross sectional area not changing as the sample is being pulled. We know, however, the cross sectional area reduces as the material stretches due to Poisson's law of volume conservation. For this reason, to plot "true stress", the changing cross sectional

[4] Pilkey, Walter D., Pilkey, Orrin H., Mechanics of Solids, Copyright ©1974 Quantum Publishers, Inc., p. 101
[5] Gencula, Simah P. E., Introduction to Metallurgical Failure Analysis, ©2012, p. 10

area must be measured per unit of increasing values of force, which will result in a higher stress curve with a path significantly different than the engineering stress curve. As shown in figure 9, the true stress curve indicates the stress is increasing between points $\mathbf{s}_o$ -> $\mathbf{s}_{u}$.. When the part starts necking (localized deformation) at maximum load, the increase in stress is due to the decrease in the cross sectional area of the specimen. This increase in stress becomes greater than the load carrying ability of the metal due to strain hardening. The applied force needing to dissipate will therefore concentrate stress on the microcracks and voids dispersed within the material leading to crack growth, then fracture. The following are typical yield stress and tensile strength values for different materials:

Table 1[6]

		σ_y (MPa)	σ_{ts} (MPa)
Metals			
Ferrous	Cast Irons	215 - 790	350 - 1000
	High Carbon Steels	400 - 1155	550 - 1640
	Medium Carbon Steels	305 - 900	410 - 1200
	Low Carbon Steels	250 - 395	345 - 580
	Low Alloy Steels	400 - 1100	460 - 1200
	Stainless Steels	170 - 1000	480 - 2240
Non-ferrous	Aluminium Alloys	30 - 500	58 - 550
	Copper Alloys	30 - 500	100 - 550
	Lead Alloys	8 - 14	12 - 20
	Magnesium Alloys	70 - 400	185 - 475
	Nickel Alloys	70 - 1100	345 - 1200
	Titanium Alloys	250 - 1245	300 - 1625
	Zinc Alloys	80 - 450	135 - 520

Nicopress sleeve products are engineered to be swaged (or cold formed) in the non-linear plastic region during installation, so that after compressing, the sleeve remains in its deformed state. After swaging, the sleeves become work hardened and stronger, which when assembled to a cable, will retain the yield and ultimate strength of its constituent material in its processed condition.

