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Coiled Tubing – Titanium Alloy, Hydraulic Applications, Aerospace

RATIONALE

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1. SCOPE

This SAE Aerospace Recommended Practice (ARP) addresses the design, installation, and testing of coiled tube assemblies using Ti-3Al-2.5V cold worked, stress relieved (CWSR) tubing per AMS4945. It specifically details five different configurations of coiled tubing.

The configurations detailed herein should be compatible with pressure levels up to 8000 psi (55.2 MPa) upon completion of analysis for the actual stress and life requirement of the intended application.

Formal qualification tests are recommended to verify satisfactory installation, clamping, and the life of each unique design.

NOTE: For information on design of coiled tube assemblies using CRES steel tubing, see ARP584.

1.1 Purpose

The purpose of this document is to provide data and information relative to design, fabrication, and installation of formed tubing made from titanium alloy. The formed tubing has the function of accepting relative motion between two points in a hydraulic system.

1.2 Field of Application

The use of coiled tubes is encouraged in the design of hydraulic systems per AS5440 or ARP4752/ARP4925, and for pneumatic systems per MIL-P-5518 when standard flexible hoses are not feasible due to installation constraints, compliance limitations, and effusion requirements.

2. APPLICABLE DOCUMENTS

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

ARP584	Coiled Tubing - Corrosion Resistant Steel, Hydraulic Applications, Aerospace
AIR1379	Prestressing (Autofrettaging) of Hydraulic Tubing Lines
AS4076	Contractile Strain Ratio Testing of Titanium Hydraulic Tubing
AS4401	Separable Fittings, Permanent Fittings, Tubing, Fluid Systems, 8000 psi, Qualification Test Standard for
AS4467	Standardization, Hydraulic Tube Walls
ARP4752	Aerospace - Design and Installation of Commercial Transport Aircraft Hydraulic Systems
ARP4925	Aerospace - Design and Installation of Commercial Transport Helicopter Hydraulic Systems
AS5440	Hydraulic Systems, Military Aircraft, Design and Installation, Requirements For
AMS4945	Titanium Alloy Tubing, Seamless, Hydraulic, 3Al - 2.5V, Controlled Contractile Strain Ratio, Cold Worked, Stress Relieved

2.2 U.S. Government Publications

Available from the Document Automation and Production Service (DAPS), Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094, Tel: 215-697-9495, <https://assist.daps.dla.mil/quicksearch/>.

MIL-P-5518 Pneumatic Systems, Aircraft, Design and Installation, General Requirements for

MMPDS Metallic Materials Properties Development and Standardization

3. CONFIGURATIONS

There are five configurations detailed in this ARP, which are as follows:

- a. Style A - Helical Torsion Configuration
- b. Style B - Torsion Tube Configuration
- c. Style C - Helical Compression/Extension Configuration
- d. Style D – Tri-Coil Compression/Extension Configuration
- e. Style E- Oval Compression/Extension Configuration

Each configuration is described in the following sections.

3.1 Style A - Helical Torsion Configuration

This configuration (Figure 1) typically consists of a 540 degree (1-1/2 coil) helical coil of tubing with a straight section projecting from each end of the coil.

The upper illustration in Figure 1 shows an installation with the tubing coming from the rod end of the actuator and the coiled tubing not only provides the required flexibility, but also enables the direction of the tube routing to be reversed. The bottom illustration shows an installation where the tubing is coming directly on to the actuator's port.

In the actual application, if the coil is properly clamped at the points defined as "1" on Figure 1, the tube may have additional bends and straight lengths to allow aligning the end fittings with the interfacing fittings.

In practice Style A may vary from 180 degrees (1/2 coil) up to 900 degrees (2-1/2 coils) where the angles quoted are the total angles through which the tubing is bent in the manufacture of each coil.

This style is widely used within the aerospace industry to accept angular motion about a defined pivot point.

Appendix A contains design data for Style A coiled tubes for 3000 psi (20.7 MPa) to 8000 psi (55.2 MPa), 1/2 to 2-1/2 coils and deflection up to 28 degrees.

