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**Analysis of Valve Springs from Hydrogen
Compressor at Solvent Refined Coal Plant,
Wilsonville, Alabama**

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SOLVENT REFINED COAL PLANT, WILSONVILLE, ALABAMA

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ANALYSIS OF VALVE SPRINGS FROM HYDROGEN COMPRESSOR AT
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R. T. King, R. S. Crouse, B. C. Leslie, E. T. Rose,
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ABSTRACT

Failure of hydrogen compressor valve springs at the Wilsonville, Alabama, Solvent Refined Coal Plant caused a total plant shutdown. Type 304 stainless steel springs had been substituted for two of three alloy X750 springs. Mainly because of their geometry, the type 304 stainless steel springs operated at a higher stress than the proper springs, and it is not surprising that they failed. The only as-fractured surface was on the alloy X750 spring. Edge damage caused by rubbing of the springs against neighboring parts may have played an important role in reducing the life of the springs.

SOURCE OF PART

The Southern Company System and the Edison Electric Institute (EEI) jointly began the pilot plant study of key steps in the solvent refining process for making low-sulfur and low-ash solid fuel from coal in March 1972. Southern Company Services, Inc., (SCS) represents the Southern Company System and provides management for the project. In April 1973, the Electric Power Research Institute (EPRI) assumed the functions of utility industry project supervision, which were formerly carried out by EEI.

The United States Energy Research and Development Administration (ERDA) joined in the sponsorship of this project for the calendar years 1976 and 1977.

The six-ton-per-day solvent refined coal (SRC) pilot plant was designed, was constructed, and is being operated by Catalytic, Inc., at Wilsonville, Alabama. Operation with coal began in January 1974.

*This work was performed under the Failure Prevention and Analysis Program sponsored by the Materials and Exploratory Research Branch of Fossil Energy.

DESCRIPTION OF PART

Three sections of helical coil spring were supplied. The geometries are given in Table 1. The spring manufacturer is not known.

Table 1. Description of Helical Springs After Service

Section	Dimensions, mm (in.)			Turns per		End Condition ^a
	Coil Diameter	Wire Diameter	Unstressed Length	meter	inch	
1	5.25 (0.207)	0.70 (0.0275)	12 (0.45)	630	16	machined, damaged fracture
2	5.28 (0.208)	0.76 (0.030)	10 (0.4)	470	12	machined, worn flat
3	5.28 (0.208)	0.76 (0.030)	10 (0.4)	470	12	machined, worn flat

^aBoth ends described.

DESCRIPTION OF SERVICE CONDITIONS AND LIFE

The springs were from a two-way-pressure valve mounted on the cylinder head of the C104 Cooper-Bessemer compressor. During plant operation, the compressor is started on nitrogen and then switched to hydrogen; the valve springs are exposed to both gases at 25°C inlet temperature and 74–88°C outlet temperatures. There are three springs on the inlet valve and three on the outlet valve. The springs in question are part of a set removed from the pump on June 9, 1977, when a valve spring failure forced a complete plant shutdown after 21 hr of operation. Since the compressor operates at 8.3 Hz (500 cycles/min), each spring was cycled at least 630,000 times. The stroke length is approximately 1.78 mm (0.070 in.) and the uncompressed nominal length of a new spring is 12.7 mm (0.5 in.).

ANALYSIS

The major concern of the plant operators was possible substitution of an improper spring during earlier maintenance on the compressor. The proper spring material was to have been alloy X750.

Part of each spring coil was analyzed at the ORNL Spectrochemical Laboratory. Section 1 was found to be alloy X750 by visual comparison with a U.S. Bureau of Standards plate, nominally Ni-15% Cr-7% Fe-2.5% Ti-1% Nb-0.7% Al. Section 2 was identified as type 304 stainless steel by the same method, while Sect. 3 was identified as type 304 stainless steel by semiquantitative and photoelectric methods. It contained 19% Cr, 8% Ni, 0.5% Mo, 0.9% Mn, 0.6% Si (by semiquantitative analysis, values in the range times 1/2 to times 2), and 0.3% Co, <0.05% Nb, <0.05% Ta, <0.05% Ti, 0.2% Cu (by photoelectric methods, with $\pm 5\%$ precision). The cobalt and copper levels are reasonable for modern steelmaking practice, according to Armco and Crucible Steel representatives. Since two out of three springs were type 304 stainless steel, an improper material substitution had occurred.

Only the alloy X750 spring had an obvious fracture surface sufficiently free of mechanical damage for fractographic analysis. Other fracture surfaces are presumed to have been damaged while the pump was still operating. The fracture surface of the X750 spring is shown in Figs. 1 and 2, viewed from two different angles by scanning electron microscopy. Most of the sample end has been mechanically damaged, and none of the intersection of the failure with the original wire surface remains. This is unfortunate because the compression of a coil spring results in an essentially torsional state of stress about the wire axis, with the highest stresses on the outer fibers. Fracture might be expected to initiate at the outside of the wire, in the absence of other defects, and progress inward. The available unsmeared fracture surface consists of dimpled regions typical of ductile tensile failures, separated by ledges where rubbing appears to have occurred, either during final separation or perhaps during cyclic straining.