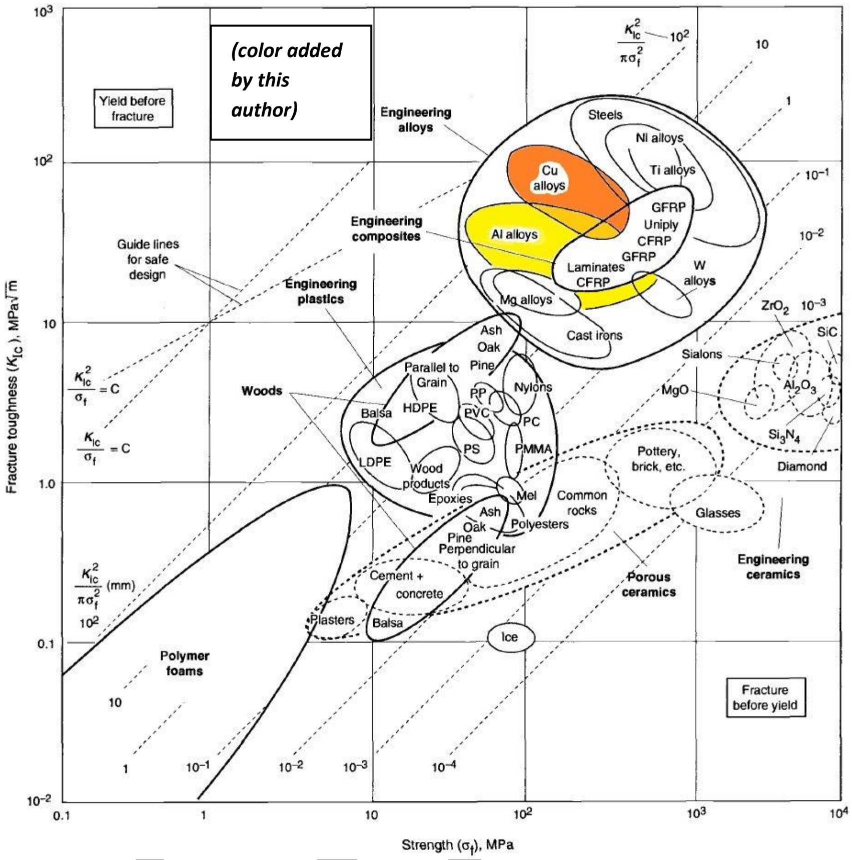
6.0 Micro-cracks & Fracture Toughness

Pure metals are made of crystalline material, all of which contain some level of defects. Defects in crystals may exist in many forms: micro-cracks occur when broken molecular bonds create new surfaces; point defects caused by impurities or alloying agents; line defects such as a dislocations; volume defects such as voids; environmental influences like oxidation; and others. Micro-cracks are mostly the result of manufacturing processes affecting the surfaces, but other processes such as: the end use applications of pressing or swaging operations for wire terminations, have an influence on them as well. Since micro-cracks are an important indicator of a materials resistance to failure, or toughness, a unit of fracture-toughness has been derived and is a common property measured in materials. The following Figure 10 plots values of fracture toughness versus yield strength. The yield strength and fracture toughness of

[6] Cambridge University Engineering Department, Material Data Book, ©2003 by Cambridge University, pg 12, Data courtesy of Granta Design LTD to Cambridge University

aluminum and copper alloys are overlapped in a small region, however, as shown, Cu alloys have generally higher values of yield strength and toughness when compared to Al alloys.

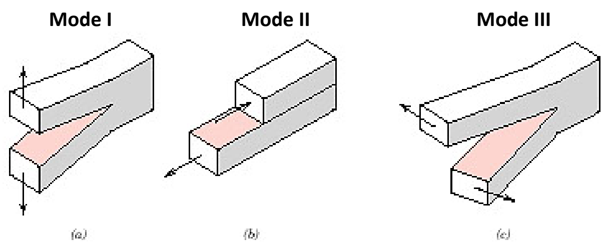
Figure 10[7] *(Note - both axis' are logarithmic and therefore non-linear, author)*



The measure of Fracture Toughness (K_{IC}) is also a measure of micro-crack sensitivity. It is a stress intensity factor value (in units of MPa(m)$^{1/2}$ or PSI (in)$^{1/2}$) and expresses the quantity required for a micro-crack to begin opening or propagating. From K_{IC}, the subscript "I" refers to the mode I of fracture as shown in figure 11a. The subscript "c" refers to the "critical" energy level to initiate crack growth.

[7] M. F. Ashby, "Material Property Charts" in ASM Handbook, Volume 20: Materials Selection and Design, edited by G. E. Dieter (©1997 ASM International) pg. 274

Figure 11[17] - Modes of Fracture which Operate on Cracks



Materials with a high yield strength and low fracture toughness may not be suitable for strength members. For example: Glass has a yield strength greater than many steels, but one would not expect the material to be a structural member without special considerations. This is due to its much lower fracture toughness of 0.8 MPa(m)$^{1/2}$, or micro-crack sensitivity, when compared to steel of 41-82 MPa(m)$^{1/2}$ and hence, while under load, may catastrophically fail with little yield. Glass will typically explode into fracture with limited yield or stretch, while steel exhibits a much greater yield strain prior to fracture.

Table 2[8]

		K_{IC} (MPa√m)
Metals		
Ferrous	Cast Irons	22 - 54
	High Carbon Steels	27 - 92
	Medium Carbon Steels	12 - 92
	Low Carbon Steels	41 - 82
	Low Alloy Steels	14 - 200
	Stainless Steels	62 - 280
Non-ferrous	Aluminium Alloys	22 - 35
	Copper Alloys	30 - 90
	Lead Alloys	5 - 15
	Magnesium Alloys	12 - 18
	Nickel Alloys	80 - 110
	Titanium Alloys	14 - 120
	Zinc Alloys	10 - 100
Ceramics		
Glasses	Borosilicate Glass	0.5 - 0.7
	Glass Ceramic	1.4 - 1.7
	Silica Glass	0.6 - 0.8
	Soda-Lime Glass	0.55 - 0.7
Porous	Brick	1 - 2
	Concrete, typical	0.35 - 0.45
	Stone	0.7 - 1.5
Technical	Alumina	3.3 4.8
	Aluminium Nitride	2.5 - 3.4
	Boron Carbide	2.5 - 3.5
	Silicon	0.83 - 0.94
	Silicon Carbide	2.5 - 5
	Silicon Nitride	4 - 6
	Tungsten Carbide	2 - 3.8
Composites		
Metal	Aluminium/Silicon Carbide	15 - 24
Polymer	CFRP	6.1 - 88
	GFRP	7 - 23
Natural		
	Bamboo	5 - 7
	Cork	0.05 - 0.1
	Leather	3 - 5
	Wood, typical (Longitudinal)	5 - 9
	Wood, typical (Transverse)	0.5 - 0.8