- = GROUND POINT
1. BRACKETS TO ACCEPT FLEXURE LOADS
 2. REQUIRED LENGTH B, FOR COIL FLEXURE
 3. REQUIRED CLAMP FOR 1 AND 2 COIL DESIGNS

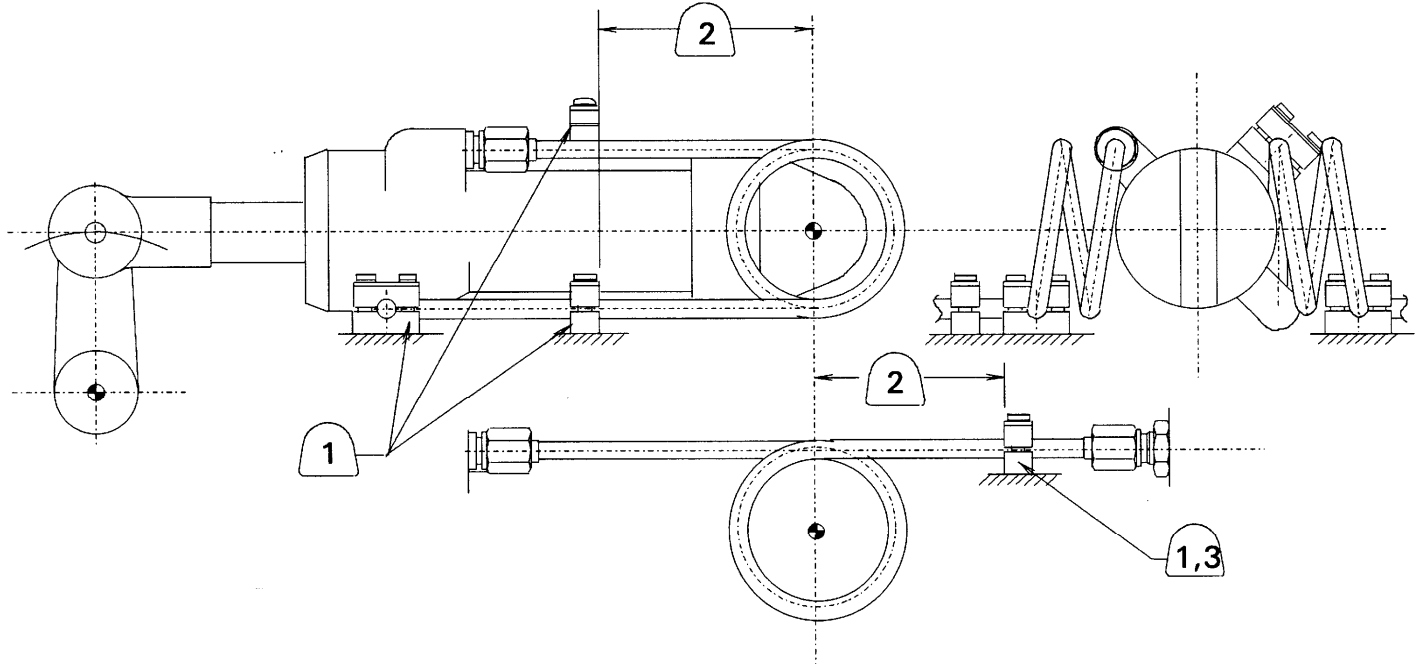


FIGURE 1 - STYLE A - HELICAL TORSION CONFIGURATION

3.2 Style B - Torsion Tube Configuration

This configuration (Figure 2) consists of three straight sections separated by two 90 degrees bends. This is not a coiled tube configuration but is included in this document to present all standard configurations used to accept relative motion between two points.

The middle straight section is twisted in operation, allowing one end to rotate about the centerline of the middle straight section.

This configuration must be clamped between the bends and the fittings to remove bending stress from the fittings.

This configuration is used to accept angular motion about a defined pivot point.