None of the spring lengths was exactly 12.7 mm (0.5 in.), the nominal new spring length. Only one end of each spring had a flat machined surface covering a whole coil circumference. Plant operators state that springs often "lose a coil," and the small pieces are not found. The remainder of the spring then must operate at a different stress. It is thus likely, but not demonstrable, that all the springs broke at least once.

Fig. 1 Oblique View of Failed Alloy X750 Spring, Including Both Areas of Mechanical Damage and a Small Region of the Original Fracture Surface. Note the ledge structure and elongated "dimples" at progressively higher magnification.

Fig. 2. View of Failed Alloy X750 Spring at Shallower Angle to Wire Axis Than Fig. 1, but Showing Much of the Same Area. The region of "elongated dimples" now has the appearance of classical "ductile dimples" usually associated with ductile tensile failure.

The alloy X750 spring was mounted and polished into the fracture area, and etched with a standard aqua regia reagent. It is shown in Fig. 3. A few small laps can be seen at the wire surface; most of the fracture end is smooth from mechanical damage. The fracture surface shows evidence of tearing that is morphologically sensible by comparison with the scanning microscopy. There is no evidence of internal fracturing away from the failure; grain boundaries are difficult to discern. Away from the fracture, several large inclusions were found (Fig. 4); large voids at either end of the inclusions along the wire axis probably formed during wire drawing. These inclusions are not unusual¹ in nickel alloys like X750. The microhardness of the material is 595 DPH, but because the material may be worked as well as aged, the significance of this number is not clear. We have identified no evidence of improper heat treatment.

A coil of a type 304 stainless steel spring was mounted, polished, and etched with 50% aqua regia — 50% water solution. Its microstructure is shown in Fig. 5. It exhibits a nonequiaxed structure, considerable deformation bands and twinning, and 603 DPH microhardness, all of which are reasonable for cold-drawn type 304 stainless steel spring wire.

Analysis of the nominal stresses of the unbroken springs gives some insight as to which spring, if any, should have broken (assuming nominal original dimensions). The nominal shear stress in a circular cross-section, helical coil spring is given by:²

$$\tau = K_a G d \delta / \pi N D^2 ,$$

where the symbol definitions are given along with values for the two springs in the unbroken condition in Table 2. The most important

¹T. K. Roche, ORNL, private communication.

²E. Oberg and F. D. Jones, *Machinery's Handbook*, 19th ed., Industrial Press, New York, 1974, pp. 494–502.

Fig. 3. Fracture Surface of Failed Alloy X750 Spring. 100×. The V-shaped region is all that remains of the original fracture.

Fig. 4. Inclusion in Failed Alloy X750 Spring. 500×. By comparison with Huntington Alloys data sheets, the smaller precipitate particles are suspected to be $\text{Ni}_3(\text{Al}, \text{Ti})$.

Fig. 5. Microstructure of Cold Worked Type 304 Stainless Steel Spring. 400x.

Table 2. Properties and Calculated Stresses of Unbroken Springs

Property	Spring 1	Spring 2
Material	Alloy X750	304 Stainless
d , Wire diameter, mm (in.)	0.70 (0.0275)	0.76 (0.030)
G , Modulus of rigidity ^a		
GPa	82	76
psi	11.9×10^6	11.0×10^6
D , Coil diameter, ^b mm (in.)	4.564 (0.1795)	4.52 (0.178)
δ , Deflection of spring, mm (in.)	1.78 (0.070)	1.78 (0.070)
N , Number of turns	8	6
$K_a = \frac{4D - d}{4D - 4d} + \frac{0.615d}{D}$	1.23	1.26
τ , Nominal shear stress		
MPa	240	340
ksi	34.8	49.3

^aData from Mechanical Properties Data Center, *Aerospace Structural Metals Handbook*, AFML-T2-68-115, Belfour Stulen, Inc., Traverse City, Mich., 1971.

^bMeasured at center of wire.

factor causing the computed stress in the type 304 stainless steel to significantly exceed that of the alloy X750 spring is the number of coils.

Knowing the computed stresses, we now ask whether the springs should have borne these stresses without failure. The answer is not straight-forward. A multitude of factors affect the allowable working stresses for springs,³ and design stresses for "light," "average," and "severe" service differ, on the basis of industrial experience and fatigue data. One simple criterion is to limit the maximum imposed tensile stress to less than 0.35 times the ultimate tensile strength, a design stress factor used for nonferrous materials for some applications.⁴ As a point of interest, the minimum UTS for type 304 spring steel is about 2.1 GPa (300 ksi) while that for alloy X750, fully age hardened, is about 1.5 GPa (220 ksi).⁵ Assuming that the materials had minimum strength properties, the calculated initial torsional stress of each spring is then about 0.16 times the ultimate tensile strength of the material.