(color added by author)

[8] Cambridge University Engineering Department, Material Data Book, ©2003 by Cambridge University, pg 13, Data courtesy of Granta Design LTD to Cambridge University

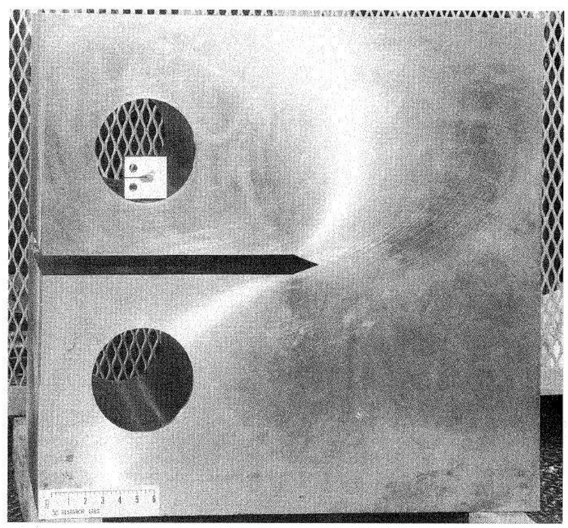
" The ideal structural steel combines high strength with high fracture toughness."[9]

This statement refers to structural steel, but the principle applies to all structural materials. A micro-crack is a stress riser; it multiplies the force acting upon a material at the location of a crack. The amount of stress riser is a function of multiple conditions, including but not limited to crystal orientation, surface damage, surface conditioning, corrosion, ageing, and others. Regardless of the stressors, the bulk failure of a material begins at localized flaws and on the surface of the part.

"Fracture cannot occur unless the stress at the atomic level exceeds the cohesive strength of the material. Thus the flaws must lower the global strength by magnifying the stress locally."[10]

The test samples for determining the K_{1C} fracture toughness value is governed by ASTM.[12] An example is shown in Figure 12. The sample is highly polished and dimensionally accurate, thus eliminates much of the typical process type micro-cracks which may occur during machining, extruding, forging, die, sand or permanent mold casting. This specimen preparation avoids extraneous variables and provides a test focused on an engineered crack in materials before they have been processed. As such, they will represent the most consistent and highest K_{1C} fracture toughness of the material.

Figure 12[11]



7.0 Fracture Work Areas

Another less consistent method of determining toughness is measuring the energy (work or strain hardening) required to fracture the material as represented by the area under the stress strain curve (Figure 13, 14, & 15), which, accounts for all pre-processed material effects. For example, in pulling a "dog-bone" test sample, the toughness determined takes into account all of the microcracks of the material dog-bone test sample (Figure 7). Note: In comparing the above test methods, the two material failure models are similar, but one is not directly dependent on the other. The K_{1C} test represents relatively pure material fracture toughness testing an engineered crack, while the energy area method includes product samples with a statistically much larger number of cracks in different orientations, process conditions, and a geometry not controlled by a standard. While one may use the energy

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[9] Sato, Koji, Improving the Toughness of Ultrahigh Strength Steel, Dissertation of University of California, Berkeley ©2002 University of California

[10] Anderson, T. L., Fracture Mechanics Fundamentals and Applications, 2nd Edition, ©1995 by CRC Press LLC, p. 33