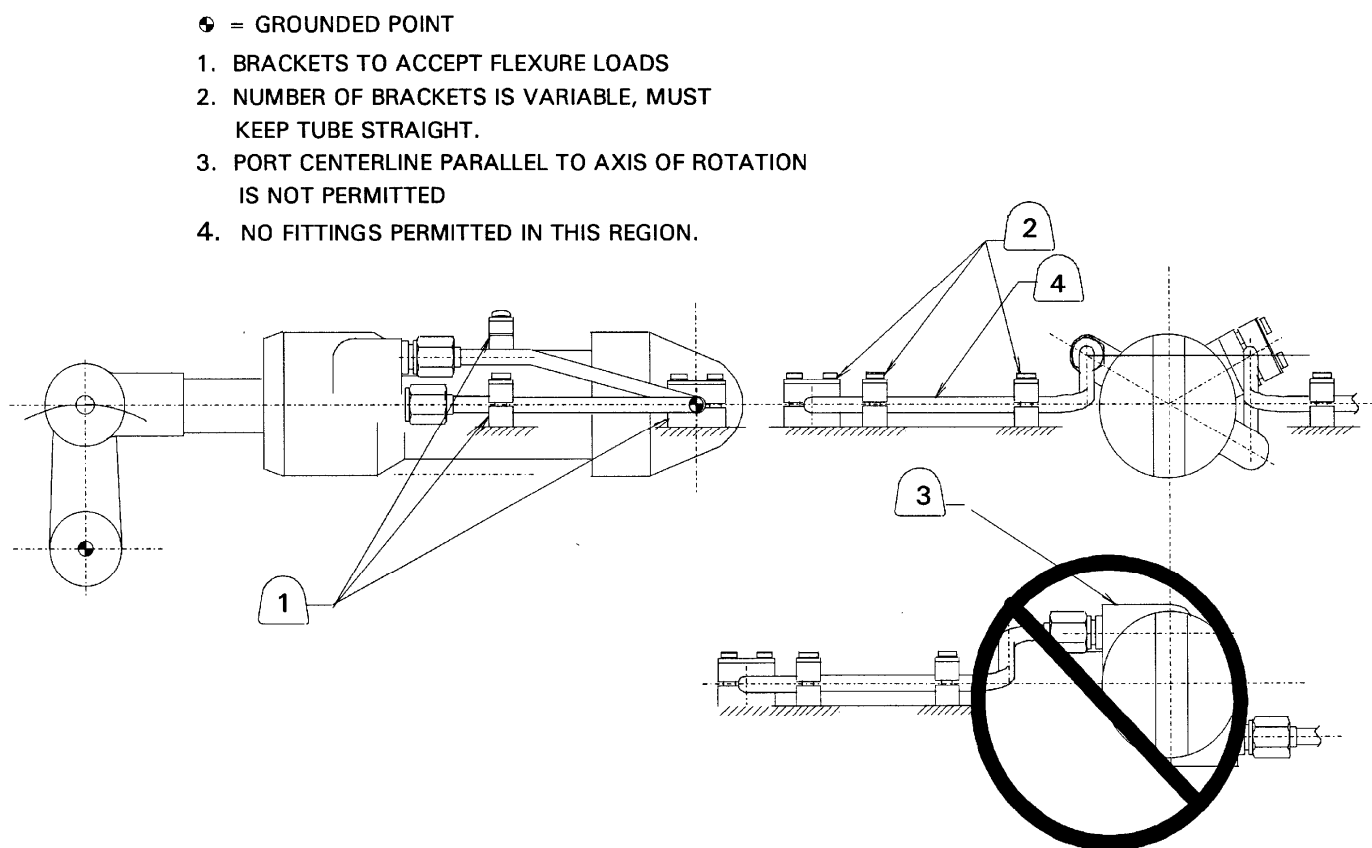


FIGURE 2 - STYLE B - TORSION TUBE CONFIGURATION

3.3 Style C - Helical Compression/Extension Configuration

This configuration (Figure 3) consists of one or more coils coiled in a helix that accepts linear extension and compression.

In order to align the coil fittings with the hydraulic component fittings, the use of specific transition bends from the tangent of the helix to the end fittings as described later in this document is recommended.

⬤ = GROUNDED POINT

1. COILS ARE AT MINIMUM LENGTH WITH ACTUATOR AT LENGTH LR.
2. COIL COMPRESSION, $\Delta = .5556 * (LE - LR)$.
3. COILS ARE COMPRESSED TO $0.0556 * \Delta$ WITH ACTUATOR AT NEUTRAL.
4. COILS EXTEND $0.4444 * (LE - LR)$.
5. COILS ARE AT MAXIMUM EXTENSION WITH ACTUATOR AT LE.