However, the duty imposed can probably be classified as "average" to "severe," the latter including "rapid deflections over a long period of time as in automobile and aircraft engine valves, pneumatic hammers, hydraulic controls, etc...,"³ with fatigue limits being the most important (see Fig. 6). The suggested 10^6 -cycle-fatigue-life stress for type 304 stainless steel spring material is slightly over 345 MPa (50 ksi) for "average" service and slightly below 275 MPa (40 ksi) for "severe" service. Failure of the type 304 stainless steel springs after 6.3×10^5 cycles at 339 MPa (49.3 ksi) is credible.

The "raw data" fatigue curves for alloy X750 in the "spring temper" in the *Aerospace Materials Structural Handbook*⁵ (Fig. 7) show some

³E. Oberg and F. D. Jones, *Machinery's Handbook*, 19th ed., Industrial Press, New York, 1974, pp. 534-39.

⁴R. LeClaire, Associated Springs, Bristol, Conn., private communication.

⁵Data from Mechanical Properties Data Center, *Aerospace Structural Metals Handbook*, AFML-TR-68-115, Belfour Stulen, Inc., Traverse City, Mich., 1971. Code 4105, p. 3 for aged-hardened alloy X750. Code 1303, p. 8, Fig. 3.0217 for spring type 304 stainless steel.

Allowable Working Stresses for Compression Springs*

* Although these curves are for compression springs, they may also be used for extension springs and for torsion springs; for extension springs, reduce the values obtained from the curves by 10 to 15 per cent; and for torsion springs, increase the values obtained from the curves by 50 to 60 per cent.

Fig. 6. Allowable Working Stresses for Compression Springs.
Reproduced with permission from Oberg and Jones, *Machinery's Handbook*, 19th ed., Industrial Press, New York, 1971.

Fig. 7. Fatigue Data for Alloy X750 in the Rolled Spring Temper Condition and After Aging. Reproduced with permission from *Aerospace Structural Metals Handbook*, Belfour Stulen, Inc., Traverse City, Mich., 1971.

variability with heat treatment condition, but 10^6 - and 10^8 -cycle endurance limits appear to be above 414 and 275 MPa (60 and 40 ksi), respectively, compared with the calculated 239 MPa (34.8 ksi) applied stress. However, *Machinery's Handbook*³ gives maximum recommended working stresses of 379 MPa (55 ksi) for both 18-8 stainless steels and Inconel X (alloy X750). Further, the industrial design allowable stress under these conditions for alloy X750, spring temper, is lower than the allowable stresses for either 18-8 or 17-7 stainless steel.⁴ Whether the alloy X750 spring should have failed before the type 304 stainless steel spring is a moot point. Alloy X750 can be used to higher temperatures than 18-8 stainless steel, but that is immaterial for this service.

Three other factors might contribute to the failure of the X750 spring:

1. Nonsymmetrical loading could occur after the presumed failure of the type 304 stainless steel springs. There is no way to judge the magnitude of this effect, if it occurs at all.

2. Stress concentrations could arise from inclusions and voids (see Fig. 4) in the alloy X750 spring. This effect is also difficult to assess quantitatively, and damage to the fracture surfaces makes it impossible to metallographically assess the likelihood that this mechanism was operative.

3. "Edge damage" observed on the outside of each spring may be a more important factor. Several spring manufacturers and suppliers warned that "edge damage," rubbing wear on the outside surface of the helix, can drastically reduce spring life. Surface condition is known to have a pronounced effect on fatigue life of most materials.⁶ The flats worn on the outside of the individual coils of each spring subtended up to 30° of included angle of the wire cross section. This damage may be more important than the basic strength considerations discussed above, but we have no way to quantitatively assess its effects.

CONCLUSIONS

Several conclusions can be drawn from this analysis:

1. Type 304 stainless steel springs had been substituted for some of the alloy X750 springs in the C104 hydrogen compressor. The lengths and end conditions of the springs suggest that each had broken, but only the alloy X750 spring had an identifiable region of fracture surface.

2. The calculated initial shear stresses in the type 304 stainless steel springs were higher than those calculated for the proper alloy X750 spring. Difference in geometry is the most significant factor affecting the calculated stresses.

3. The calculated initial stress in the type 304 stainless steel springs was near the 10^6 -cycle fatigue life according to available fatigue curves. Edge damage may have played a role in the presumed

⁶J. F. Watkinson, "The Influence of Some Surface Factors on the Torsional Fatigue Strength of Spring Steels," pp. 445-458 in *Proc. Int. Conf. Fatigue of Metals*, New York, Nov. 28-30, 1956, Institution of Mechanical Engineers, London, 1957.

failure of the type 304 stainless steel springs. However, the known data base suggests strongly that for low-temperature service, a properly designed type 304 stainless steel spring may be adequate, rather than the more costly alloy X750. This point deserves further exploration.

4. The undamaged alloy X750 spring was loaded to the same calculated fraction of its ultimate strength as the type 304 stainless steel spring. Loading effects from failure of the type 304 stainless steel springs, stress concentrations resulting from inclusions, or edge damage from rubbing against other surfaces may have played a role in the failure, with the latter likely the most important.

RECOMMENDATIONS

The following actions are recommended:

1. Springs should be carefully identified and substitutions avoided.
2. The possible use of a properly designed spring made of type 304 stainless steel should be explored.
3. Possible redesign to avoid edge damage to springs should be explored.

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