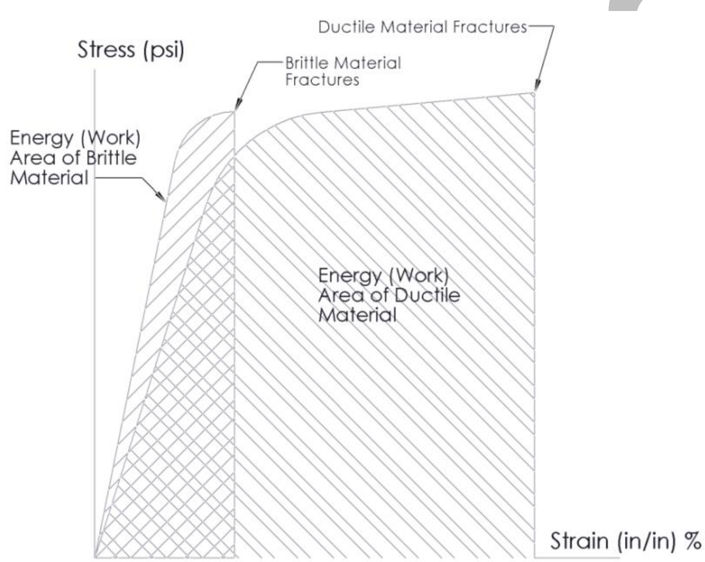
[11] Dowling, Norman E., Mechanical Behavior of Materials, ©1999 by Prentice-Hall, Inc., p.319

[12] Annual Book of ASTM Standards, Nonferrous Metals Products, © by American Society of Testing and Materials

method to compare fracture toughness of geometrically similar samples in alternate materials, it is important to understand K_{1C} is a material property value established through more extensive testing.

Work by definition is force applied over a distance. If one were to raise a five (5) pound weight twelve (12) feet vertically, it would have required sixty (60) pound-feet of energy (or work). If one were to lower this weight the same amount of distance of twelve (12) feet, the energy could be recovered. When one reviews a stress strain curve of a material deformed to failure, the units map force as applied over displacement or distance. The area underneath the curve therefore is the amount of energy the material can absorb before it fails:

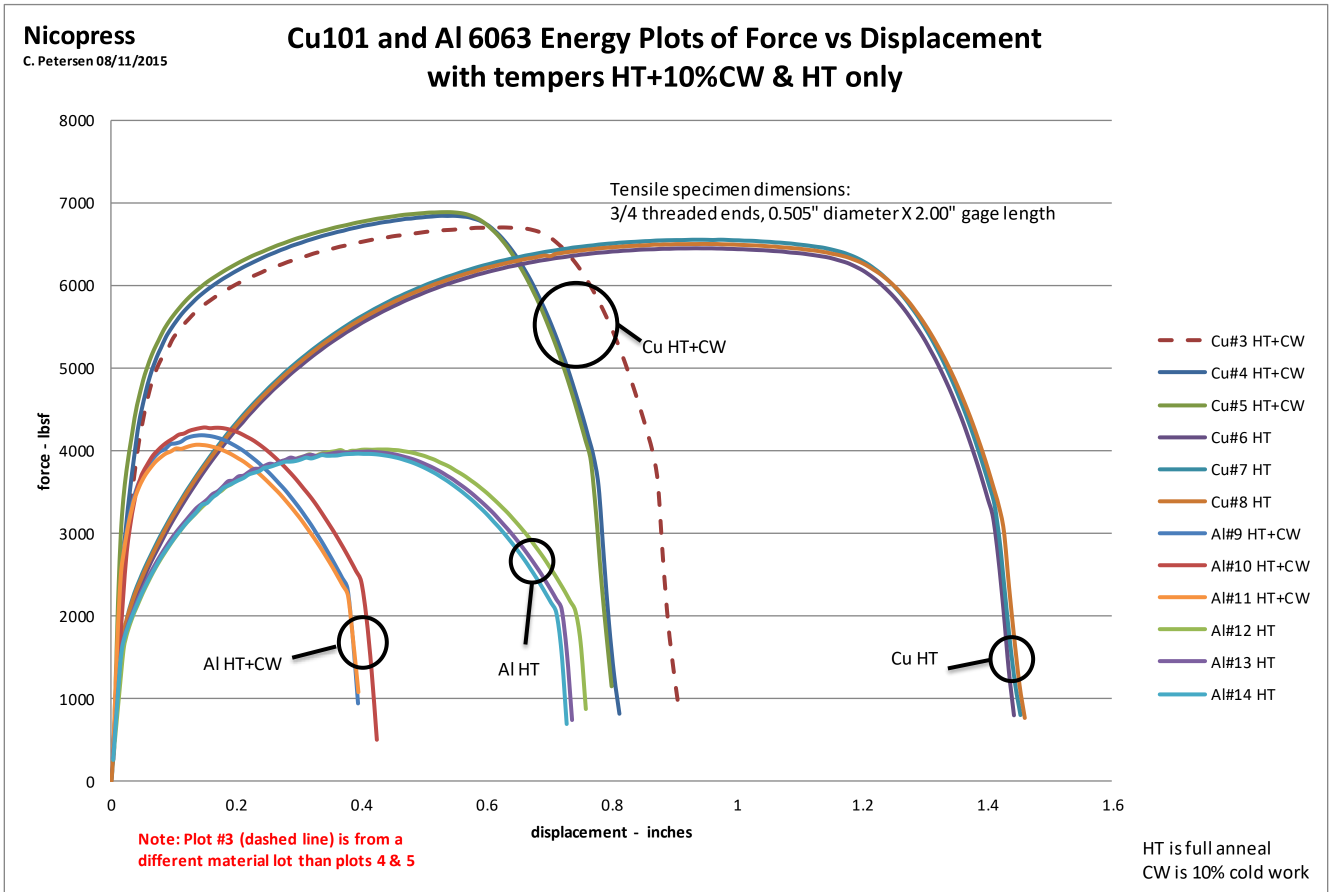
Figure 13:



This also applies to a compressed sleeve on a wire rope. The assembly is such that the amount of energy supplied by the tension on the rope, when overstressed, would need to dissipate. The more energy the sleeve/wire-rope assembly can absorb, the more resilient either are to fracture. The two stress/strain curves shown in Figure 13 show that ductile material (with greater fracture toughness or less microcracks) out-performs a more brittle material. One generally acknowledged example of this concept is brittle cast iron with high UTS; it does not always perform as well as ductile alloy steel with lower UTS, since the ductile steel will have relatively greater fracture work area.

In an independent study conducted by NTS, 4 tensile plots (see Figure 14) were generated measuring force versus displacement (from 0 inches to rupture) for 2 materials Cu 10100 and Al 6063. Each material was tensile tested in an annealed state and after 10%CW for a total of 4 plots. The total energy to pull the specimens to rupture was calculated by integrating the force vs displacement curves. The results show that pure Copper has higher (approx. 3X) fracture toughness than the aluminum materials tested for both the annealed and cold worked specimens. For both materials the annealed specimens possess approximately twice the fracture energy than cold worked specimens.

Figure 14 – Plots of Total Tensile Toughness Energy to Rupture



Fracture Energy values determined from pulling specimens to rupture - Energy values are area under the curves by integration											
Copper HT + CW	**lbsf-in**	**lbsf-ft**	**Copper HT only**	**lbsf-in**	**lbsf-ft**	**Aluminum HT + CW**	**lbsf-in**	**lbsf-ft**	**Aluminum HT only**	**lbsf-in**	**lbsf-ft**
Plot #3 Cu, HT+CW	~~5236~~	~~436~~	Plot #6 Cu, HT only	7731	644	Plot #9 Al, HT+CW	1363	114	Plot #12 Al, HT only	2524	210
Plot #4 Cu, HT+CW	4710	393	Plot #7 Cu, HT only	7894	658	Plot #10 Al, HT+CW	1484	124	Plot #13 Al, HT only	2441	203
Plot #5 Cu, HT+CW	4725	394	Plot #8 Cu, HT only	7886	657	Plot #11 Al, HT+CW	1331	111	Plot #14 Al, HT only	2387	199
ave	**4718**	**393**	**ave**	**7837**	**653**	**ave**	**1393**	**116**	**ave**	**2451**	**204**
std dev	**7.5**	**0.6**	**std dev**	**75.0**	**6.3**	**std dev**	**65.9**	**5.5**	**std dev**	**56.3**	**4.7**

As indicated below in Figure 15, the area underneath the copper curve is larger than the area underneath the aluminum curve.