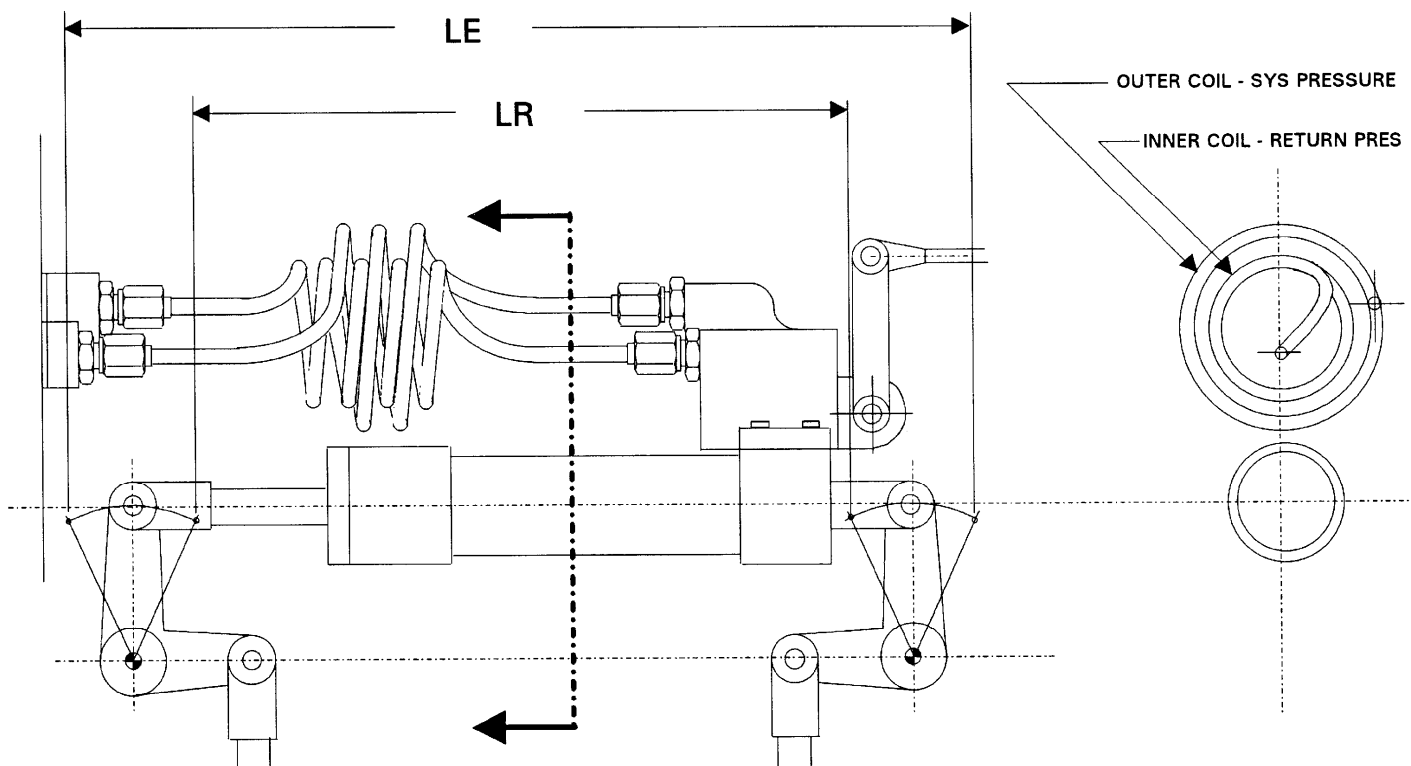


FIGURE 3 - STYLE C - HELICAL COMPRESSION/EXTENSION CONFIGURATION

3.4 Style D - Tri-Coil Compression/Extension Configuration

This configuration (Figure 4) consists of three sets of helically wound coils connected by straight lengths to allow linear motion between the end fittings.

⊕ = GROUNDED POINT

1. COILS ARE AT FREE POSITION WITH ACTUATOR AT LENGTH LR.
2. COIL ARE AT MAXIMUM DEFLECTION WITH ACTUATOR AT LENGTH LE.
3. FOR THIS APPLICATION, COIL STROKE = $(LE - LR)/2$.
4. FOR CYLINDER FIXED, ROD MOVING OR ROD FIXED, CYLINDER MOVING, THE STROKE = $LE - LR$.

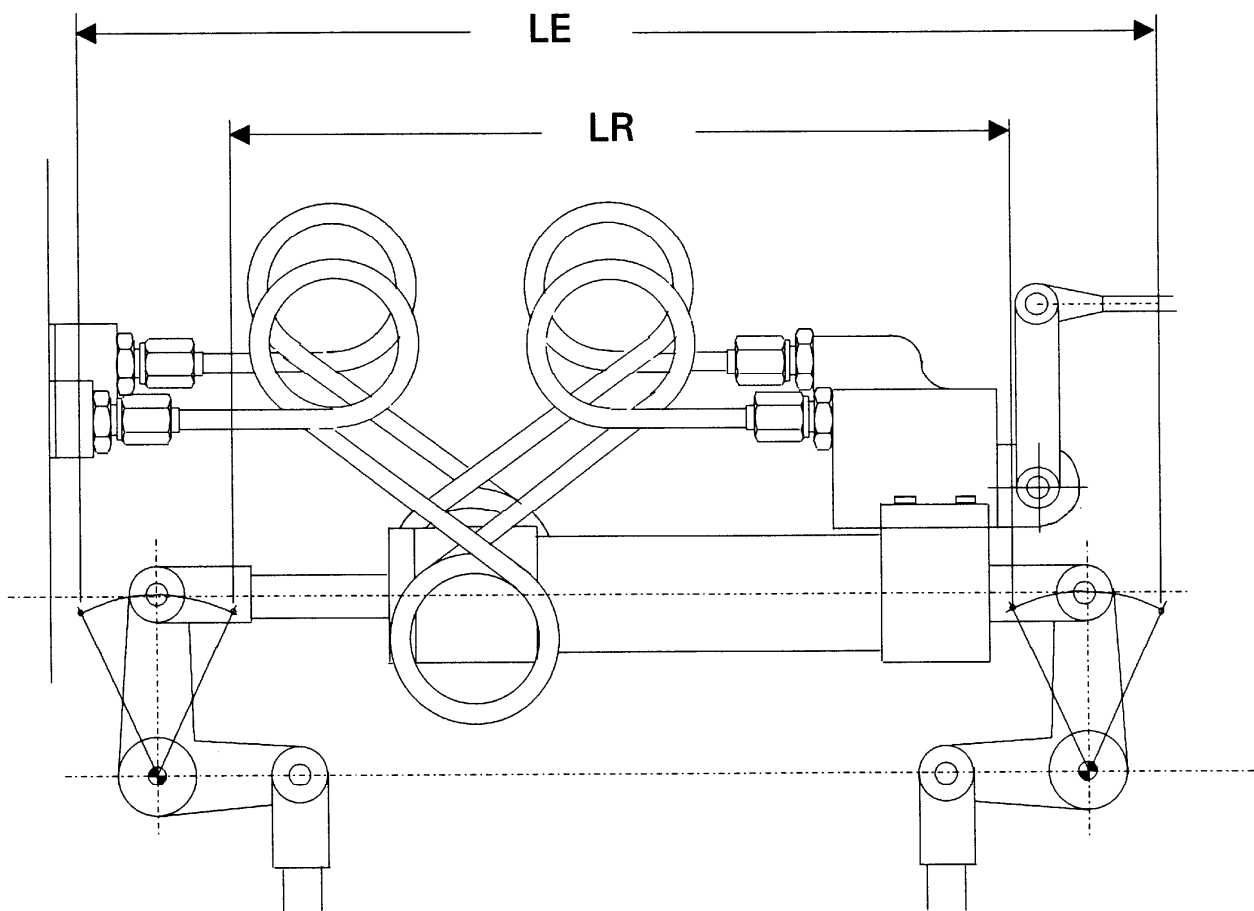


FIGURE 4 - STYLE D - TRI-COIL COMPRESSION/EXTENSION CONFIGURATION

3.5 Style E - Oval Compression/Extension Configuration

This configuration (Figure 5) is a special case of Style C where instead of coils being wound about a helix of constant diameter, the coils are oval shaped with straight lengths between semi-circular coils.

This configuration has the advantage of being able to fit into shallow envelopes or to be installed coaxially around the outside of the moving hydraulic component for space efficiency. Another advantage of this configuration is that it requires fewer coils because of the large effective diameter of the coils.

⦿ = GROUNDED POINT

1. COILS ARE AT MINIMUM LENGTH WITH ACTUATOR AT LENGTH LR.
2. $\Delta = \text{COIL COMPRESSION. } \Delta = 0.5556 * (LE - LR).$
3. COILS ARE COMPRESSED TO $0.0556 * \Delta$ WHEN ACTUATOR IS AT NEUTRAL.
4. COILS EXTEND $0.4444 * (LE - LR).$
5. COILS ARE AT MAXIMUM LENGTH WITH ACTUATOR AT LENGTH LE.