Figure 15[13]

Color Highlighting Added by this Author

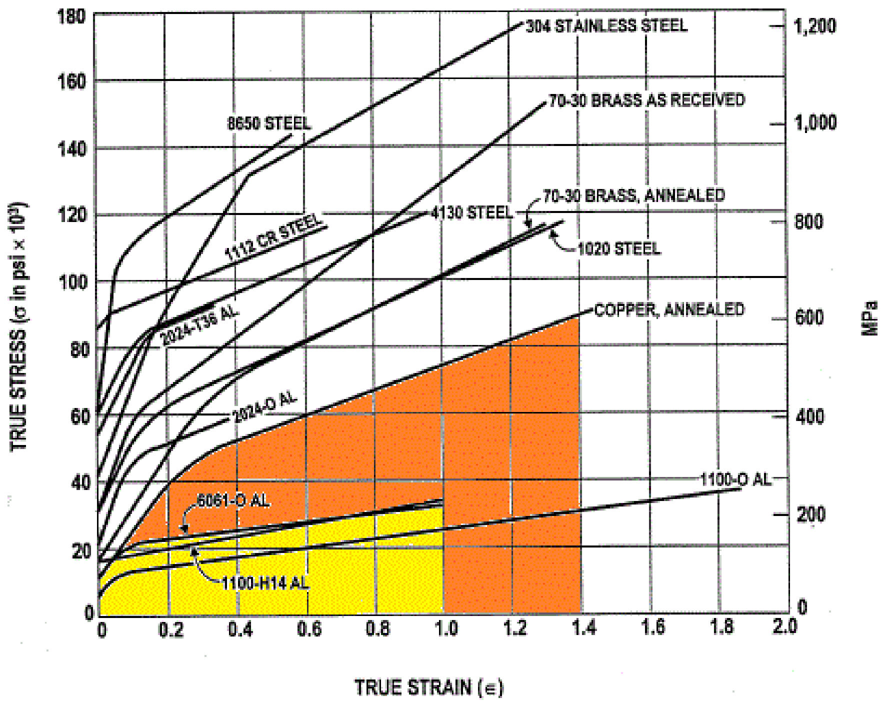


Figure 15 visually demonstrates differences in Al and Cu materials with lower and higher ductility. Each "dog bone" pair shown represents the sample before and after pulling. The samples were created by pulling on tensile specimens of equal geometric shape and cross-sectional areas. The top pair of Al samples is less ductile than the lower pair since the pulled Al sample stretches less before necking than the pulled Cu sample.

Figure 15: Examples of sample pairs before and after pulling for Al versus Cu test specimens

[13] Keys to Metal Website, True Stress to True Strain Curves: Part Two, ©2012 Keys to Metal AG

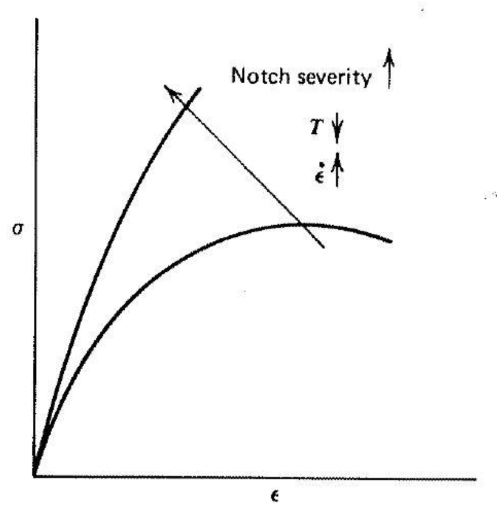
8.0 Coefficients of Thermal Expansion

Due to their atomic and molecular structure, materials expand or contract at different rates as a function of temperature. There is a value assigned to each material and it is known as the Coefficient of Thermal Expansion (CTE). This is an important property since at low temperatures, a material may become more brittle; at high temperatures it may become more ductile. How much a material changes dimensionally with temperature is represented by its CTE. When a material CTE is larger than another material, it indicates it will expand more given the same temperature changes and size of specimen. The numbers are a linear ratio of one another. If one material has a CTE of 200, and another a CTE of 100, the first will expand twice as much as the second for the same change in temperature.