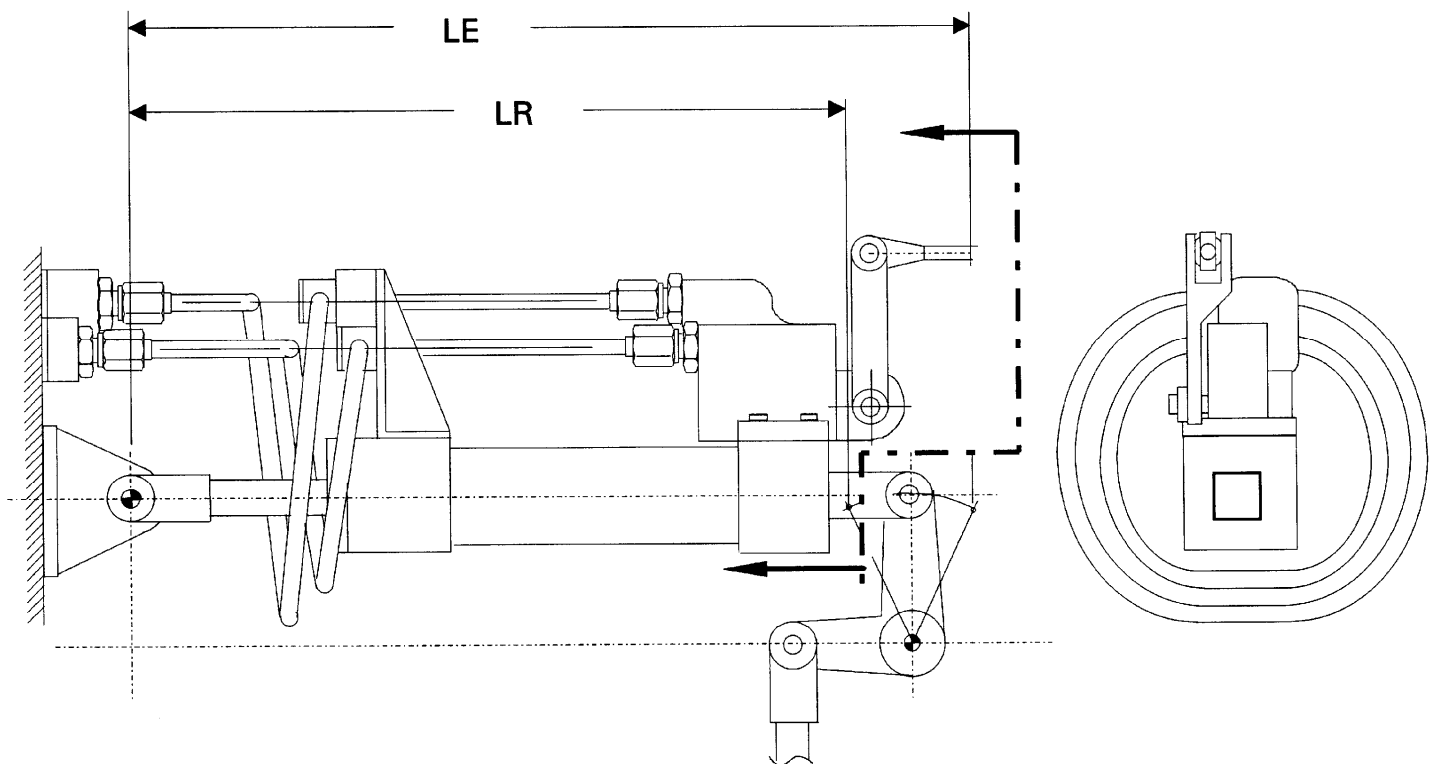


FIGURE 5 - STYLE E - OVAL HELICAL COMPRESSION/EXTENSION CONFIGURATION

4. MATERIAL PROPERTIES

The recommended material is seamless titanium alloy tubing, Ti-3Al-2.5V in the CWSR condition in accordance with AMS4945 or equivalent.

4.1 Basic Allowables

Room temperature allowables for this material are:

- a. Ultimate tensile strength, F_{tu} (min): 125 000 psi (862 MPa)
- b. Yield tensile strength, F_{ty} (min): 105 000 psi (724 MPa)
- c. Elastic modulus, E : 15 000 000 psi (103 421 MPa)
- d. Torsion modulus, G : 5 680 000 psi (39 162 MPa)
- e. Poisson's ratio, μ : 0.32

4.2 Endurance Allowables

In the design of the various configurations for a specific fatigue life, the use of the correct allowable stress is critical to the life of the design. Specific tests should be conducted on instrumented coils of the configuration to be used in order to determine the allowable number of mechanical flexure cycles at each stress level. The data may be put into the form of a Goodman constant life diagram in order to be easily used.

Ideally, for Styles A and D, planar flexure of curved tubing would give equivalent fatigue data.

For Style B, torsion flexure of straight tubing is recommended.

For Styles C and E, torsion flexure of curved tubing or rotary flexure of curved tubing would give reasonable fatigue data.

If the tests to determine fatigue life of specimens are conducted at room temperature, the stress allowable determined at each level of cycles should be reduced by an appropriate factor when designing coils which would have to operate in an environment at a higher temperature than the test temperature. A conservative method of correcting for property reduction at elevated temperature is to ratio the tensile yield stress at the elevated temperature to the tensile yield stress at the test temperature. This is achieved by multiplying the fatigue allowable at the test temperature times the ratio. Temperature correction data for several titanium alloys are published in MIL-HDBK-5.

Basic S-N curve type summation flexure and impulse fatigue data on straight tubing, bent tubing, and tube/fitting joints is required in sufficient quantity to establish a true performance scatter band to a 0.9 confidence level. This data may be obtained from the tube/fitting qualification test program similar to AS4401. From this data, modified Goodman (constant life) diagrams for the tube/fitting should be prepared using the low end of the scatter band (i.e., that S-N curve which represents a 99.9% certainty that all performance data points that lie on or below the curve represent non failure conditions) as the basis for preparing the diagram.

4.3 Contractile Strain Ratio

During tubing fabrication, crystallographic textures that develop in alpha titanium alloys such as Ti-3Al-2.5V CWSR as a result of cold reduction can cause significant anisotropy or directional properties in finished tubing. These directional properties manifest themselves as excessive thinning or the rupture of the tube wall on the outer bend radius during bending. Other manifestations are reduced yield and burst strength under internal pressurization and reduced fatigue life in pressure-flexure testing. The material properties to give a balance of performance between the extremes may be determined using a test property called contractile strain ratio (CSR). AS4076 (referenced in AMS4945) gives a method for determining the CSR.

5. STRESS ANALYSIS

There are a number of methods that may be used to analyze the total stresses at critical points in the coils, including:

- a. Von-Mises Distortion Energy Failure Theory for loading in multiple axes.
- b. Finite Element Analysis (FEA) is another technique for stress analysis of the sometimes irregular configurations required of coiled tubing. Any FEA software that is used should have bar elements for possible nonlinear cases.

6. FITTINGS

The following fitting systems have been tested or used with coiled tube installations successfully:

- a. MS flareless
- b. Flareless with brazed or swaged sleeve
- c. Dynamic beam seal with internal swaging
- d. Dynamic beam seal with external swaging
- e. Cryogenic swaged

These currently used fitting systems will work with coiled tubing under the following conditions which must be considered in the design. The stresses at the end of the fittings should be separately analyzed as they may be higher than those in the coils. Any combinations of torsion and linear loading should be avoided unless specifically addressed in the qualification testing of coiled tube designs.

7. FABRICATION

7.1 Style A

Style A coiled tubing may be fabricated using one of several methods of forming the coils. The use of mandrels or rollers which closely match the tubing outer diameter is recommended in order to control flattening or ovality of the tube in the curved sections after forming. For Ti-3Al-2.5V CWSR material the final ovality should not exceed 3% using the following definition:

$$\text{Ovality} = \frac{(\text{OD}_{\text{Max}} - \text{OD}_{\text{Min}}) \times 100}{\text{OD}_{\text{Nominal}}} \quad (\text{Eq. 1})$$

7.1.1 Conventional Tooling

The conventional die block which contains a semicircular shaped groove around 180 to 270 degrees of its external surface must be replaced by a similar block containing a groove which spirals through 600 degrees (1-2/3 turns). As this spiral die block turns, it must be free to shift along its axis, or the feed block must move relative to the spiral die to accommodate the lead of the spiral. The feed block (which supports the unbent tube) must be tilted to an angle approximately equal to the helix angle, which can be adjusted to produce the correct pitch (typical spring winding technique).

7.1.2 Spiral Mandrel

Another type of tooling which may be used for Style A coiled tubing is a spiral mandrel that moves along its axis as it is turned to form the pitch of the coils. This type of tool is shown on Figure 6. This type of tooling may be used for all styles of flexible tubing that use coils. It consists of a machined mandrel with reduced coil diameter to compensate for material springback and reduced pitch to compensate for pitch springback after forming.

Two details that require particular attention are the method of clamping the formed end of the tubing to the mandrel and the provision of adequate torque multiplication to keep force required for forming constant and well within human factors limitations.

Tubing greater than 3/8 in (9 mm) diameter should be formed using a powered tool.