> "…temperature changes can generate residual stresses that ultimately may lead to the fracture of components."[14]

The above statement is supported by the fact that when a material cycles between hot and cold, residual microcracks are being *worked*, i.e., constantly being stretched and compressed in the material during cycling. This effect is represented in the following Figure 16:

Figure 16[15]



Stress (psi or pounds force/in^2) is represented by **s;** strain (percentage inch/inch) is represented by **e**. While 'T' or temperature decreases, notch severity or crack sensitivity increases, and the stress/strain curve becomes steeper as indicated by the diagonal arrow. Also indicated in the figure, is the effect of strain rate "$\dot{\epsilon}$", or, (*d***e**/*dt*). As it increases (or material stretches at a faster rate), the material becomes more micro-crack sensitive.

The following table shows the CTE of different materials:

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[14] Hertzberg, Richard W., Deformation and Fracture Mechanics of Engineering Materials, ©1996 by John Wiley & Sons, Inc., Chapter 7, p.279

[15] ibid

Table 3[16]

(color added by author)

Metal	Coefficient of Thermal Expansion µ in./in. °C	Expected Expansion of a 120 inch sheet* (in)	Expected Expansion of a 3 meter sheet* (mm)
3003 Aluminum	23.2	0.11	2.79
5005 Aluminum	23.8	0.11	2.79
6063 Aluminum	23.4	0.11	2.79
Copper	16.8	0.08	2.03
Gilding Metal	18.1	0.08	2.03
Commercial Bronze	18.4	0.08	2.03
Jewelry Bronze	18.6	0.08	2.03
Red Brass	18.7	0.09	2.29
Cartridge Brass	19.9	0.09	2.29
Yellow Brass	20.3	0.09	2.29
Muntz Metal	20.8	0.09	2.29
Architectural Bronze	20.9	0.10	2.54
Phosphor Bronze	18.2	0.08	2.03
Silicon Bronze	18.0	0.08	2.03
Aluminum Bronze	16.8	0.08	2.03
Nickel Silver	16.2	0.07	1.78
Iron	11.7	0.05	1.27
Steel	11.7	0.05	1.27
Cast Iron	10.5	0.05	1.27
304 Stainless Steel	16.5	0.08	2.03
Lead	29.3	0.13	3.30
Monel	14.0	0.06	1.52
Tin	23.0	0.10	2.54
Zinc – rolled	32.5	0.15	3.81
Zinc-Cu, Tn Alloy	24.9 with grain	0.11	2.79
Zinc-Cu, Tn Alloy	19.4 across grain	0.09	2.29
Titanium	8.4	0.04	1.02
Gold	14.2	0.05	1.27

For example, the above table indicates aluminum expands approximately 39% more than copper in micro-inches per degree C. This increases crack growth in the aluminum versus the copper in similar applications of temperature variations. The above demonstrates how a given material behaves with changes in temperature due to its material property value of CTE possessing expansion rates affecting crack growth.

In addition to intrinsic processes occurring within a single material, there are applications where 2 or more materials are used in assemblies. For example, using the table values above for Cu, Al 6063, & SS (304 stainless steel): a Cu material will expand and contract ~2.4% more than SS, whereas, the Al will expand and contract ~42.7% more than the SS. The result: large differences in expansion rates (CTE's) between mating parts in an assembly may cause loosening between or cracking within the component parts.

9.0 Application

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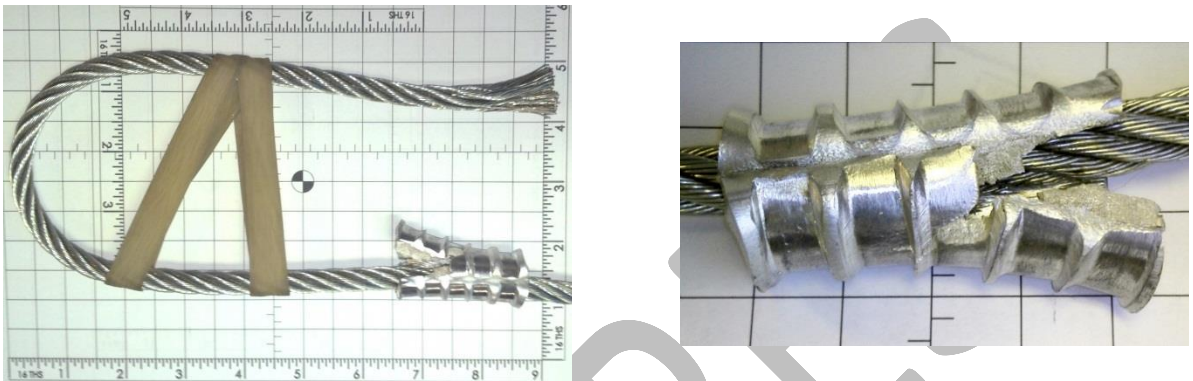
[16] A. Zahner Company, 1400 East 9th Street, Kansas City, MO 64106, T:816.474.8882, ©2012 by A. Zahner Co.
[17] University of Illinois Materials Science & Eng. Dept., MatSe280: Intro to Eng. Materials, pg. 29, D. Johnson 2008
[18] Ashby, M. F., Jones, D., Engineering Materials 1, ©1991 Pergamon Press, p. 78