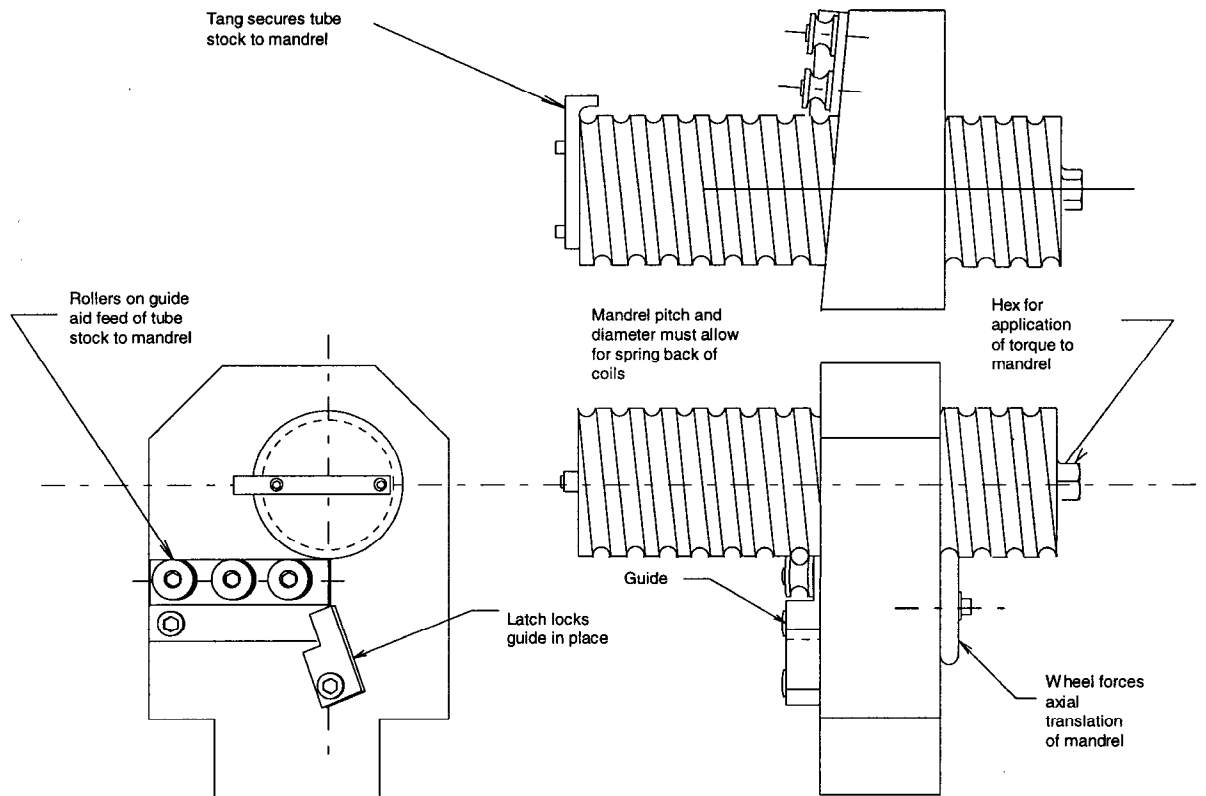


FIGURE 6 - SPIRAL MANDREL COILING TOOL

The following equation may be used to determine the diameter of the mandrel to use for a required coil diameter after springback. This equation has an accuracy of 2% of the coil diameter.

$$Da = \frac{1.02 \times R}{\left[\frac{R}{(Ds - R)} \right] + \left(1.85 \times \frac{Ftu}{E} \right)} - Do \quad (\text{Eq. 2})$$

where:

Da = arbor diameter

Ftu = ultimate tensile stress allowable

E = modulus of elasticity

Do = tubing OD

Di = tubing ID

Ds = coil OD

and

$$R = \frac{\sqrt{2}}{2} \times \sqrt{D_o^2 + D_i^2} \quad (\text{Eq. 3})$$

Other factors that will affect the accuracy of the final coil diameter are the consistency of the torque applied during forming and the variation of material properties from lot to lot.

7.1.3 Other Tooling

Other types of tooling may be used to form helical coils. These types are based upon the positioning of rollers which deflect the tubing as it is fed into the rollers through a guide. This type of tooling is normally used for fabrication of springs and is available in the form of coiling machines from manufacturers. The machines range in complexity and capability from manually adjusted to microprocessor controlled designs.

In a survey conducted in 1985, none of the machines surveyed were immediately acceptable for use in forming coiled tubing. Two principal problems were that the machines required continuous roll supply stock and used shear methods to cut-off the stock at the end of a forming cycle. However, with development, these sophisticated machines could be used for forming coiled tubing with the advantage of being adaptable to a wide range of tube diameters, coil diameters, and pitches. This is contrasted to the conventional tooling based on mandrels or machined helices to form the coils.

7.2 Style B

Style B coiled tubing may be fabricated using conventional bending equipment normally used for bending tubing.

7.3 Style C

Style C coiled tubing may be formed using any of the tooling described for Style A in 7.1.2 and 7.1.3.

7.4 Style D

Style D coiled tubing may be formed using any of the tooling described in 7.1.1 through 7.1.3.

7.5 Style E

Style E coiled tubing may be formed using tooling described in 7.1.1 or 7.1.3.

7.6 Surface Finish

During fabrication and handling the surface finish of the tubing inner diameter and outer diameter should be protected from scratches and dents. Lubrication of the mandrels may be required to prevent linear scratches in the tube wall during forming.

7.7 Autofrettage

This is a technique that is used to reduce ovality and improve fatigue life of the tubing by pressurizing the tubing until the stress at the inner wall of the tubing is in the plastic range. By applying internal pressure in this manner ovality is reduced by forcing the tube to assume a shape closer to the original diameter. Also, after removal of the pressure, the inner wall has a residual compressive stress that reduces the effect of minor imperfections and irregularities in the inner tube wall. Tests by major airframe manufacturers demonstrated increased fatigue impulse life after autofrettage of tubing. These benefits are a function of the amount of ovality with little advantage when ovality is less than or equal to 2%.