Figure 10 and Table 1 show copper alloys have generally greater tensile strength ($\mathbf{s}_u$) than aluminum alloys at the low end, and approximately equal at the high end. This implies if one were only considering tensile strength, for acceptance criteria, these materials might be considered comparable. However, large numbers of tensile tests indicate that aluminum does not fail in the same manner as copper. Figure 17 below is an example of one type of brittle fracture which occurred on an eye splice using an aluminum sleeve:

Figure 17



Other types of failure may occur with aluminum sleeves such as: shear slip, where Al sleeve material swaged into the interstices of cable strands shears from the ID of the sleeve, thus allowing the cable to slip out of the sleeve.

All of the preceding sections on material behavior and failure types indicate several properties of Aluminum and Copper materials should be considered for proper material selection criteria:

1. Tensile Strength (UTS) – while over a range, copper and aluminum alloys may have similar tensile strengths; in practice copper sleeve material is usually higher than aluminum.

2. Fracture Toughness (K_{1C}) – except for a small overlap seen on Figure 10, the fracture toughness of copper is greater than aluminum. The copper alloy types used by Nicopress for compressed sleeve components are above this overlap region. Therefore, copper sleeves are less sensitive to cracks, both from pre-processed material and post forming processes. When a metal sleeve is compressed into shape (Figures 2 & 4) some microcracks will mechanically close and others will open. The closed or smaller microcracks will have a lower stress riser influence, the larger microcracks, a higher stress riser influence. Since larger microcracks may be present in a pressed or swaged sleeve, it is wise to choose a tougher material to resist crack propagation.

3. Fracture Work Areas – Determined from pull tests and as Figure 15 indicates: most copper alloys have a better ability to absorb the type of forces which contribute to a fracture since the energy (area under the curve) required for failure is larger for Cu as opposed to Al. This suggests copper sleeve materials will withstand higher loads and exhibit more ductility before failure than sleeves with aluminum material used in the same application.

4. Thermal Expansion (CTE) – (Table 3) indicates aluminum expands and contracts more than copper during equal temperature changes due to their temperature coefficients. Most

application environments expose cable assemblies to significant and constant variations in temperature. Moreover, higher material temperature coefficients contribute to: crack sensitivity, work hardening, fatigue, and ultimately fracture. Also, in applications with sleeves used on steel cable, the Cu will not change dimensionally as much as Al with variations in temperature.

11.0 Conclusion

Materials have many properties affecting their mechanical behavior. As reviewed in this paper, tensile strength (UTS) is an important factor in sleeve material selection; however, a closer inspection of other material properties reveals equally important factors to consider. We have addressed that Nicopress sleeves are pressed (or swaged) beyond the material yield point to plastically deform (or "cold form") them in cable termination applications. Once assembled, we have found the strength of the sleeve/cable assembly is controlled to a large extent by the sleeve material properties of: tensile strength, fracture toughness/energy, and temperature expansion coefficient. It was shown copper alloy materials are, in general, tougher with a greater fracture energy required for failure when compared to the aluminum alloys used for compression sleeves. It is recommended when considering a compression sleeve material for cable applications, all of these factors be considered for proper application and use. Furthermore, in critical performance applications and those with human safety concerns, Cu alloys may be the best choice for compression sleeve material.

NICOPRESS

Disclaimer:

Not all physical and environmental factors such as: pressure, corrosion, fatigue, creep, radiation, or, chemical agents have been addressed herein, which may also affect mechanical behavior of materials. It is important to identify all physical, chemical, environmental factors, and, the appropriate tests required in determining the most suitable material in any given application.